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Exploring how adaptive resistance can be used to create exergame mechanics that increase physical output and improve posture.

Exploring how adaptive resistance can be used to create exergame mechanics that increase physical output and improve posture.

By

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AUTHORS DECLARATION

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of others, is indicated as such. Any views expressed in the dissertation are those of the author.

Signed:

[redacted]

Dated:

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LIST OF ACRONYMS

BPM: Beats Per Minute
EMS: Electrical Muscle Stimulation
GPU: Graphic Processing Unit
GSR: Galvanic Skin Response
GUI: Graphical User Interface
GVS: Galvanic Vestibular Stimulation
HAR: Human Activity Recognition
HCI: Human Computer Interaction
HMD: Head-Mounted Display
HUD: Heads Up Display
IMU: Inertial Measurement Unit
LBP: Lower Back Pain
LT: Lactate Threshold
MR: Mixed Reality
PACES: Physical Activity Enjoyment Scale
PWC: Physical Work Capacity
RPE: Rate of Perceived Exertion
SDK: Software Development Kit
TENS: Transcutaneous Electrical Nerve Stimulation
TLX: Task Load Index
TUI: Tangible User Interface
UI: User Interface
VE: Virtual Environment
VR: Virtual Reality
WMSD: Work Related Musculoskeletal Disorder
XR: Extended Reality

PUBLICATION LISTING

The following outputs were published during my period of research. Certain material and concepts from these publications will necessarily be presented within the body of this work.

CONFERENCE PAPERS

ECCE 2019: Proceedings of the 31st European Conference on Cognitive Ergonomics.
Carrot & Stick: Electrical Muscle Stimulation output generated through incentivised / de-incentivised exergames.

ECCE 2019: Proceedings of the 31st European Conference on Cognitive Ergonomics.
Switching it Up: Designing Adaptive Interfaces for Virtual Reality Exergames.

ECCE 2019: Proceedings of the 31st European Conference on Cognitive Ergonomics.
CartRight: Maintaining Good Posture in the Presence of Adaptive Haptics.

TEI 2018: Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction. Feeling Virtual Worlds: An Exploration into Coupling Virtual and Kinaesthetic Experiences.

INVITED TALKS

Campbell, J: Adaptive haptics within immersive exertion based tasks. European Virtual Reality and Healthcare Symposium. December, 2019, Dublin.

Campbell, J: Enhancing Wellness Through Physiologically Controlled Immersive Video Games. Pervasive Media Studio Lunchtime Talks. May 2019, The Watershed, Bristol.

Campbell, J: Feeling Virtual Interaction. 3DCamp Dublin AR / VR Meetup. February 2019, Workday, Dublin.

Campbell, J: Gamification of Physical Exercise in Immersive Environments. Cork VR Meetup. January 2018, Crawford College of Art and Design, Cork.

DOCTORAL CONSORTIUM

CHI 2018: Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems.
Exploring The Relationship Between VR Immersion, Adaptive Resistance and Physical Exertion.

INDUSTRY INTERVIEWS

Campbell, J: Feeling Obstacles in VR With a Wheelchair. October 2017. Hackster.io.

Campbell, J: How Unreal Engine is Impacting Exergaming Research. September 2017. Showcased Developer, UnrealEngine.com.

Campbell, J: Simulating VR Obstacles With Wheelchair Brakes. June 2017. Hackaday.com.

POSTERS

IHCI 2015: Proceedings of the 9th annual Irish HCI conference. 'Carrot & Stick'; a comparable study of physical output generated through incentivised / de-incentivised exergames.

CONTENTS

CHAPTER 1: INTRODUCTION

1.1: OVERVIEW

In 2022, more than 1.9bn adults are classified as being overweight with studies predicting that one fifth of adults worldwide will be obese by 2025 (NCD Risk Factor Collaboration, 2016). Diet and sedentary lifestyle choices are some of the contributory factors; for example, less than half of American adults adhere to the recommended 2.5 hours of moderate, aerobic physical activity per week (Ward et al., 2013). The application of gamified immersive physical exercise is one way to counteract obesity and its associated health conditions. Research has demonstrated that exergames can motivate enhanced physical output (Peng et al., 2011) and that “encouraging young adults to switch from inactive to active videogames may provide a substantial population-level public health benefit for obesity prevention” (Leatherdale et al., 2010).

Rizzo et al. (2011) maintained that exergames lacked the fidelity to fully replicate conventional exercise, however, they did believe it had potential, stating: “advances in full-body interaction systems for providing vigorous interaction with digital games are expected to drive the creation of engaging, low-cost interactive game-based applications designed to increase exercise participation”. The availability of affordable VR hardware (Oculus Quest 2, 2019) and unprecedented financial growth in the exergaming sector, justifies their predictions to some extent.

At the 2021 annual AR & VR conference, Facebook's CEO and Founder, Mark Zuckerberg announced that their exergaming title, ‘Beat Saber’, had amassed in excess of $100 million in revenue, making it the highest selling title on the Oculus Quest since the platforms inception (Suttrich, 2021). During the same month, Facebook (rebranded as Meta) announced its intention to acquire the LA based exergame studio Within for $400 million (Heater, 2021). These acquisitions demonstrate that billion dollar companies like Meta see potential growth from developing and investing in virtualised home exercise.

In addition to immersion and embodied interaction, certain virtual exercycling platforms (Zwift, 2019; Peloton, 2018) utilise smart trainers which allow the exergames to generate physical resistance relative to the slope and terrain of the virtual cycling environments. Zwift subscription rates currently exceed three million (Reed,2021), demonstrating the training platform's appeal. However, not everyone is content with a *commercial* exergame experience. Unimpressed by the visual fidelity on offer in mainstream exercycle games, an underground cohort of virtual cyclists have taken matters into their own hands and have modified a version of the commercial video game Grand Theft Auto Five (Rockstar Games). In GTBIKE V, players can exercise while experiencing some of the artificial antics on the virtual island of ‘Los Santos’ (Matas, 2021).

The fact that 1300 former Zwift players made an informed choice to migrate to an amateur cycling platform based on the visual and interactive fidelity demonstrates the importance of keeping visual and interactive exergame experiences on par with commercial video games.

The way that commercial games apply resistance is limited and would appear to have a lot more potential. Rather than using dynamic resistance to replicate virtual slopes and terrain, kinaesthetic feedback could instead be used to encourage output by dictating task intensity. Separating user autonomy from task intensity would allow the game, rather than the person, to maintain optimum output. This type of game mechanic could be used to motivate physical activity and in doing so support healthy lifestyles. In addition to health and fitness it could also assist with proprioceptive training, skill acquisition and rehabilitation.

One final aspect in relation to developments in immersive interaction is how enhanced feedback on task performance could be used to improve the quality of physical output. Given the growth in the virtual fitness sector and predictions that mixed reality use in the workplace is set to increase significantly in the coming decade (Dalton & Gillham, 2019) it makes sense that people engage in these environments correctly to enhance performance and reduce injury.

1.2: AIMS

The research question addresses these issues by asking ‘How can variable or adaptive resistance be used to create motivating game mechanics?’. The question is answered through the development and user testing of several exertion based immersive games which feature novel physiological interface design and adaptive resistance. Each game alters exertion and challenge at key moments, providing a medium in which to investigate the relationships that exist between task intensity and user output.

With a view to supporting the research question, studies in this Thesis will examine the possibility of generating robust kinaesthetic feedback using limb actuation and brake friction. These preliminary studies will facilitate the use of incentivised or disincentivised game mechanics and determine if their application increases physical output. Haptic and visual feedback will also be combined in a separate study focused on motivating task quality.

A secondary research area (which serves the primary research question) is to ensure the immersive games used in these studies provide participants with graphical fidelity on par with commercial exergames. The enhanced visual medium will facilitate two other supporting motivational aspects: whether exercising while immersed in head-mounted VR can enhance output; and whether manipulated user data displayed on a heads-up display can increase exertion. I hypothesise that the proposed interventions will generate enhanced physical performance and that the results will be a novel contribution to both the HCI and virtual fitness communities.

The studies in this Thesis were developed and tested over the following periods: Carrot or Stick: December 2014 - June 2015, Switching It Up: September 2015 - June 2016, Feeling Virtual Worlds: September 2017 - June 2018, CartRight: November 2018 - July 2019 and Chase or Be Chased: January 2021 - September 2021.

1.3: THESIS STRUCTURE

The body of work described in this Thesis consists of a series of exploratory studies which aim to investigate how variable resistance can be employed in the design of exergame mechanics to encourage higher levels of physical output or to guide form.

With a view to assisting the narrative, the studies will be presented relative to category rather than the chronological timeline. The two strands of work are those which feature the influence of resistance alone and studies which feature the influence of augmented resistance. The influence of resistance alone is explored in Chapter Three (Carrot or Stick) and Chapter Four (Chase or Be Chased). In the second, the influence of augmented resistance is investigated in Chapter Five (Switching it Up) and Chapter Six (CartRight). The following paragraphs outline the structure of the Thesis and provide an overview of the content covered in each Chapter.

1.3.1 Literature Review

This chapter discusses publications which have been influential on this body of work. It is categorised into the areas of resistance, embodied interaction and immersion. The resistance section describes the various methods used by HCI practitioners to simulate haptic feedback. These methods have been categorised under the headings of tactile feedback and kinaesthetic feedback. The elements discussed in these sections are electro muscular stimulation, robotics, electromechanics, electromagnetics, air propulsion and pneumatics. Following that, the second section of the chapter examines research that has combined physiological output with machine input. It provides a brief history on the legacy of exergaming and human activity recognition and reviews prior work that has applied movement guidance in real and virtual environments for a variety of applications. The section also discusses novel biofeedback loop systems used in exergaming in addition to industry guidelines for integrating real-time biofeedback data within VR UI design. The third and final section relates to immersion and how it can be used as a game mechanic to motivate behaviour in physical exercise. The section discusses the dissociative properties of immersion and how they can be used to enhance output and increase enjoyment during resistance based activity. The importance of high visual fidelity in HCI studies is also discussed as is the use of deception as a game mechanic in immersive exergaming. The chapter concludes by identifying existing gaps in the related work and how the studies in this Thesis intend to address them.

1.3.2 Technical Contribution

Chapter Three documents the workflow and iterative design process that led to the generation of bespoke interface design featured in all of the user studies. In addition to providing a technical breakdown on the interfaces used in Chapters Four, Five and Six, the chapter also features two exploratory studies, Carrot or Stick and Feeling Virtual Worlds. Carrot or Stick investigated whether electro muscular stimulation could be used to actuate limb movement during a weightlifting exergame. The technology was not robust enough to fulfil the projects requirements and therefore discontinued. Feeling Virtual Worlds was a feasibility study that investigated whether brake friction and VR motion tracking could be combined to create a mobile mixed reality interface capable of withstanding full body force. A modified version of this system features in Chapter Six. In addition to hardware customisation the chapter also contributes by demonstrating how high-end graphical fidelity can be used in research studies through the use of commercial game engines and the customisation of existing commercial games.

1.3.3 Exploring The Impact Of Unaugmented Resistance On The Quantity Of Exertion

A lack of automated task control within exergame design has meant that exercise intensity and output is reliant on human motivation rather than mechanised intervention. The study in this chapter addresses this issue by removing the user from the decision process and allowing the computer to dictate the level of task intensity expected from the user. Chase or Be Chased adjusts the resistance on a smart trainer relative to the user's performance while they play an exercycle game. Two conditions were compared to investigate whether incentivised game mechanics can be used to encourage enhanced physical output. If a user is working below a specified threshold, resistance on the physical interface increases, hindering their game performance. Correspondingly, if a user's output level is above a predefined benchmark, resistance decreases, facilitating task completion. Task intensity is generated in this exergame using dynamic resistance by means of electromagnetics. Taking Kahnemans' loss aversion theory into account the hypothesis is that participants will work harder to avoid increased resistance in the Being Chased condition than they will to earn decreased resistance in the Chase condition (Kahneman et al., 1991).

There was no relevant data to differentiate between the benefits of variable resistance framed as a penalty or as a reward as a game mechanic. However, the study demonstrates that chase based game mechanics can be used to motivate enhanced physical output through the medium of an exergame without diminishing the enjoyment aspects of gamified physical activity.

1.3.4 Exploring The Impact Of Augmented Resistance

Switching It Up is a physiologically controlled exergame in which the player's exertion influences their avatar's performance. The study continues to explore relinquished control in exergame design and investigates whether user output can be increased when task intensity is adjusted manually by another person (simulating system control as a game mechanic).

In addition to augmented resistance, the study design investigated how other factors in VR known to influence exercise output - varying display immersion and manipulated physiological data - might interact with variable resistance. Immersion was compared by playing the exergame in a fully interactive VR environment viewed through a HMD and as a non-immersive version that only features basic data displayed on a monitor. For the manipulated physiological data condition, heart rate (BPM) displayed to players was reduced by 20%.

Based on the effect dissociation has on enhancing physical output (Razon, 2009; Chuang, 2003) I expect that VR immersion will generate enhanced output. Falsified heart rate has never been used to motivate physical output, however researchers have managed to do so using other forms of deception (Stone et al., 2012; Löchtefeld et al., 2016). On this basis, I hypothesise that a falsified reduction in displayed user heart rate will generate increased physical output. No prior research has investigated the relationship between resistance and exertion and therefore this aspect of the study has no hypothesis to work off. I expect that the interaction effects between the conditions will enhance the experience generating greater output than their main effects.

The study showed that players were able to achieve increased exertion through one of three game interventions (immersion) and that there was a significant interaction between resistance, immersion and deception which impacted on the participants' perception of time pressure. When there were no adjustments made to resistance, and displayed player heart rate was manipulated the users in the non-immersive condition perceived that the exercycle task was more rushed than it had done when viewed through the HMD. In addition to validating the dissociative benefits of visual stimuli, the findings also suggest that immersion and data manipulation can be used independently to reduce the perceived time pressure in an exertion based task, however when used simultaneously they nullify the dissociative benefits of enhanced immersion.

1.3.5 Exploring The Impact Of Augmented Resistance On The Quality Of Exertion

Enhancing the quality of a physical task through a virtual medium is an underexplored area which has the potential to improve people's physical health. Whereas Chase or Be Chased and *Switching It Up,* focused on enhancing the *quantity* of physical output, C*artRight* aims to address this issue by focusing on enhancing the *quality* of the task performance during exergame activity. C*artRight* is an immersive exergame based around the day-to-day activity of grocery shopping. The interface features a type of ‘hybrid reality’ design whereby physical resistance can be replicated in the real world based on the user’s virtual interactions.

Two experimental studies were conducted to explore whether adaptive haptics can affect user posture, and determine whether real-time feedback on posture can increase a user’s ability to be mindful of their postural choices. Based on prior findings by Glitsch et al. (2007), I hypothesise that pushing hindered by dynamic haptic interventions will increase the likelihood of incorrect or poor posture.

On the basis of prior work by Vignais et al. (2013), I expect that augmented visual feedback will improve user posture. Finally, on the basis of results published by Michalski et al. (2019), I expect that improved posture will remain after the feedback is removed. The results demonstrated that resistance directly influenced posture negatively, and that visual feedback led to a significant improvement in user posture, during and beyond the presence of postural feedback.

1.3.6 Discussion

Chapter seven discusses the research gaps identified over the duration of this Thesis and the methods used to investigate these areas. The chapter focuses on the contributions made relating to the bespoke interface development used to address the research question, in addition to discussing the outcome of their application in the user studies. The chapter expands on the contributions made in each of the studies and discusses how they could be applied in different scenarios with a view to supporting researchers and designers seeking to motivate output using resistance based game mechanics. In addition to discussing the contributions of this work I also draw attention to its limitations and suggest ways in which to address these conditions in future work. The chapter concludes reflecting on how research and industry have changed over the duration of this Thesis and how my contributions align with current and predicted trends relating to exertion based virtual interaction.

The following chapter provides an overview of influential research and commercial activity which have motivated me to focus on the areas of resistance, embodied interaction and immersion.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

This chapter provides a brief review of related work focusing on the areas of resistance, immersion and embodied interaction. The purpose of the review is to identify research that has been conducted in these areas to date in addition to identifying gaps that can be exploited with a view to assisting the research question. These gaps inspire and motivate the subsequent game designs as well as inform the methods used during the empirical studies.

Section 2.2 describes the various methods used by HCI practitioners to simulate haptic feedback. These methods have been categorised under the headings of tactile feedback, kinaesthetic feedback and involve the use of electro muscular stimulation, robotics, electromechanics, electromagnetics, air propulsion and pneumatics. The section identifies a lack of investigation relating to EMS and other actuating hardware for use in robust kinaesthetic feedback

Section 2.3 reviews prior work relating to immersion and how it can be used as a game mechanic to motivate behaviour in physical exercise. The section discusses the dissociative properties of immersion and how they can be used to enhance output and increase enjoyment during resistance based activity. The importance of high visual fidelity in HCI studies is also discussed as is the use of deception as a game mechanic in immersive exergaming. A review of the literature reveals a gap in existing research relating to user testing with the latest stereoscopic hardware, in addition to a limited understanding of how resistance interventions impact on physical output. Furthermore, I also identify a lack of visual fidelity in bespoke HCI studies which can impact on the player experience. Finally, a review of physiological deception identifies how manipulated user data could potentially motivate output during immersive exergame activity.

Section 2.4 examines research that has combined physiological output with machine input. It provides a brief history on the legacy of exergaming and human activity recognition and reviews prior work that has applied movement guidance in real and virtual environments for a variety of applications. The section also discusses novel biofeedback loop systems used in exergaming in addition to industry guidelines for integrating real-time biofeedback data within VR UI design. The literature review reveals limited use of adaptive resistance within immersive postural studies. Any studies that do feature haptics, have used tactile feedback only.

The chapter concludes by summarising the gaps which have defined the research question in this Thesis (*How can variable or adaptive resistance be used to create motivating exergame mechanics that increase physical output and improve posture*), and outlines how these areas will be addressed in the coming chapters.

2.2 RESISTANCE

Haptic is a term derived from the Greek "haptesthai" which means "to come in contact with" by providing the sense of touch with both tactile (cutaneous) and kinaesthetic (proprioception) feedback. The area of haptics can be divided into tactile feedback and kinaesthetic feedback. Tactile feedback describes the sensations felt by the skin, it allows us to feel texture, vibration and temperature. Kinaesthetic force feedback enables us to recognise a force that is applied to our body by the help of sensoric cells located at the end of the tendons or between the muscle strands (Ramsamay et al., 2006).

Although the area of haptic feedback is divided between tactile feedback and kinaesthetic feedback, these areas have been redefined by different researchers according to different classifications. Certain researchers prefer to use the terms active and passive rather than tactile and kinaesthetic to distinguish between feedback styles (Teng et al., 2018). This classification is made on the basis of power usage. If a haptic device has a battery it is deemed to be active, otherwise it is passive. The vibration in a mobile phone or the rumble in a game controller are examples of active haptic feedback. The Logitech K830 keyboard is an example of how passive haptics can be used in a VR environment (McGill et al., 2022). The physical keyboard seamlessly overlaps with a virtual counterpart allowing users to type on their computer keyboard while in a virtual environment.

Those working with exoskeleton technology identify three categories of haptic feedback: passive, semi-passive and active. Passive haptics: devices that do not move, semi-passive haptics: devices that do not move but can stop movement and active haptics: devices that move. The Logitech K830 keyboard could also be applied to the passive haptic scenario in this classification. An example of a semi-passive object is the Dexmo exoskeleton (Zhang et al., 2016). This device features powered actuation units, however, rather than using them to actuate movement they are used to restrict movement, known as haptic constraint. By limiting finger movement the Dexmo device can replicate the sensation of grasping a virtual model. The area of active haptics (also referred to as 'Haptic Rendering' (Salisbury & Srinivasan, 1997)) involves some form of actuation on the user's skin or limbs. Research to date has generated active haptics using varied mechanical, electromagnetic and pneumatic technologies.

Haptic and force feedback are classified in different ways and there is no absolute taxonomy that is adhered to. For the purpose of consistency and clarity, haptic feedback in this chapter will be divided into two categories, tactile haptics and kinaesthetic haptics.

2.2.1 Tactile Feedback

Tactile haptics involves stimulation generated by touch only and involves no form of rendered force. They have been used extensively in real environments to provide an alternative feedback modality (Knapp, 2001), to improve training (Stach, 2011) and to reduce poor posture (Zheng & Morrell, 2010).

These will be discussed in the haptic guidance section. The following paragraphs will focus on various ways that tactile haptics have been generated in virtual environments.

Tactile haptics can be implemented in a Virtual Environment without having any powered actuators or moving elements. This is done using static physical props to generate tactile clues. Simeone et al. (2015) generated several immersive experiences to create what they describe as substitutional reality. This concept involves replicating every physical object in a room with a virtual counterpart. Insko (2001) refers to this type of tactile feedback as passive haptics and has demonstrated that they can be used to enhance perceived immersion. In his Thesis, user data showed significant increases in behavioural presence, heart rate change, and skin conductance when passive haptics augmented the virtual environment.

A popular method for simulating tactile feedback in immersive interactive applications is through the use of glove worn exoskeletons. Yem & Kajimoto (2017) developed FinGAR (Finger Glove for Augmented Reality) by combining electrical and mechanical stimulation to achieve high fidelity tactile sensation. Other developers have experimented with air as a medium to generate tactile sensations in VR. Aerial uses air vortex generation to deliver tactile sensations in free air and enables users to feel virtual 3D objects, experience free air textures and receive haptic feedback on gestures performed in free space (Sodhi et al., 2013). Whitmire et al., (2018) heightened tangible immersive experiences through the use of textural sensation. Their Haptic Revolver interface consisted of a handheld virtual reality controller with a motorised wheel that rotates beneath the user's finger to render a variety of physical textures. As the user's finger moves over a virtual surface, the device rotates under the fingertip generating dynamic tactile sensations relative to the texture in the virtual environment (Figure 2.2, 3).

Ramsamy et al. (2006) argue that physical feedback can influence presence in virtual environments and that haptic interfaces can enhance the virtual interaction by enabling users to "touch" and "feel" virtual objects that are simulated in the environment. They posit that the haptic cues of touch and force, complement the usual visual and aural modalities used in current VR simulations and that immersive human interaction capabilities are restricted if the users are deprived of sensorial cues experienced in the real world. I concur with this statement, and I believe that the studies I have discussed do enhance the virtual experience, however, there are limits to the forces these devices can generate.

2.2.2 Kinaesthetic Feedback

Kinaesthetic haptics have the ability to physically move parts of the user's body using force feedback technology. Dynamic kinaesthetic feedback has been replicated using commercial robotic arm actuators such as the Phantom Omni, which render external forces against the finger or hand (Silva et al., 2009).

Morris et al. (2004) developed a bone surgery simulation platform, which permitted an instructor to remotely provide real-time feedback to the trainee. However, the force generated by a Phantom Omni is designed to replicate the physical feedback encountered in medical procedures and is not robust enough to generate or withstand the full force of an adult limb. Limitations such as these have meant that research has had to rely on bespoke interface development in order to generate alternative kinaesthetic feedback. The following examples feature innovative hardware that has been developed to bypass the strength limitations of existing resistance hardware, using electro muscular stimulation (EMS), robotics, electromechanics, electromagnetics, air propulsion and pneumatics.

2.2.2.1 Electro Muscular Stimulation

An unconventional approach to generating force feedback, which has emerged in HCI circles in recent years, is the use of EMS. Unlimited Hand is a commercial hardware device, which uses EMS to generate involuntary limb actuation. It can be used to enhance realism and presence in virtual gaming by its ability to adjust the movement of the user's forearm, palm and fingers (Unlimited Hand 2019) (Figure 2.1 1).Transcutaneous electrical nerve stimulation is generally applied to stimulate nerve endings in order to block pain, whereas neuromuscular electrical stimulation is widely used for training muscles, both in the sports area and for rehabilitation purposes. Both methods are based on the electrical stimulation of nerves or receptors using impulses at different frequencies and intensities. According to Kruijff et al. (2006), in theory every kind of nerve or nerve ending, or receptor can be triggered by electrical stimulation, depending on the kind of stimulus provided to the user. These stimuli differ in pulse length, frequency, amplitude and triggering mode.

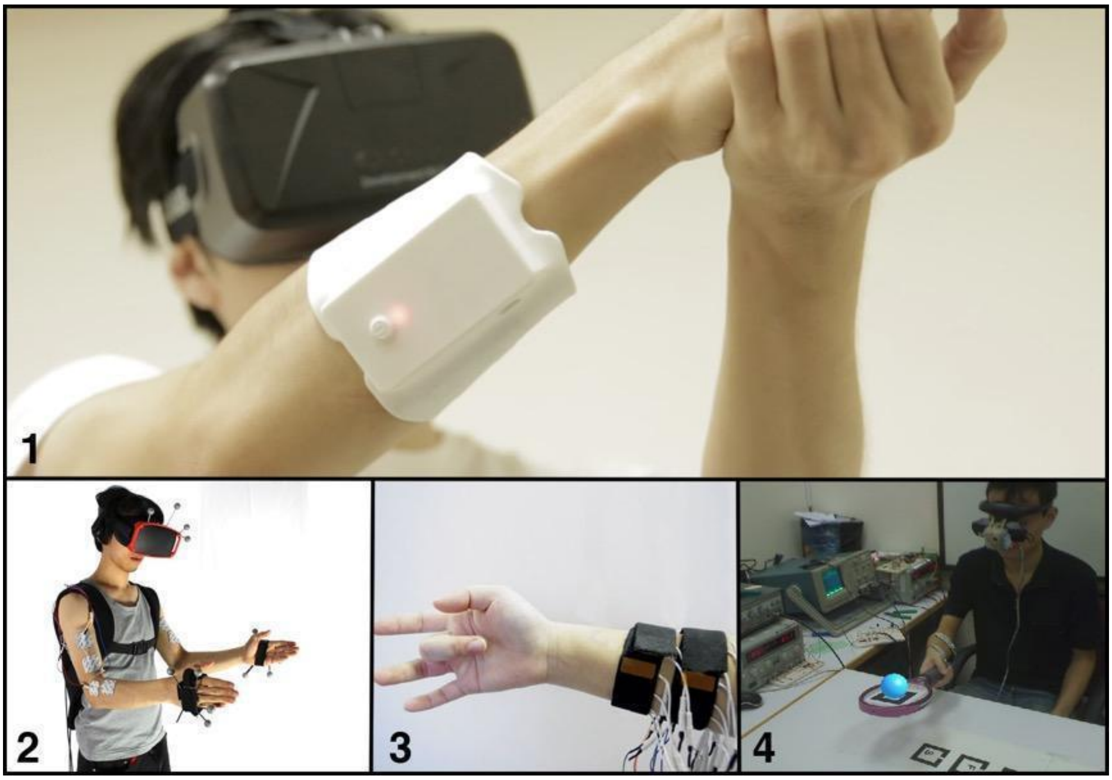

Figure 2.1 Montage of EMS Related Projects. 1. Unlimited Hand. 2. Haptics for VR Walls. 3. Possessed Hand. 4. Haptic Feedback for Mixed Reality Tennis.

An example of EMS being applied in an HCI setting can be seen in Tamaki et al.'s (2011) PossessedHand. The device can control a user's fingers by applying electrical stimulus to the muscles around the forearm (Figure 2.1, 3). Each muscle is stimulated via twenty eight electrode pads. Muscles at different depths in the forearm can be selected for simulation by varying the stimulation level. The authors proposed using their device to train muscle memory and facilitate learning musical instruments (for example guiding and hinting finger movements and tempos and rhythm through involuntary actuation). PossessedHand could automatically calibrate its system for individual control and could stimulate the motion of 16 joints in the hand, however the forces generated by EMS actuation were not sufficient to grab a real object.

Lopes & Baudisch (2013) used electrical muscle stimulation to miniaturise force feedback for use in a mobile gaming application and demonstrated the merits of such scaling over physical actuators that are hard to scale down while maintaining force. During their study they measured the force of the involuntary palm contraction and noted that their interface was able to generate force equal to and above that generated by a Phantom Omni.

Farbiz et al. (2007) created a mixed reality tennis game consisting of a physical racket and a virtual ball. Electrical pulses generated muscle contraction on the user's forearm proportional to the collision impact of the virtual ball (Figure 2.1, 4). Although the authors claim that 'the moment the player hits the virtual ball, they feel the muscle contraction on their forearm proportional to the collision impact as if they hit a real ball'. However this research was presented in poster format, no follow up user study was conducted, no paper was published and therefore there are no findings to reference. In saying that, the fact that it involved EMS generated kinaesthetic feedback to simulate the sensation of a physical activity in an immersive world was of interest.

In a subsequent study, Lopes et al. (2017) integrated EMS generated force feedback within a virtual environment which could provide virtual objects with physical forces (Figure 2.1, 2). They demonstrated a fully mobile system that empowered a Mixed Reality Game experience with mid-air force feedback by means of electrical muscle stimulation. Their system used EMS stimulation to actuate the user's wrists, biceps, triceps and shoulder muscles, generating what they termed as 'repulsion' feedback. The premise was to discourage participants from passing through virtual walls by actuating their limbs when collision was detected. 'Repulsion' feedback was generated in two conditions, using haptic feedback with vibrotactile motors and using kinaesthetic feedback with EMS. The results demonstrated that the EMS-based design performed better. However, there were limits to the force generated by the 'repulsion' feedback and if a user wanted to, they could have put their hands through the virtual walls.

TECHNICAL CONTRIBUTION: APPLYING EMS TO EXERGAMING

In their paper Muscle-Propelled Force Feedback: Bringing Force Feedback to Mobile Device, Lopes & Baudisch (2013) reference Tamaki et al.'s PossessedHand, stating that *"The technique targets situations where the user's input must be mediated or assisted, such as while learning to play a musical instrument. Unlike this assistive approach, our work counters the users' input, causing it to be perceived as force feedback"* . I agree with this statement and am particularly drawn to the use of the word 'perceived'. The way Lopes & Baudisch generated actuating forces on par with a Phantom Omni is commendable. However, in the same way that the Phantom Omni has a force limitation, so too does the level of EMS actuation generated in both of their studies. I don't dispute that their studies generated kinaesthetic feedback but I was eager to see whether EMS was robust enough to be exploited in an exergaming context to fully dictate limb movement rather than being used as a perceived force.

Carrot or Stick is an exploratory study discussed in Chapter Three that aims to actuate a user's limb while they are holding a dumbbell weight. The purpose of the study is to see if EMS is a viable and practical way to implement limb actuation and also whether it is robust enough to generate adequate force feedback for use in further studies involving resistance. Having discussed EMS resistance the following paragraphs will discuss studies which have generated kinaesthetic feedback using robotics, electromechanics, electromagnetics, air propulsion and pneumatics.

2.2.2.2 Robotics, Electromechanics, Electromagnetics, Air Propulsion And Pneumatics

In 1993 Kazerooni & Her (1993) created a 'two degree of freedom' electrically powered exercise machine at the University of California-Berkeley's Motion Control Laboratory Lab. The prototype used robotic resistance to generate kinaesthetic feedback, facilitating dynamic levels of limb resistance. The authors stated that "A limitation in passive exercise machines is that they do not offer flexibility in their dynamic behaviour, existing weight machines can only produce constant forces (i.e., gravity) for the users". This motivation was very related to certain aims in this Thesis, however their design was never expanded upon or applied to an exergame interface.

That same year, McNeely (1993) described a 'conceptual solution' that in decades to come could be used to replicate tactile sensations based on interactions and touch based gestures within VR. His proposed design "robotic shape display" involved a force-feedback robot equipped with a "shape cache," a variety of shapes and textures to simulate all the possible objects that could appear in a particular VR scenario. Araujo et al.'s Snake Charmer study (2016) took this concept and put it into practice twenty five years after McNeely's conception. The system consisted of a robotic device which aligned physical surfaces to virtual objects, exactly as McNeely had envisaged. The robot dynamically rendered texture, temperature, and physical weight to provide richer tactile feedback in virtual reality. However, the level of resistance generated was limited and would bend if participants pushed too hard against the arms endpoint.

Strasnick et al. (2018) developed ‘Haptic Links’, electro-mechanically actuated physical connections that can generate varying levels of tension between two VR handheld controllers. The connections between the handheld controls (Figure 2.2, 1) have the ability to adjust the perceived force(s) between the user’s hands and in doing so enabled kinaesthetic feedback within several pre-designed virtual scenarios. Users found virtual interactions with haptic feedback to be more realistic than those without. The maximum stiffness level in the device was enough to present rigidity, however, it could be overcome through the user’s full strength, demonstrating limits in the system's force.

Figure 2.2 Research Projects Using Actuated Hardware. 1. Haptic Links. 2. RealWalk. 3. Haptic Revolver. 4. Taclim Cerevo.

Commercial smart trainers such as the Wahoo Kickr use electromagnetics to generate dynamic resistance on a stationary bicycle relative to the virtual slope and terrain of their avatars environment (Wahoo, 2021). Hardware customisation on these devices is restricted so as to maintain customer loyalty with affiliated third party exercycle companies (Zwift, 2019). A lack of access to SDK and API data has limited researchers in adopting this hardware for use in bespoke projects. Out of one hundred and twenty seven articles on google scholar that have featured a Wahoo Kickr, only one had involved customising the device; all of the others used the proprietary or affiliated software. PaperDude did utilise the incoming speed from a Kickr however, when contacted, the authors confirmed that their game design did not feature resistance implementation (Bolton et al., 2014).

Realwalk used a smart fluid based haptic actuator called magneto rheological fluid which immediately changes its viscosity when subjected to a magnetic field (Son et al., 2018) (Figure 2.2, 2). The game engine dynamically adjusted the viscosity of the fluid by varying the magnetic field intensity depending on the type of virtual surface to create kinaesthetic feedback of ground deformation and tactile feedback of texture thus providing a high fidelity VR walking experience.

Their study compared RealWalk with vibrotactile-based haptic shoes (Figure 2.2, 4) and demonstrated that the RealWalk provided higher ratings for discrimination, realism, and satisfaction. A limitation of the device was its reliance on a power source which meant that both shoes were constantly tethered limiting mobility.

Thors Hammer used propeller propulsion to generate air based kinaesthetic feedback within VR (Heo et al., 2018). The device could generate 4 N of continuous and precise force feedback in various directions and enabled participants to interact with virtual simulations such as the resistance of water flow and being pulled by a leashed pet. A user study demonstrated that interacting with the device helped participants feel more immersed in each of the VR scenarios. The developers noted that high latency limited the use of the device to interactions that didn’t require instant feedback.

Ye et al. (2019) used pneumatic artificial muscles to actuate the user’s body to move up to 15 cm by pulling his or her hands. The muscles work to generate linear motion based on the retraction or extension of an inner pneumatic tube, which the authors refer to as *active kinaesthetic force feedback*. Users perceive the kinaesthetic force feedback by suspending their weight with arm exertion during the interaction. This tube was placed inside a braided mesh and enabled various actuated exercises in VR such as moving with the waves in kitesurfing and up-soaring motions in paragliding. Limitations of the device were slight latency from the air compressor and a lack of mobility caused by the suspended nature of the device and its necessity to be tethered to the air compressor.

According to Stach & Graham (2017), exergames currently lack the physicality of real world sports and that haptic feedback is crucial to activate the tactile sensations associated with physical exercise. They believe that exergaming interactions can feel artificial, as they are less physical than those experienced in real world exercise. In order for an exertion based interface to realistically emulate levels of resistance encountered in real world scenarios it is important that it can generate sufficient levels of physical force and that the controlling mechanism can be dynamically adjusted. I agree with these comments and want to make immersive physical activity more realistic with a view to enhancing physical output. However, in order to generate sufficient levels of force, its necessary to have an interface capable of robust kinaesthetic feedback.

TECHNICAL CONTRIBUTION: APPLYING KINAESTHETIC FEEDBACK VIA BRAKE FRICTION

The kinaesthetic feedback used in the studies discussed can generate force to some extent, however issues with latency, weight or movement restrictions prevent systems such as these from being used in a fully mobile exergame. The robotics used in Snake Charmer and the motorised actuation in Haptic Links lacked sufficient force. The air propulsion system used in Thors Hammer had too much latency for real-time dynamic feedback. While Pull-ups and Realwalk generated sufficient force, Pull-ups had to be tethered to a compressed air source and Realwalk had to be tethered to a power supply limiting both systems from being used in a mobile exergame.

This is a gap that is addressed in Chapter Three and Chapter Six of this Thesis. Feeling Virtual worlds is an exploratory study discussed in Chapter Three that aims to generate kinaesthetic feedback capable of withstanding full body force on a mobile mixed reality interface. The study employs incremental brake friction to generate varied resistance. The interface developed in Chapter Three also facilitates a further study (CartRight, Chapter Six) to investigate the relationship between task intensity and user posture.

2.3 IMMERSION

The following section will review previous research relating to the area of immersion. The areas being discussed are motivational behaviour in physical exercise, immersion & dissociation, immersion & resistance, visual fidelity, and immersion & deception.

2.3.1 Motivational Behaviour In Physical Exercise

An authoritative sports psychology paper published by Morgan et al. (2008) studied the cognitive strategies of marathon runners and demonstrated how differing cognitive strategies play a pivotal role in determining how an exertion based task is perceived and executed by a user. The authors defined two key exercise categories: association where runners focus on their own bodies, and dissociation in which attention to the environment distracts from the body. They found that associative approaches were dominant in elite marathon runners, while amateur runners used a dissociative strategy. Prior research has shown that thought content becomes less dissociative and more associative as the intensity of a physical activity increases. As dissociation from the physical task decreases, the user becomes more aware of the unpleasant signals coming from their body leading to a reduction in physical output (Baden, 2004).

Exergames seek to increase physical output by distracting participants from real world exertion using goal oriented immersive gameplay. Prior research by Glen et al. (2017) compared psychological and physiological output during interactive and non-interactive exercycle activity and demonstrated that dissociation and enjoyment are higher when playing the exergame. Although dissociation can enhance output, Hutchinson & Tenenbaum (2007) posit that there is a limit as to how long distractions can enable people to remain in a dissociative state; there is a cut off point when the task intensity gets so high that users become unable to take their mind off the physical task and user exertion drops. According to Ekkekakis et al. (2011) ensuring that the user enjoys the exercise experience is important, otherwise dissociation from the physical task decreases and the user becomes more aware of the unpleasant signals coming from their body.

One of the ways in which enjoyment and dissociation can be maintained is through combining audio and visual stimulation during physical activity. According to Mäyrä & Ermi (2011), sensory experiences such as these support the engagement process by leading players to forget about the sensory input from the real world and focus on the sensory input from the virtual world. Fritz et al. (2013) investigated the effects of music on perceived exertion during a physically strenuous task.

In their study they measured psychological exertion during a workout with and without musical agency while simultaneously acquiring metabolic values. Results showed that musical agency significantly decreased perceived exertion during workouts, indicating that musical agency may actually facilitate physically strenuous activities. Correspondingly, Karageorghis & Priest (2012) showed how music could reduce perceptions of effort at low to moderate intensities of exercise. These studies have demonstrated that intervention in the form of an aural modality could positively impact on a user's motivation during a task involving physical exertion.

An expansion of the aforementioned research can be seen in the work of Razon et al. (2009). Their research examined links between perceived exertion and dissociation by focusing on both auditory *and* visual sensory modalities. They note that several sensory modalities are required to effect perceived exertion and attention allocation while engaging in demanding workload. Participants that were given both forms of sensory information remained in a dissociative strategy for a significantly longer duration than participants in all other conditions. They argue that the distractions are likely to contribute to the pleasantness of the exercise experience, ultimately leading to increased exercise participation and reduced dropout rates.

The positive impact audio and visual media had on dissociation influenced a review of prior studies which had incorporated immersive techniques. The following paragraphs will discuss studies that have been conducted to investigate the impact of immersive interaction on pain reduction, dissociation and energy expenditure.

2.3.2 Immersion & Dissociation

According to Jennet et al. (2008), 'immersion involves a lack of awareness of time, a loss of awareness of the real world, involvement and a sense of being in the task environment. Most importantly, immersion is the result of a good gaming experience'. The following examples look at how immersive technologies have been applied to various studies to increase distraction, enjoyment and energy while reducing fatigue, pain and tiredness.

The potential of immersion to distract from physical pain can be seen in the work of Gold et al. (2005) which used VR gaming to facilitate pain distraction during the treatment of chemotherapy and venipuncture patients. Although the game is not exertion based it demonstrates the power that enjoyment and immersion have in limiting associative thinking when necessary.

The dissociative benefits of immersion have also been used to reduce sensations of physical pain and fatigue during virtual exercise. Chuang et al. (2003) compared the physiological responses between immersive exercycling and regular exercycle activity. Their results demonstrated that VR provides mental support and motivated participants to resist fatigue and maintain endurance. The VR content used in their user study was displayed on a TV screen.

Mestre et al. (2011) examined the impact of music and video feedback on physical performance during an exercycle game. They maintain that ‘sensory stimulation appeared to have a dissociative role on participants’ attentional focus during exercise’. Their findings suggest that music diverted participants’ attention from the exercise whereas video feedback alone did not have any significant effect. It should be noted that although VR featured in the study title the virtual environment was video footage rather than computer generated.

Plante et al. (2003) conducted a user study whereby eighty eight participants were randomly assigned to one of three cycling conditions: cycling on a stationary bike, playing a mountain bike video game (involving an avatar cyclist but requiring no real world cadence), and a VR exergame that was controlled by cycling a stationary bike. Their study demonstrated that exercise performed through the medium of VR enhances enjoyment and reduces tiredness. The immersive content in both of the VR conditions was displayed on a computer monitor.

Finally, Glen et al. (2017) compared psychological and physiological output during interactive and non-interactive exercycle activity. Their study featured two exergame conditions with varying levels of immersion. The authors demonstrated that increased immersion generated greater dissociation and enjoyment. Reductions in perceived pain and fatigue noted in the studies highlight the dissociative benefits of VR and how this dissociation is relative to the level of immersion.

These studies have demonstrated the merits of immersion in reducing perceived pain during physical activity however none of the exergame studies featured VR headsets which according to Cummings & Bailenson (2016) is better than visual content for enhancing immersion. This is a limitation that will be discussed at the end of this section. The following paragraphs discuss studies which have examined the impact interactive gaming can have on motivating enhanced energy expenditure.

Warburton et al. (2007) demonstrated that a training program linking interactive video games to cycle exercise resulted in greater improvements in health related physical fitness than that seen after traditional cycle exercise training. Furthermore, Monedero et al. (2015) posit that ‘a single bout of interactive cycling video game resulted in a significantly higher rate of energy expenditure than a bout of conventional cycling'. These hypotheses are also confirmed in Porcari et al.’s (1998) study which demonstrated that participants exercising in a virtual environment had higher heart rates and burned more calories than participants without virtual simulation. The outcomes of all of the exergaming studies clearly outline the linkages between immersion dissociation and exertion.

RESEARCH GAP: ANALYSING THE RELATIONSHIP BETWEEN HMD IMMERSION & PHYSICAL OUTPUT

An issue with studies involving emerging technology is the rate at which the medium being researched can date. As the dissemination of video game entertainment has evolved with various platform changes and societal trends over the last four decades, so too has the level of immersion afforded to the user. Developments in Graphics Processing Units (GPUs), affordable and lighter head-mounted displays (HMDs) and real-time game engine rendering have provided a new wave of exertion based experiences. Cummings & Bailenson (2016) conducted a meta-analysis of eighty three studies involving immersion to understand the effect immersive system technology has on user experiences of presence and concluded that stereoscopy had the greatest impact on perceived presence. Although stereoscopic displays do enhance immersion, all of the exergaming studies mentioned in the previous paragraphs used either monitors or projection screens, none featured head-mounted displays.

This gap is addressed in Chapter Six. The study Switching It Up features a comparable immersive condition, to determine if head-mounted display immersion impacts on physical output during exergaming activity. The user study features interactive gameplay on a VR headset (Oculus, 2016) for the immersive condition and basic user data on a computer screen for the non-immersive condition. This will be a replicated study, however, the use of an Oculus Rift DK2 was unique in 2016.

2.3.3 Immersion & Resistance

One aspect which I was interested in was the impact adaptive interfaces might have on physical output and how they could be utilised within an immersive exergame to motivate enhanced output. The following section examines prior exergame studies which featured adaptive resistance. One item to note is that although some of these studies did feature head-mounted displays, none of these studies were conducted prior to the Switching It Up study in Chapter Five.

Farrow, et al.'s (2019) exercycle study measured user output but also integrated resistance to see if intensity can be increased without impacting the users' level of enjoyment. Their study demonstrated that resistance can be increased by 10% without impacting on the user experience. In their study, intensity was raised by adjusting the ergometers' resistance, however, the rate of resistance was not dynamic and had no correlation with the virtual terrain viewed by the user.

Ijsselsteijn et al. (2006) conducted an exergame experiment to examine whether exercise behaviour can be stimulated through immersive technologies with the use of a virtual coach. The authors contend that this is possibly due to the fact that the presence of a virtual coach acted more as an extrinsic motivator than an intrinsic one. Their interface included variable resistance but the resistance only changed relative to the virtual slope of the environment and was not altered at specific times based on the user study or on game performance.

Dynamic resistance featured in Haller et al.'s (2019) study 'HIIT the Road'. The exergame involved cycling through a virtual environment in which various props would trigger contrasting results once hit. Colliding with an 'obstacle' caused extra resistance on the physical interface whereas collecting a 'reward' lowered its resistance. Similarly, a study by Shaw et al. (2017) featured virtual obstacles that could temporarily increase bike resistance if collided with. Michael & Lutteroth's study (2020) *Race Yourselves,* combined competition with dynamic resistance and enabled participants to race and compete against 3D representations of their estimated fitness potential. Although these three studies did implement resistance as game mechanics, player performance had no bearing on the degree to which it was implemented.

RESEARCH GAP: ANALYSING THE RELATIONSHIP BETWEEN VARIED RESISTANCE AND PHYSICAL OUTPUT

An aspect that is not addressed in any of the discussed immersive exergames is that none of the studies consider or analyse interactions between varied resistance and physical output. Without this feature, user output is reliant on user motivation rather than machine or third party dictation. This is an area worth investigating as it will demonstrate how dynamic or third party control of task intensity during exergame activity impacts on physical exertion.

The gap is addressed in Chapter Four, whereby the required level of exercise intensity is dynamically controlled by the videogame and not the player. The gap is also addressed in Study Five, whereby the interface resistance is manually adjusted by a third party at a specific moment during the exergame play.

2.3.4 Visual Fidelity

McMahan et al. (2012) examined the impact increased display and interaction fidelity had on the user experience and demonstrated that designers concerned with achieving high levels of presence, engagement, or usability should consider that higher levels of fidelity may be most suitable.

This sentiment is also echoed by Robertson & Good (2005) who posit that HCI experiments involving interactive games should present users with an experience at a standard equivalent to other interactive and immersive activities that they are used to performing. The authors used the Unreal Game Engine to develop 'Ghostwriter' a video game which would teach social development and ethical decision making to children. Their rationale for using the game engine was so that participants would experience the high quality graphics that they would already be accustomed to playing on home consoles.

Researchers might argue that their studies are not targeting video game enthusiasts however a person does not have to play video games to differentiate between visual detail or lack of.

This argument has previously been voiced by Lew et al. (2011) who posit that aesthetic differences in the visual quality of an experimental interface and the interface as encountered in real life can confound an experiment. The authors demonstrated that crude mock-ups and low level visuals in research experiments can negatively impact on user engagement. The authors claim that 'a lack of realism in the experimental interface or setting can undermine external validity' and in doing so alerts participants that they are being tested. This in turn can influence participants' mindsets by reducing their interest or pleasure which can influence the user's interaction with the manipulated treatment.

I have placed an emphasis on the visual quality of the exergame designs in each of my studies through a combination of bespoke virtual environment design and through the modification of commercially available game titles. In doing so, participants will be provided with industry standard immersive content. In doing so I aim to support the resistance based game mechanics by heightening immersion, increasing dissociation and enhancing physical output.

RESEARCH GAP: INTEGRATING VISUAL FIDELITY IN EXERGAME STUDIES
The visual quality and graphic fidelity in the bespoke HCI videogames I had researched had not been done to a high standard. This is an issue that needs to be addressed, as subjecting participants to visual and interactive experiences that are dated and lower in quality than experiences they engage with on a regular basis will have consequences on the data. A person does not have to play video games to differentiate between visual detail or lack of. This argument has previously been voiced by Lew et al. (2011) when their study demonstrated that aesthetic differences in the visual quality of an experimental interface and the interface as encountered in real life can confound an experiment. This design issue has been addressed in all of the studies in this Thesis through the use of bespoke game design, commercial game engines, detailed lighting, materials and modelling, and modifying commercial game titles. In doing so, I aim to increase user dissociation and enjoyment with a view to amplifying the motivational capabilities of the resistance based game mechanics.

2.3.5 Immersion & Deception

Various HCI studies have used psychological strategies to motivate enhanced output, one of them being deception. The following paragraphs discuss the topic of disinformation and its application to the realm of physical exertion.

Valins (1966) made use of real-time physiological feedback to demonstrate that physiological reactions can serve as a source of information that influence emotional behaviour. While not strongly linked with exertion, his study is one of the first to involve temporary user deception with regard to physiological feedback. Hutchinson et al. (2008) provided participants with false positive/negative feedback on completion of certain tasks. This study correlated exertion and physical tasks, although the feedback given was neither real-time nor physiologically based.

Stone et al. (2012) demonstrated that secretly augmenting an exercycle game with information from a prior workout enabled participants to complete a 4km time trial quicker than with accurate feedback. While the results were significant, resistance was not altered at any stage during the game play and the interface was projected rather than being viewed through a VR head-mounted display.

RESEARCH GAP: ANALYSING THE RELATIONSHIP BETWEEN DECEPTION & PHYSICAL OUTPUT

An aspect which I felt needed to be addressed was the lack of research examining the relationship between manipulated user data and physical output viewed through a VR head-mounted display. Immersive exergames have the ability to distract users from body pain during physical exercise, however there is a limit to everybody's level of dissociation, regardless of how immersive the environment is. When enjoyment lessens during exertion based tasks, users become more associative in their thought processes. This phase of exercise provides researchers with an opportunity to explore other game mechanics, one of them being deception. What I propose doing is creating a heart rate controlled exergame in which the users' heart rate will be displayed at all times but in certain conditions the displayed heart rate will be false. This game mechanic is implemented in Chapter Five and was a unique feature in a VR exergame when the study was conducted in 2016. The hypothesis being that marginal reductions in displayed BPM will generate enhanced physical exertion. Having discussed research relating to immersion, the following section will focus on related work in the domain of embodied interaction.

2.4 EMBODIED INTERACTION

The use of physiological output as a medium for interface control forms a common theme throughout this body of work. A necessity to merge human output with machine input led to a focus on related work that had examined the relationship between physical movement and computer interaction. The following sections will examine prior work relating to embodied interaction in the areas of exertion, movement guidance, biofeedback loops and biofeedback.

2.4.1 Exertion

Studies involving the use of exertion within Human Computer Interaction span multiple disciplines, from recreational activity (IJsselsteijn et al., 2004) to physical fitness (Monedero et al., 2015), from quantity based energy expenditure (Leatherdale et al., 2010) to quality based performance analytics (Velloso et al.,2016), as well as a multitude of highly relevant and related areas such as motivational psychology (Morgan et al., 2008), physical wellbeing (Kim et al., 2014), proprioceptive learning (Morris et al., 2007) and postural improvement (Wozniak et al., 2020). Exertion has been widely researched amongst the HCI community for various purposes and the most influential area of study on this body of work has been exertion based gaming or exergaming.

Recreational video games involving some aspect of physiological control are not necessarily a new phenomenon and have been in existence since the early 1980s. In 1982 Atari developed a proof of concept exergame known as the Atari Puffer (Figure 2.3 A). This game required the user to pedal a stationary exercise bike while wearing a breath measurement apparatus. Rate of breathing was relative to the speed of the virtual cyclist shown on an Atari 2500 console. For various reasons the Atari Puffer was never commercialised, yet its concept helped to inspire the design of contemporary commercial exergame hardware (Wahoo Fitness, 2021) (Figure 2.3 J), (VZfit, 2017) (Figure 2.3 K), (Beat Sabre, 2018) (Figure 2.3 L)

Figure 2.3: Montage of Exertion based Game Interfaces: A. Atari Puffer. B. RacerMate CompuTrainer. C. Nintendo Power Pad. D. Foot Craz. E. Tectrix VR. F. Exertainment System. G. Dance Dance Revolution. H. Kilowatt. I. Nintendo Wii Fit. J. Zwift. K. VZfit. L. Beat Saber.

In addition to the Atari Puffer, Atari also released a balance board peripheral 'The Joyboard' for the Atari 2600 video game console (1982). It was controlled by standing on it and leaning in a certain direction, which would in turn control a virtual avatar. In 1986 RacerMates CompuTrainer (Figure 2.3 B) was released which utilised a stationary bicycle to control the speed of a virtual cyclist and in the following year Nintendo released a new edition of its NES game console which included the Power Pad (Figure 2.3 C) a peripheral which facilitated interaction by means of foot control. In the same year Exus released a similar peripheral known as the Foot Craz pad controller (Figure 2.3 D) for the Atari 2600.

During the 1990s several cadence based peripheral devices were developed that required some level of limb based exertion to propel a virtual avatar: Tectrix VR (Figure 2.3 E) in 1992, The Exertainment System (Figure 2.3 F) in 1994 and the CatEyes Game Bike in 1999. Dance Dance Revolution was also released in 1999 (Konami, 2019). It was a video game controlled by the user's feet while performing various dance combinations (Figure 2.3 G).

The game is of a particular genre called *Bemani*, a type of rhythm/music video game produced by manufacturer Konami. Another peripheral, albeit a less known one, is the Kilowatt (Figure 2.3 H) from Powergrid Fitness. The Kilowatt facilitated isometric exercise, it had no moving parts and used force sensors to translate player exertion into in-game movement.

The demise of the ‘video arcade’ brought about by the popularity and affordability of the home console market in the mid-late nineties helped perpetuate the legacy of exergaming. Gesture based recognition hardware such as Nintendo Wii (Nintendo, 2014), Microsoft Kinect (Microsoft, 2021) (Figure 2.4 A) and Sony EyeToy (2014) helped to bring the concept of exertion based gaming to the masses. EyeToy: Kinetic (Kendall, 2005) (Figure 2.4 B) was a commercial example of how low cost activity recognition technology could be utilised to target the home fitness market. It used a webcam to capture the user’s body and composit it on screen with virtual game elements, which the user had to interact with. During gameplay, a virtual trainer would provide feedback on the user's performance.

In 2007 Behrenshausen realised the impact that this affordable activity recognition technology would have on the gaming industry when he wrote ‘articulating dance with game play similarly explodes discourse of video gaming as a disembodied activity; the stereotypical image of the video gamer slouching sedentary on a sofa is completely undone by the notion of a video game that instead requires players to engage it with a locomotive, kinaesthetic, rhythmic, and wholly corporeal whirlwind of movement’ (Behrenshausen, 2007). Wii Fit and Wii Fit Plus (Figure 2.3 I) had combined sales of over 11 million units worldwide (Peng et al., 2011), highlighting how Behrenshausens enthusiasm was universal.

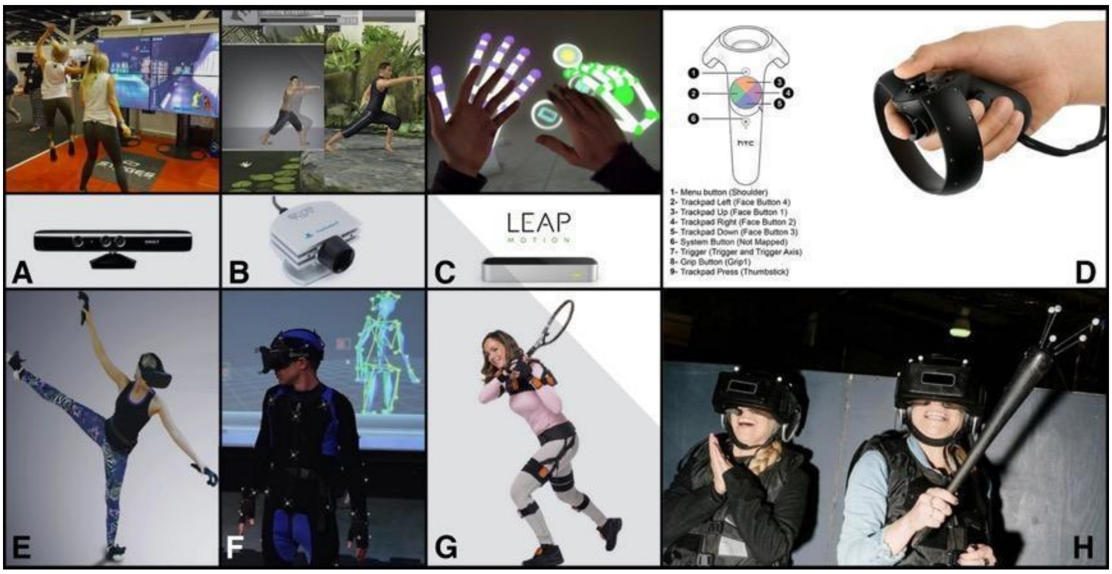

Figure 2.4 Montage of Human Activity Recognition Hardware. A. Microsoft Kinect. B. Sony EyeToy. C. Leap Motion. D. Vive Hand Controller. E. Motion Capture using Vive Trackers. F. Vicon Motion Capture Lab. G. XSens Wireless Motion Capture Suit. H. The Void.

In addition to the popularity based on revenue, research has also demonstrated that embodied interaction during video game play enhances enjoyment, immersion, exertion and energy expenditure. Bianchi-Berthouze (2013) argues that video games involving embodied interaction are successful because body movement during game play results in increased enjoyment (generated by cognitive and emotional processes). Nijhar et al. (2011) posit that increasing the precision of movement recognition within virtual interaction leads to higher levels of immersion. In addition to generating higher levels of immersion, it has also been attributed to motivating increased exertion. Kim et al. (2014) conducted a study to investigate how the level of interface embodiment effects physical activity during exergame play. They created three levels of user interface embodiment: low (Nintendo Wii), medium (Nintendo Wii Fit) and high Microsoft Xbox 360 Kinect). Their results revealed that the level of user interface embodiment increased participants' level of energy expenditure (change in heart rate); and intention to further engage in exergame-play exercise.

2.4.2 Movement Guidance

In addition to using Human Activity Recognition technology for the purpose of entertainment in the exergaming sector, it is also being used to facilitate motion capture and postural analysis. Recently there has been a switch from using expensive fixed optical motion capture systems to using Inertial Measurement Units (IMUs). Optical motion capture systems such as Vicon (Figure 2.4 F) use multiple infrared cameras, which are used to track the movement of body-worn retro-reflective markers in order to recreate the movement pattern in a real-time 3D application. Disadvantages associated with this type of motion capture are the time required to calibrate the cameras, the necessity to conduct user tests in a pre-calibrated lab and the hardware expense linked with the camera equipment. Bulling (2014) suggests that efforts to recognise activities in unconstrained daily life settings caused a shift toward using accelerometers or gyroscopes. Inertial measurement units such as accelerometers or gyroscopes have facilitated a less constrained and lighter affordable means of activity recognition. Smaller, portable and more affordable, the sensors require little or no calibration, have low power requirements, and enable untethered activity tracking over prolonged periods. Khan et al. (2014) were able to use a single accelerometer to recognise multiple states and activities in user’s daily lives over a four week period with an average accuracy of 97.9%. In an effort to establish the reliability of IMUs, Wong & Wong (2008) simultaneously recorded human activity data from a Vicon system and a sensor based posture monitoring system. Users participated in a series of daily tasks and posture data was found to be highly correlated and reasonably close in magnitude to those of the motion analysis system.

Limitations in these studies are that they were focused on measuring the quality of the technology rather than measuring the quality of the participants. However, when human activity recognition technology is combined with augmented guidance, it can be used to enhance performance and task quality. The following paragraphs examine this looking at previous work conducted in real and virtual environments.

2.4.2.1 Movement Guidance: Real Environments

Haptic guidance by a force feedback device provides additional proprioceptive cues during visuo-motor learning tasks. The following paragraphs examine prior studies which have applied this training method in practical scenarios with a view to enhancing manual dexterity, music technique and sitting posture, and maintaining concentration.
Feygin et al. (2002) used haptic interaction for the purpose of skill training, which they referred to at the time as haptic guidance. In their study participants were tasked with learning a complex 3D motion under three training conditions (haptic, visual, haptic and visual). Their findings demonstrated how haptic guidance can benefit performance, especially when training the temporal aspects of a task.

Van Der Linden et al. applied haptics to facilitate virtual training in an artistic context. Van Der Linden et al.'s Good Vibrations (2009) and MusicJacket (2010) studies combined vibrotactile feedback and motion capture to assist novice students learn the violin. Their system captured player posture and bow position while also providing user feedback relative to their bow movement. In the MusicJacket study, the authors compared conventional teaching methods with vibrotactile feedback and demonstrated that vibrotactile feedback was effective at improving straight bowing technique even when vibrotactile feedback was discontinued.

Zheng & Morrell (2010) used tactile feedback to assist with seated posture guidance. Force-sensitive resistors applied to an office chair were used to detect posture quality. Whenever the chair detected incorrect posture, vibrotactile actuators were used to direct participants towards a more ergonomic sitting posture. Results demonstrated that the feedback improved user posture and also led to postural improvement when the haptic feedback was subsequently disabled without the subject's knowledge.

According to MacLean, 'haptic interfaces offer the promise of creating an auxiliary information channel that can offload some of the cognitive load (associated with screen based platforms) by transmitting data to the human brain through a range of vibrations or other touch based feedback' (Wright, 2011). An example of this can be seen in a project conducted by the US Naval Aerospace Medical Research Laboratory. Researchers utilised haptic feedback to counteract spatial disorientation which can sometimes be generated by a pilots vestibular and somatosensory systems. The vest or the Tactile Situational Awareness System, alerted the pilot if they drifted off course and consisted of a matrix of vibrotactile motors which gave off vibrations based on information supplied by a small, portable computer from aircraft sensors (Knapp, 2001).

I do not see any limitations in any of the findings however, while the studies do entail some degree of movement, I was interested to discover further studies that had applied some form of guidance to tasks that involved a greater degree of physical exertion. The following paragraphs examine prior studies which have focused on guiding improved posture in the areas of golf (Woźniak et al., 2020), snowboarding (Spelmezan et al., 2009) and weightlifting (Kowsar et al., 2016; Velloso et al., 2013) using a variety of modalities.

In relation to guidance and physical activity in a real environment, Woźniak et al. (2020) developed an interface to improve beginner golf performance and facilitate unsupervised practise. The Subteltee system compared different modalities to see which had the best impact on improving stance, balance and elbow bend. User studies demonstrated that visual and vibrotactile feedback increased swing quality, however, the authors noted that audio feedback caused frustration and also lowered balance quality.

Spelmezan et al. conducted work on wearable automatic feedback devices for assisting people during daily physical activities and for supporting instructors and students during sports training (Figure 2.5). By using haptic technology along with a variety of pressure and inertial sensors they could improve student-instructor communication during snowboarding lessons. Instructors were able to remotely monitor a student's posture and when necessary guide the student to an improved stance using tactile or aural cues. A limitation of this study was the fact that it focused on real-time improvement where an instructor was always present. The system lacked any use of automotive assistance, preventing its use when there was no trainer present. The interface also lacked the ability to record performance for post ski analysis.

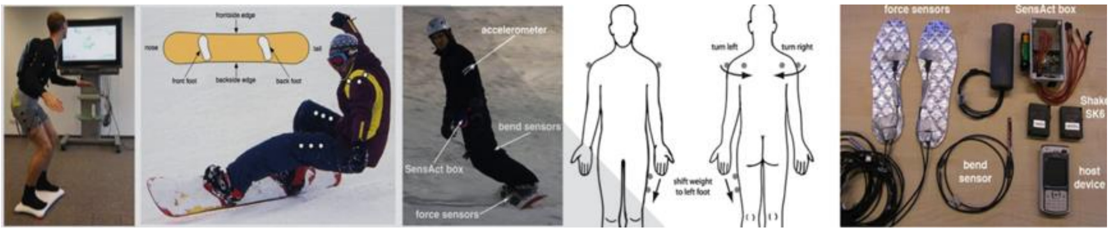

Figure 2.5 Tactile Motion Instructions for Physical Activities.

Kowsar et al. built a system to monitor technique when performing free weight exercises. Their design recorded the trainee performing a single correctly performed weightlifting routine which was then used as a quality benchmark to detect incorrect performance for the duration of the exercise session. A mathematical model designed by the authors could detect the start and end point of each repetition, while the user was performing a sequence of the recorded exercise. Using a biceps curl exercise they demonstrated that they could detect unseen anomalies in weight lifting exercises with 98 percent accuracy. Although the authors maintained their system could be used to improve technique and reduce injury, their claims were reliant on post-exercise analysis.

Velloso et al. conducted research on weight lifting activities with a view to enhancing the quality of the physiological interaction. The authors posit that conventional activity recognition is concerned with identifying which activity is performed, while qualitative activity recognition is concerned with assessing how well the activity is performed. By making use of activity recognition technologies they were able to determine how well a weightlifter executed a gym exercise in terms of their skeletal pose as opposed to the number of repetitions they completed. In addition to grading the quality of physical actions their system was able to provide audio and visual feedback to the user on how to improve their movements.

Results from their user study demonstrated that participants made 79.22% fewer mistakes performing bicep curl exercises with their system than without.

No performance data was gathered in Spelmezan et al.'s study, therefore it was not possible to establish how successful haptic guidance had been in terms of skill acquisition. While the system did generate haptic guidance, the relayed instruction was reliant on a remote trainer. Kowsar et al.'s study lacked any form of concurrent feedback. What was of interest however was the way in which Woźniak et al. had used vibrotactile feedback to improve a physical activity and how Velosso et al. had used visual guidance to enhance a task that involved a high degree of exertion. Qualitative supports such as these would have a lot of potential in improving technique and reducing injury during exergame interaction. However, they had been applied to non-immersive scenarios and no screens, projectors or HMD's had been used. Before applying real world qualitative guidance in an immersive context it was important to review what level of prior work existed in this domain.

2.4.2.2 Movement Guidance: Virtual Environments

In addition to being as reliable and affordable as more expensive mocap systems, IMU's and low cost movement based peripherals such as the Leap Motion (Leap Motion, 2016) (Figure 2.4 C), VR trackers (HTC, 2022) (Figure 2. 4 D & E) and Motion Capture Suits (Roetenberg et. al, 2009) (Figure 2.4 G) have enabled full body interaction to be used as a reliable controlling mechanism within the realm of virtual exertion based gaming. Technological advances such as these have facilitated a shift in focus within the domain of exertion based research from one of quantity to one of quality.

Virtual fitness is a rapidly expanding commercial sector with greater numbers of users engaging in virtual workouts on a daily basis (Peloton Investor Resources, 2021). However, they do so without knowing how efficiently their body is being put to use. Commercial VR exergames focus entirely on motivating output and in doing so they ignore the qualitative aspects of the physical activity. Games can motivate players to burn calories, however no data is collected on how well the tasks are performed, or how the user engages ergonomically. Given the lack of emphasis on task quality within exergame design, users are putting themselves at risk of injury by participating in virtual activities, without any feedback on the quality of their physical movement. On this basis, there is a need to promote task quality within the realm of exertion based interaction.

The following examples look at how qualitative recognition has been applied in virtual environments in relation to the areas of health and safety, workplace ergonomics, exergaming strategies, performing arts, physiotherapy and remote physical training.

Augmented visual feedback has been used to examine the influence of real-time postural feedback on participants involved in manual tasks in a real environment. Vignais et al. (2013) used a see-through head mounted display to notify participants about their posture.

Their research demonstrated how real-time ergonomic feedback can decrease hazardous postures and in doing so optimise worker performance.

Hu et al. (2011) also focused on improving employee posture in the workplace and recreated industrial workplaces in the form of simulated virtual mock-ups to identify potential ergonomic problems during an early design stage. They posit that eliminating issues in advance will reduce design time and costs, increase quality and improve customer satisfaction. Daria et al. (2018) pushed the boundaries on existing ergonomic studies by integrating motion capture and heart rate measurement. VR-Ergo permitted employers to test a workstation without having to build it physically in advance. By using immersive reality, the operator was able to move and interact within a virtual workplace environment, facilitating faster ergonomic assessments. Although these studies considered movement guidance the end user was either seated or standing with limited physical activity involved.

Pasch et al. (2008) conducted a movement analysis study which aimed to identify playing styles and related movement patterns adopted by exergamers while playing a boxing game. Using motion capture data, video recordings, and observer ratings they identified two specific motivational approaches used by the participants, in addition to playing strategies associated with these approaches. The authors noted that the Gypsy 6 motion capture suit (Gypsy, 2022) used to assist them with user analysis during exergame play was 'intrusive and potentially influences the gamers' experience'.

YouMove was an application that recorded an instructor's body movements, which were subsequently used to instruct trainees (Anderson et al., 2013). Users learnt physical movements by matching the pre-recorded movements which were visually augmented on the surface of a large mirror (Figure 2.6). Participants' movements were detected using a Microsoft Kinect (Microsoft, 2021). Results demonstrated that using YouMove generated better short-term retention scores than a video-based learning approach. However, issues with occlusion prevented the Kinect from tracking every limb accurately during certain poses.

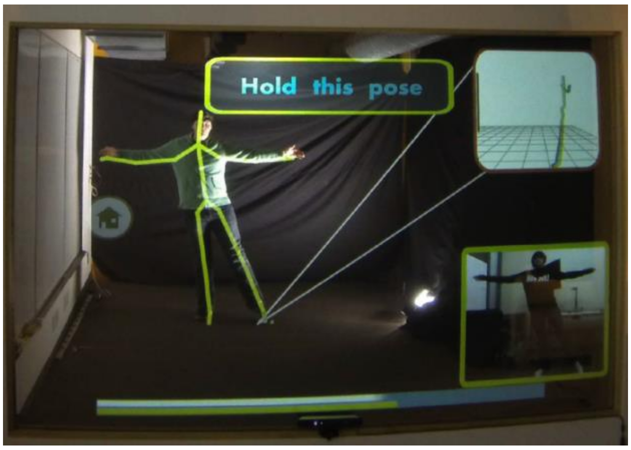

Figure 2.6 YouMove: enhancing movement training with an augmented reality mirror.

In their research paper ‘ Project Star Catcher’, Elor et al. (2018) used a combination of low cost motion capture and immersive gameplay to assist with upper limb rehabilitation. IMU’s within the HTC Vive hand controllers captured motion tracking data to assist with offline analysis. The findings demonstrated how virtual reality can be used to increase patient motivation during physiotherapy sessions and generate higher adherence rates compared to traditional forms of therapy. The use of the HTC Vive to track hand movement was of interest however the study lacked mobility or user exertion.

Hoang et al’s Onebody (2016) brought virtual training into a fully immersive setting and demonstrated how remote posture guidance during sports or physical activity training can be applied in a VR context. The instructor's avatar was rendered in place of the users’ virtual body, providing them with a first person perspective of the movement instruction. Their system implemented skeletal tracking of both the coach and the student, which were rendered as overlaid avatars. Unlike Youmove, which relied on pre-recorded instructor guidance, Onebody enabled the student to visualise the instructor’s limb positions and movements from a first person view in real-time within the head-mounted display. Comparable studies demonstrated that ‘posture matching accuracy’ was greater using OneBody, than with pre-recorded video, or third person VR. Although real-time feedback was visible to the user, it was reliant on the instructor being present. There was no mechanism to record or analyse user performance, to gauge task improvement or measure skill acquisition.

TECHNICAL CONTRIBUTION: ANALYSING THE IMPACT OF DYNAMIC RESISTANCE & VISUAL FEEDBACK ON MOVEMENT GUIDANCE IN VR

Enhancing the quality of a physical task through a virtual medium is an underexplored area which has the potential to improve people's physical health. Providing real-time postural feedback during exergame activity has the potential to improve physical performance and counteract threats of physical strain on the body. However, the research that has been discussed has limitations. The studies conducted by Daria, Hu and Elor did feature embodied interaction, but movement in these scenarios was minimal due to the fact that the studies were targeting bed bound patients or office workers. The study by Pasch et al. did involve exertion and posture, however, it was focused towards identifying various playing strategies rather than improving technique or posture. Findings from the studies conducted by Vignais, Anderson and Hoang demonstrated that augmented visual feedback could be used to improve posture and performance during physical activity. Their results aligned with findings from Wozniak et al. and Velloso et al. who demonstrated that visual feedback can improve the quality of a real world exertion based task.

The use of adaptive resistance within immersive postural studies does not exist in current research. Any of the immersive studies that featured haptics used tactile feedback to generate haptic guidance. Any of the studies that involved significant resistance did not feature immersion. What I propose is using kinaesthetic and visual feedback as a motivational game mechanic to improve task performance in an immersive exergame. This gap will be addressed in Chapter Six.

2.4.3 Biofeedback Loops

Biofeedback loops are a common feature in exergame design and involve some form of physical activity to control an immersive video game. Exergames have claimed to stimulate greater interaction and movement during play compared to traditional video game systems (Leatherdale et al., 2010). One of the most widely used forms of determining a user's physical output is with the Borg Scale (Borg, 1962), which is sometimes referred to as Rate of Perceived Exertion (RPE). This measurement technique involves asking a participant to quantify their perceived level of physical output on a scale between six and twenty. The scale starts with "no feeling of exertion," which rates a 6, and ends with "very, very hard," which rates a 20. Moderate activities register 11 to 14 on the Borg Scale ("fairly light" to "somewhat hard"), while vigorous activities usually rate a 15 or higher ("hard" to "very, very hard"). Dr Gunnar Borg, set the scale to run from 6 to 20 as a simple way to estimate heart rate. Multiplying the Borg score by 10 gives an approximate heart rate for a particular level of activity. This scale was used as a means of quantifying user exertion in each of the studies in Chapters Four, Five and Six.

Existing research has measured and compared energy expenditure rates between both mediums. A study by Lanningham-Foster et al. (2006) demonstrated that playing an exergame can expend double the amount of energy used in playing a traditional video game. Although such comparative results sound impressive, their significance depends on the level of energy expended in the traditional video game. Not all researchers have held the same optimism regarding exergaming energy output. Rizzo et al. (2011) suggest that exergaming activities do not deliver the recommended daily amount of exercise for children. However, they believe it may change in the future as 'new advances in novel full-body interaction systems for providing rigorous interaction with digital games are expected to drive the creation of engaging, low-cost interactive game based applications designed to increase exercise participation in persons at risk for obesity'.

It was apparent that some of the claims made in relation to exergaming energy expenditure were ambiguous and that there was a need to focus on studies that had quantified exertion output in a detailed manner. Studies by Miyachi et al. (2010), Albinali et al. (2010) and Leatherdale et al. (2010) have made use of up-to-date technologies and in doing so have provided the research community with precise energy measurements relative to the tasks involved. Miyachi et al. conducted a study that utilised a metabolic chamber to measure the energy expenditure of sixty eight activities in Wii fit plus and Wii fit sports. They conclude that the time spent playing one-third of the activities supplied by Wii Sports and Wii Fit Plus could count towards the daily amount of exercise required according to the guidelines provided by the American College of Sports Medicine and the American Heart Association. Albinali et al. looked at how real-time measurement of energy expended during everyday activities could enable and improve the development of novel health monitoring and wellness technologies. In their study they developed a system to estimate energy expenditure using wearable accelerometers. Leatherdale et al. demonstrated that energy expenditure is significantly higher playing an active video game compared to the inactive video game according to heart rate monitor estimates.

A frequent form of feedback in projects that have involved physiological interaction is that of user heart rate. The Wii Vitality sensor (a pulse oximeter peripheral for Nintendo's Wii console) was launched in 2009. The device was designed for use in relaxation games and was eventually disbanded due to inconsistent user readings. This illustrates how physiological monitoring is not without its technical challenges. This issue is discussed in Chapter Three, where several brands of commercial heart rate monitors were piloted before a satisfactory BPM reading was brought into the system.

In addition to the usage of commercial heart rate peripherals these technologies have been influential on certain academic papers. Masuko & Hoshino (2006) integrated real-time heart rate readings to develop a fitness game, which can dynamically adjust graphics and gameplay based on a user's movements and physiological parameters (Figure 2.5). The system can detect whether the user is exercising at, below, or above the optimal intensity and thus dynamically require the Games subsystem to switch.

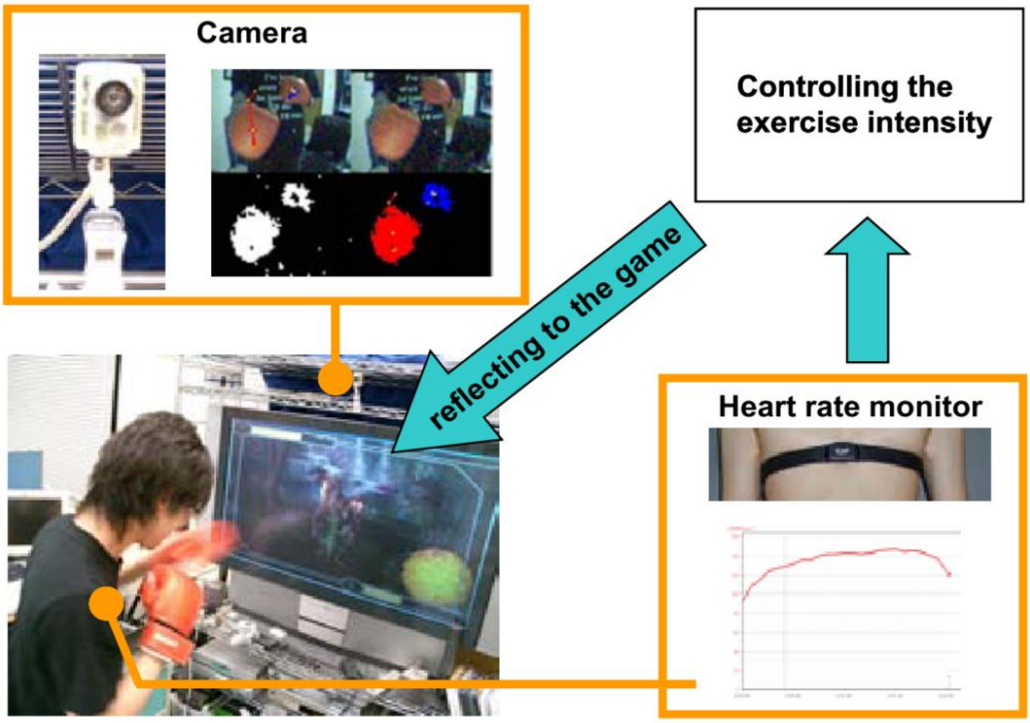

Figure 2.5 Fitness game reflecting heart rate.

Heart rate can be seen in the paper published by Stach et al. (2009). This study introduces a dynamic aspect to exergame design by basing game performance on the player's effort relative to their fitness level rather than on pure power. Real-time heart rate data is used to scale the game performance.

Furthermore, Nenonen et al. (2007) integrated user heart rate as a user variable to control a physically interactive biathlon (skiing and shooting) computer game. In this study the avatar's skiing speed is directly proportional to the user's heart rate.

Mokka et al's 'Fitness Computer Game with a Bodily User Interface' (2003) used immersion in the form of a projected virtual environment; while the project did measure heart rate, the BPM measure was not used to control the virtual character.
In 'Jogging over a Distance', Mueller et al. (2010) created what they term a 'technologically augmented social exertion experience'. Their system uses heart rate data to control a spatialised audio setup, which in turn facilitates a collocated running program.

Having researched these studies I was confident that immersive exergames could be used to motivate enhanced exertion and that heart rate could be used as a physiological measurement to control an exergame. There was no apparent gap identified at this stage. The following section will look at recommendations for relaying physiological data with an immersive interface.

2.4.4 Biofeedback

Augmented or extrinsic feedback is defined by Schmidt et al. (2015) as information that cannot be elaborated without an external source such as a trainer or display mechanism. Inversely, intrinsic feedback is the proprioceptive sensation felt by a performer as they engage in physical movement. Feedback can be provided 'concurrently', during a task, or 'terminally' after the action has been completed. Ruffaldi et al. (2011) argue that concurrent or real-time feedback is a 'fundamental feature for developing the training scenario and it is the natural choice in the context of Virtual Environment technologies'. Michalski et al. (2019) utilised augmented visual feedback within a VR game to investigate whether such a medium would be viable for improving skill acquisition among table tennis players. Their results demonstrated that concurrent feedback improved technique even when the augmented visuals were removed.

It is one thing to understand the benefits of augmented visual feedback in a virtual world however it is also important to know how to put this into practice. The use of relaying dynamic data within VR game environments is not without its challenges, particularly in relation to displaying concurrent physiological data. Oculus discourages the use of traditional 2D heads-up display design, and instead encourages developers to embed that information into the environment: *'Remember that users can move their heads to glean information in a natural and intuitive way that might not work in traditional video games. For instance, rather than a mini map and compass in a HUD, the player might get their bearings by glancing down at an actual map and compass in their avatar's hands or cockpit'* (Yao et al., 2014).

Although there is a definite gap in available resources relating to UI design for VR interfaces, seeking or providing answers to this question would be a PhD in itself. While industry best practices in this area were minimal the recommendations that could be found (Yao et al., 2014; Alger, 2016) were instrumental in deciding how to relay data within the VR heads-up display in Switching It Up (Chapter Five) and in CartRight (Chapter Six).

2.5 CONCLUSION

Having reviewed related work in the area of resistance, immersion and embodied interaction I have identified the following gaps: an uncertainty relating to the kinaesthetic limits of EMS (2.2.2.1); a need for untethered hardware that can withstand human force (2.2.2.2); a need for exertion data that has been measured using up-to-date immersive hardware (2.3.2); the potential of resistance intervention as a game mechanic (2.3.3); the importance of visual fidelity in interface design (2.3.4); how user output might be enhanced through the manipulating of displayed physiological data (2.3.5); a need to investigate the possibilities of adaptive resistance within immersive postural studies (2.4.2.2).

The research gaps I have identified will be addressed through a combination of technical prototyping, empirical studies and aesthetic consideration. These have been facilitated through the development and user testing of several exertion based immersive games; all which feature novel physiological interface design and adaptive resistance. The following paragraphs will advise on where the various gaps are addressed in this Thesis.

The viability of different forms of resistance intervention are investigated in two prototype studies Carrot or Stick (3.1.1) and Feeling Virtual Worlds (3.2.2). Carrot or Stick addresses the uncertainty relating to the kinaesthetic limits of EMS by investigating if the technology is robust enough to implement limb actuation during a weightlifting activity. Feeling Virtual Worlds aims to generate kinaesthetic feedback capable of withstanding full body force on a mobile mixed reality interface using incremental brake friction to generate dynamic resistance.

In addition to testing the viability of different prototypes, the integration of dynamic resistance provides an opportunity to examine its capacity to motivate enhanced physical output. The Wahoo Kickr used in Chase or Be Chased (Chapter Four) adjusts task intensity relative to user performance, doing so enables the videogame rather than the user to dictate user output. Resistance intervention also features in Switching It Up (Chapter Five) and addresses the interactions between varied resistance and physical output.

The potential of dynamic resistance as a game mechanic to motivate the quality of physical output is addressed in CartRight (Chapter Six). This study uses incremental brake friction to generate varied resistance on an untethered wheeled interface; this setup facilitates an investigation between task intensity and user posture in a virtual environment.

The studies also aim to support the motivational benefits of resistance based game mechanics through the use of supporting visual elements. Graphic fidelity has been incorporated in all of the studies in this Thesis through the use of bespoke game design, commercial game engines, detailed lighting, materials and modelling, and modifying commercial game titles. Switching It Up features a comparable immersive condition, to determine if head-mounted display immersion impacts on physical output during exergaming activity.

Deception features as a game mechanic in the same study, and involves manipulated data displayed on the user heads-up display. Finally, augmented visual feedback features in the CartRight study with a view to improving postural quality.

The studies in the next four chapters address the various gaps that have been identified. In doing so I aim to demonstrate ‘how variable or adaptive resistance can be used to create motivating game mechanics’.

CHAPTER 3: TECHNICAL CONTRIBUTION

3.1 INTRODUCTION

The research question being asked in this Thesis is '*How can variable or adaptive resistance be used to create motivating exergame mechanics that increase physical output and improve posture* ?'. In order to answer this research question it was necessary to develop a number of systems that combined high-quality graphical environments with hardware devices that were able to apply variable resistance during exergaming. The initial studies necessarily used bespoke technologies: at the time, no exercise equipment was available that offered algorithmically controllable resistance able to support the planned studies. As this research was conducted part-time over approximately eight years, exercise hardware gradually became available that was able to be adapted with bespoke elements. By the time of the final study the Wahoo Kickr (Wahoo, 2021) platform could be used which generated resistance dynamically on a stationary bicycle. The graphical environments followed a similar trajectory: while in early studies they required significant development work to provide high quality environments to users, by the final study a mod of a commercial game (Grand Theft Auto V, 2022) was able to be used, allowing access to a very high quality virtual environment that cost $265 million to make. This Chapter seeks to highlight the technical work that underpinned the empirical studies presented in this Thesis by presenting the iterative development process emphasising the approach taken, and discussing the technical contributions that might be provided to the HCI community.

3.2 RESISTANCE ALONE

3.2.1 Carrot or Stick

In recent years exertion based video games have sought to encourage physical activity through goal oriented immersive gameplay. A challenging aspect of designing such games lies in mimicking the necessity to follow through with a series of repetitive strenuous tasks as one would in a non-gaming real world scenario. This first study sought to investigate whether incentivised and de-incentivised resistance intervention was capable of encouraging enhanced physical output while playing an exergame. At the time of this first study, force feedback had yet to be integrated within an exergame as a means of coercing physical output. Although various works had been published relating to kinaesthetic feedback generated through haptics, actuators and exoskeletons (Chapter 2.2.2); and equally HCI (Human Computer Interaction) projects had facilitated embodied interaction by means of commercial and bespoke peripheral hardware (Chapter 2.4.1). However, no investigation had harnessed both technologies with a view to examining their potential in motivating physiological output. This disparity influenced a study which replicated continuous repetitive exertion through a combination of embodied video game control and involuntary limb movement.

The aim of Carrot or Stick was to discover whether supporting (‘Carrot’) or impeding (‘Stick’) muscle actuation was more likely to enhance physical performance while playing an exergame. Task difficulty was automated in real-time by applying force feedback on the user's body, however, rather than doing so with a physical interface, force feedback was replicated by triggering involuntary limb movement on the user's upper body

The concept of a user’s limb being controlled involuntarily based on the performance of their *virtual self* through the medium of a video game offered the ability to produce a truly unique and embodied exertion based games experience. The system design required a method of dynamically adjusting real-time exertion on a player’s forearm while they performed a series of bicep curls holding a dumbbell. A critical factor in bringing such an idea to fruition was the successful implementation of dynamic force feedback.

Prior work has demonstrated that resistance and tactile sensations can be dynamically adjusted. Prototypes such Thor’s Hammer (Heo et al., 2018) uses propeller propulsion to generate force feedback, and Realwalk (Son et al., 2018) uses magnetorheological fluid to simulate the sensation of walking on various outdoor ground coverings. It was apparent that a lot more options were available when creating handheld prototypes but less creative freedom when replicating force feedback on a larger scale. When writing about the capabilities of haptics within VR systems, Benko et al. (2016) wrote, “the capabilities of current devices to render meaningful haptics lag far behind their abilities to render highly realistic visual or audio content,” stating “a clear need for haptic solutions that offer more than simple buzzing and rumbling to the hand”.

Dynamic force feedback has been replicated using robotic arm actuators such as the Phantom Omni (Salisbury & Srinivasan, 1997), which render external forces against the finger or hand. Morris et al. (2004) developed a bone surgery simulation platform, which permitted an instructor to remotely provide real-time feedback to the trainee. This method of resistance is suitable for low level force feedback but lacks the power to withstand the full force of an adult limb. A more robust form of resistance has been generated using robotics which can withstand dynamic levels of limb resistance. Kazerooni & Her (1993) designed a ‘two degree of freedom’ electrically powered exercise machine to do so. The system can be programmed to give the human arm a sensation of various desired forces.

Robotics and exoskeletons had the power to create dynamic resistance capable of counteracting the force of a user’s body however the use of such hardware in interface prototyping and future consumer exergames is not feasible due to the associated cost. Influential studies involving pseudo-haptic feedback generated through neuromuscular electrical stimulation were discovered while researching resistance methods. Kruijffs et al. (2006) utilised electrical stimulation to map avatar injury onto the player’s arm muscles while playing the video game Quake, however, the level of muscular stimulation was only sufficient to generate tactile feedback as opposed to kinaesthetic feedback which Carrot or Stick was looking to generate. Tamaki et al.’s ‘Possessed Hand’ (2011) demonstrated how actuation could be used to generate precise finger control.

The device had numerous practical applications such as assisting beginners to play musical instruments, however the design only actuated digits and not limbs. Lopes & Baudisch (2013) utilised electro muscular stimulation (EMS) to actuate a user's wrist while they held a mobile phone, however, the system used low level force feedback and similar to the previous examples it had not demonstrated sufficient power to control upper body limb actuation during a weight lifting exercise.

Carrot or Stick was an exploratory study to see if electro-stimuli-triggered muscle contractions could be used as a viable means to generate resistance on a user's forearm. The game was designed using the Unity game engine over a six-month period between December 2014 and June 2015. At this time no other work had implemented force feedback as a means of coercing physical output during exergame activity. A pre-rigged 3D character was imported into the Unity Game Engine (Unity, 2014); the character's default walk cycles were altered to give the avatar two levels of movement: walking and running. A virtual camera was placed behind the avatar's head providing a third person view of the avatar on a flat running surface. JavaScript was used to make the virtual camera follow the character in 3D space and to control the input/output data of an Arduino Uno (Arduino, 2019) via the laptop's serial port (Figure 3.1). The Arduino sent user exertion data to the game engine while simultaneously receiving game performance data. A TENS device was connected to the Arduino using a relay switch which meant that its power could be toggled on or off. In addition to being connected to the Arduino, the TENS device was also connected to electrodes which were placed on the users' biceps and triceps muscles. The configuration of the game engine, Arduino, relay switch, TENS device and user electrodes enabled limb actuating electro-stimuli to be controlled in real-time based on game performance. Flex sensors worn by the user also facilitated embodied in-game avatar control.

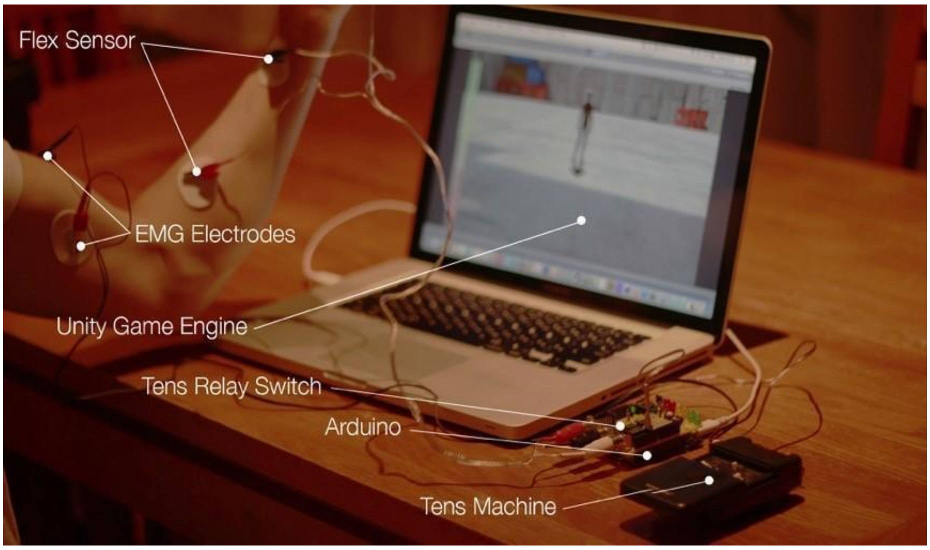

Figure 3.1 Technical setup.

Carrot or Stick used participant muscle flex values to control the speed of a virtual avatar (Figure 3.2). The object of the game was to get an avatar to cover as much virtual distance as possible within a thirty second period. Twelve participants (seven male) aged between 28-45 participated in this study. Users mobilised the static video game avatar by raising the height of an in-game virtual accelerometer or power bar (Figure 3.3) by completing a series of dumbbell bicep curls. A flex sensor attached to the user's arm measured physical output, which was directly mapped to the physical speed of a virtual avatar. The cumulative value of the flex sensor increased the height of a GUI power bar, and the height of the power bar dictated the speed of the avatar.

Power bar strength was relative to the cumulative strength of each digitised flex value passed from the player's forearm into the game engine. The power bar began at a value of 0 virtual power units; if the power bar increased to more than 100 virtual power units the character would walk, if the power bar increased to a height of more than 300 virtual power units the character would run. As well as increasing, the power bar's strength could also decrease at a rate of 10 units per second if a null flex value was read. This aspect of the game design was included with a view to motivating consistent physical output by the participants. Virtual distance covered by the avatar as well as real-time flex readings were shown on the GUI.

Figure 3.2 Virtual avatar, Unity game engine.

The faster the bicep curl was completed, the faster the character would move. The minimum flex value from the flex sensor was 1 and the maximum flex value was 1023. Incoming flex values captured by the sensor were passed from Arduino into Unity where they were categorised into six possible flex categories. These categories were mapped in a linear form relative to the amount of bend. Power bar height increased relative to the quality of the bend value. If the power bar altered above or below a predefined threshold the relay switch would trigger limb actuation via a Tens device.

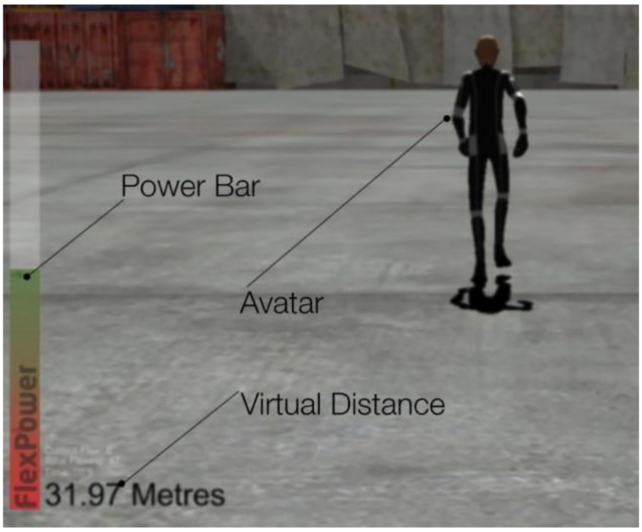

Figure 3.3 Dynamic power bar GUI.

Preliminary results using an Arduino flex measurement sensor were not successful due to signal noise and dropout and therefore a more robust EMG sensor (Backyard Brains, 2014) was sourced (Figure 3.4). The use of EMG sensors facilitated real-time energy transfer from the real world into the virtual world and by allowing the participant's limbs to act as a controlling mechanism, embodiment became an integral part of the game interface.

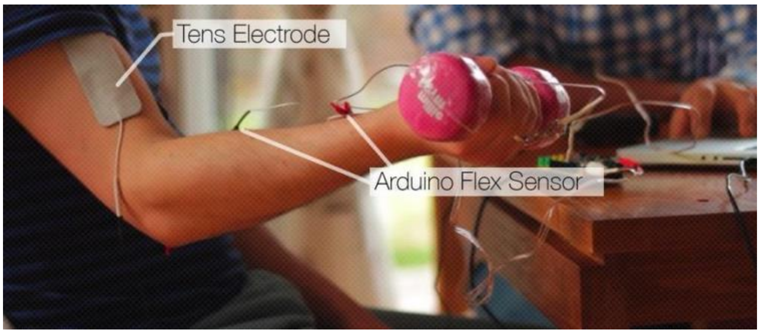

Figure 3.4 Tens electrode and EMG muscle sensor.

In the first game, 'Carrot', if a participant managed to increase the power bar by a predefined amount within a set time an electric current was triggered and passed through an electrode attached to the participant's bicep. Once triggered, the current would cause the participant's bicep muscle to flex involuntarily, raising the user's forearm. The incentive was to flex at a sufficient rate so as to trigger actuation, reduce task resistance, and support 'dumbbell curl' completion; hence the term 'Carrot'.

An exact replica of the virtual game environment was created for the second game, 'Stick'. In this condition the flex sensor continued to be relative to the avatar's speed, however the electrodes were attached to the player's triceps and were triggered if the energy bar decreased rather than increased by a predefined height within a set time. If triggered, the current would cause the participant's triceps muscles to flex involuntarily, extending the user's forearm.

The incentive was to flex at a sufficient pace in order to prevent involuntary actuation hampering the voluntary task of lifting the weight; hence the term ‘Stick’.

While the exergame was functional there were limitations in the system design. Electro muscular stimulation technology (EMS) had made dynamic resistance possible; however, there were issues with the EMG sensors as the TENS current (Figure 3.4) distorted the flex sensor signal. Electrode placement and user calibration also proved troublesome and time consuming. Prior to user testing it was vital that electro stimuli would actuate the user’s limbs accurately to ensure consistent implementation of the hardware across all participants. As there was no precise physiological reference point that could be used to ensure this, the gelled electrodes used to generate resistance had to be adjusted and tested multiple times on each of the participants. There was no way of knowing if the electrodes were correctly placed on an individual’s muscle until voltage was applied. The amount of voltage required to actuate a limb varies from user to user depending on their physiology. In many instances, the voltage would not actuate the muscle which meant removing and reapplying the electrode a few millimetres away from the previous location and repeating the process.

There were additional issues associated with the nature of the bicep curl task as the rapid arm movement and subsequent wire shaking sometimes caused the electrodes to fall off. When EMS did work users could feel the sensation of the impeding and supporting body actuation. This sensation was enough to add a degree of limb support during the Carrot game but the level of power was not strong enough to make the user have to work hard to fight against the impeding actuation of the Stick game. If the user wanted to stop the downward arm actuation caused during the Stick game they could have done so with minimal effort. Carrot or Stick needed a robust form of force feedback, and these findings ruled out its use in such an exergame design.

Due to technical issues this preliminary study was not able to determine the impact of incentivised and de-incentivised resistance on user exertion. EMS was found to be a suitable method for tactile feedback (Sodhi et al., 2013) and limited kinaesthetic feedback (Lopes et al., 2017) but not for replicating full body force feedback in a resistance based exergame. Issues relating to the calibration, consistency and force generated by the EMS electrodes made it an unsuitable choice of hardware. It may also be the case that EMS was too unreliable for commercial use also. Unlimitedhand was a commercial entity set on producing an EMS peripheral for use in VR (Unlimitedhand, 2017). It gained a lot of public attention in 2017, however the website has not been updated since then 2017 and no publications have used it for research purposes. On the basis of the overall experience from working with EMS during this preliminary study a decision was made to generate resistance through alternate means in the following studies. The integration of Arduino flex sensors did not facilitate a detailed capture of exertion output and this was an influencing factor in ensuring that the interface designs of Chase or Be Chased and Switching It Up were able to record absolute power.

3.2.2 Chase or Be Chased

This study sought to pursue whether incentivised and de-incentivised resistance intervention was capable of encouraging enhanced physical output while playing an exergame. A key finding from the Carrot or Stick feasibility study was that EMS was not suitable to generate robust kinesthetic feedback on a user's upper and lower limbs. Taking this into consideration an alternative method of integrating resistance had to be sourced. One piece of consumer hardware that had not been available while undertaking Carrot or Stick (2015) was the Wahoo Kickr. The Kickr (Figure 3.5) is a smart cycle trainer that can be connected to a regular bicycle and can control the cadence resistance in real-time. The lack of force generated by EMS and the robust and consistent way that the Kickr generated resistance caused the studies to move away from 'free weight' exercises using dumbbells and focusing instead on cycling as a mode of game interaction. In continuing with the exploratory concept of impeding and supporting game mechanics used in Carrot or Stick, the objective of Chase or Be Chased was to discover whether participants would be motivated to cycle faster when being chased *or* when chasing after a rival avatar in an exercycle videogame.

Figure 3.5 Wahoo Kickr smart trainer.

The challenge with the Kickr was that nobody had ever managed to establish two-way communication with it using a commercial game engine which prevented it being used in bespoke exergames or user studies. PaperDude (Bolton et al., 2014) had managed to capture the incoming speed from a Kickr however, when contacted, the authors confirmed that their game design did not feature resistance implementation. The issue with the smart trainer was compounded further by the fact that there was no SDK available from its developer. Although there were several third party exercycle games such as Zwift (Zwift, 2019) and Peloton (2018) that used the Kickr as a control interface none of these games allowed developers to customise their game environments.

A workaround was made possible by a modification or mod made for the non-commercial cycling community found on the virtual isle of *Los Santos* more commonly referred to as Grand Theft Auto Five (GTAV). Mods are used to customise and create levels, challenges and abilities which were never featured in the original GTAV game.

The modifications are scripted in C# and integrated within the main GTAV.exe file through a third party application called ScriptHookDotNet (Scripthookvdotnet, 2022). This particular mod ‘GT Bike V’ (Matas, 2021) facilitates real-time synchronisation between the smart trainer and a choice of virtual cyclist, allowing users to tour the vast terrain within the iconic video game. Although the GT Bike V mod menu provides the user with a selection of cyclists and bikes to choose from (Figure 3.6), a decision was made to keep the player’s avatar and the AI vehicles as cars. This decision was made so as to keep the game style in line with the Carrot or Stick metaphor. If the user avatar was a bicycle and they got rammed by another bicycle it wouldn’t have seemed threatening; if the user avatar was a bicycle and they continued cycling after being rammed by a large car, it would not have seemed realistic.

Figure 3.6 GT Bike V mod in cycle mode.

The ‘GT Bike V’ ‘mod’ is one of hundreds written for the popular video game series by an underground community of coders. It should be noted that coding documentation or script support has never been provided by the creators of GTAV and that the C# variables have been meticulously reverse engineered and archived over several years by these devotees. In essence a gaming platform that cost $265 million dollars to develop over a period of five years by a team of more than one thousand developers has been liberated by an informal group of gaming enthusiasts.


Figure 3.7 A modified version of GT Bike V featuring a car as the avatar.

3.2.2.1 Being Chased

For this condition, the avatar car was placed at the starting line of the 1.5km route and users were tasked with getting the car to the virtual finish line by means of pedalling the smart trainer. This condition also featured an AI vehicle that was programmed to ram the players' car should the users' bike speed drop below a chosen pre-test threshold. Each time a collision was detected between the chasing car and the avatar a penalty was given in the form of a five second increase in wheel resistance. If the players' car remained greater than or equal to the chosen pre-test threshold the chasing car would shadow the players car by driving parallel to it.

3.2.2.2 Chasing

Once this game was initiated an AI car was generated and automatically driven at the speed of the users' pre-test threshold along the predefined path between the start and finish line. The players' car was placed parallel to the AI car on the starting line and users were tasked with pedalling the smart trainer so as to move the avatar vehicle to the finish line at their own pace and were also given the option to race against or overtake the AI car if they wanted to. Each time the users' car overtook the AI vehicle a bonus was given in the form of a five second reduction in wheel resistance.

This study demonstrated that a smart trainer can be used to generate reliable, robust, and consistent dynamic physical resistance relative to user performance. Another unique aspect in this study was the way in which a commercial video game was modified successfully for research purposes. Elson & Quandt have previously written about the benefits of modding and how it provides the research community with the 'necessary tools for powerful variable manipulations and operationalisations' (Elson & Quandt, 2016). They provide a meta-analysis of prior studies which have involved some form of modding. However, the methods that the authors discuss and examine are based on games, simulators or SDK's which have originally been developed with a view to being used by the gaming community. Chase or Be Chased differs in the way it has used a commercial game title that was never designed to be customised in any way. Doing so has provided participants with high-fidelity visuals rather than the low-quality graphics that feature in many HCI interface prototypes. The benefits of using detailed graphics and providing participants with a professional level of interactive quality that they are familiar with is discussed in more detail in Chapter Two and Chapter Four.

In relation to the aspect of incentivised and de-incentivised resistance, this study has shown how chase based game mechanics can be used to motivate enhanced physical output through the medium of an exergame without diminishing the enjoyment aspects of gamified physical activity. This study can be read in full detail in Chapter Four. Chase or Be Chased answered the question that had originally been asked in Carrot or Stick and in doing so concluded the use of dynamic resistance as an *unaugmented* condition within the realm of exertion based gaming.

The following studies describe the technical findings when resistance was implemented within exertion based immersive experiences as an *augmented* game mechanic. In both of the following studies, resistance has been augmented with a view to enhancing physical exertion in Switching It Up and enhancing physical wellness in CartRight.

3.3 AUGMENTED RESISTANCE

As outlined in Chapter One, the exploratory studies presented in Chapter Five (Switching it Up) and Chapter 06 (CartRight) examine the impact of augmented resistance: the former uses augmented resistance from the perspective of improving physical output and the latter features augmented resistance with a view to enhancing physical wellness through improved posture. The terms augmented and unaugmented resistance were used to categorise the way resistance was applied to the studies in this body of work. Carrot or Stick and Chase Or be Chased focused on the effect of variable resistance in isolation on exercise behaviour. As these two studies did not involve any other conditions, they are categorised under unaugmented resistance. Switching It Up and CartRight featured variable resistance alongside conditions such as physiological and postural data; the data was augmented visually in the respective heads-up display's. These studies were categorised under the heading of augmented resistance.

3.3.1 Switching It Up

While bike-controlled resistance based exergaming had been explored in the Chase or Be Chased Study (Chapter Four) there was an existing gap in the research relating to the interactions between resistance and immersion and resistance and the representation of physiological effort. Switching It Up examined whether physical output could be enhanced through the medium of an exergame when aspects of the video game were augmented using varying display immersion, physical resistance, and some deception in the representation of physiological data to users.

Presenting the user with an exergame environment displayed through the medium of an Oculus DK2 headset provided the opportunity to study the impact of HMD Immersion on user exertion. Resistance was adjusted at specific moments in the exercycle game, however these adjustments were done manually by a third party rather than automated by the game. Switching It Up also featured heart rate as the method of physiological control. This provided an opportunity to experiment with deception and see whether it could be used as a game mechanic to enhance motivation.

Switching It Up investigated whether adaptive interventions could encourage users to increase physical output at appropriate moments within exergame play. A cycling based exergame was developed (Figure 3.8) in which the avatar's speed and distance covered were controlled by the user's heart rate. As this study was conducted five years before Chase or Be Chased (Chapter Four), the Wahoo Kickr hardware was not yet available. Consequently, users were asked to pedal a more traditional exercise bike - a stationary Wattbike (Wattbike, 2018).

Figure 3.8: (1) Heart Rate, (2) Virtual Bike Gear, (3) Virtual Distance Covered, (4) Timer Countdown (5), Virtual Cyclist.

The system design was achieved by developing a physiologically controlled exergame in which the player's exertion would influence the avatar's performance. In 2022 there is a choice of interactive exercycle training games to choose from. However, at the time of this study in 2016 no commercial virtual cycling platforms existed. Using an off the shelf video game was not an option as there were too many unique aspects which necessitated designing a bespoke exergame. In order to study the impact of immersion on physical exertion a fully immersive game was played while viewed by the user through a HMD. For the control condition a non-immersive game displayed the user's physiological data on a PC monitor without any 3D environment present.

Similarly, the GTAV mod used in Chase or Be Chased (Chapter Four) was not available in 2016. Therefore, to keep the quality of the immersive experience at least comparable with the lighting, sound and graphic fidelity found in commercial virtual titles the exergame was developed using the Unreal Game Engine. A Wattbike was used as the physical interface and an Arduino interface was used to relay physiological data to the game engine which in turn dictated virtual bike cadence.

From a chronological perspective Switching It Up was developed after Carrot or Stick over a duration of ten months between September 2015 and June 2016. In order to overcome issues relating to the accuracy of captured flex data in the Carrot or Stick study, Switching It Up used a heart rate monitor as it was felt that it provided greater veracity in terms of physiological transfer. BPM had a direct link with pedal speed and its utilisation within the system still maintained a connection, albeit an indirect one, between that of the physical bike interface and the virtual cyclist.

Results from different previous work reviewed in Chapter 2.4.3 had demonstrated how heart rate could be used as a form of exergame control (Mokka et al., 2003; Masuko & Hoshino, 2006; Nenonen et al., 2007; Stach et al., 2009).

A mapping system was developed to dynamically adjust the virtual bike's speed based on participant heart rate data. Mapping cadence indirectly to the virtual bike speed using the user's heart rate enabled examining the influence of manipulated real-time physiological feedback on physical output. Mapping the user's pedalling with that of the virtual cyclists would have lent to a greater sense of interactive fidelity (McMahan et al., 2012), however bike cadence would have been difficult to falsify. Heart rate provided a physiological control variable that could be manipulated (to an extent) and relayed to the user without arousing suspicion.

Inaccurate sensor data and impractical heart monitors led to several design iterations. I experimented with the Pulse Sensor (Arduino Heart-rate Sensor, 2018) and Easy Pulse Monitors (Easy Pulse Sensor, 2017), however, inaccurate readings coupled with the awkward sensor placement for a bike game made them impractical (both were worn on the finger when the user had to simultaneously hold onto bike handlebars and control a gamepad). Eventually the Polar Heart Rate Monitor (Polar Wireless, 2018) was used, which had been reconfigured to pass heart rate data wirelessly through an Arduino board and into the game engine using the UE4Duino plugin (UE4Duino, 2019). The monitor readings became weak beyond a two metre radius which necessitated the receiver being placed beneath the saddle of the bike.

Coupling between user output and videogame input was enhanced through the use of a common physical and virtual interface in the form of a bicycle. The Wattbike interface provided an accurate method of measuring exertion transfer, as output generated by the user was 'absolute' power measured in Watts and recorded by the Wattbike computer (Figure 3.9). The use of a Wattbike also provided an alternative method of resistance generation as it included a 'climb' lever which could be used to examine the effects of 'indirect actuation' i.e. altering limb exertion through involuntary resistance adjustment.

Figure 3.9 Wattbike computer.

The ‘climb' lever had seven incremental settings which could be adjusted to alter the exertion levels required to turn the bike’s pedals. The lowest setting ‘1’ generated the resistance of a level road and the highest setting ‘7’ simulated resistance to that of a very steep gradient. In all of the tests involving resistance alteration, the lever was changed from ‘level 5' to ‘level 7' on the magnetic resistance dial mid-way through each game. The dial remained static at 'level 5’ in all other games.

There were definite challenges in the development particularly in relation to integrating real-time sensor and Wattbike data into a game engine and having it work on a VR platform. Initially the projected timeframe for development had been three months however little information was available on how to integrate physiological sensors in VR game engine design is niche, so a significant amount of time went into iteratively developing this link, as well as troubleshooting data and sensor conflicts relating to various combinations of HMD’s, Arduino boards, operating systems, baud rates and Wattbike operating system updates.

An Oculus Rift DK2 (Oculus Rift Development Kit, 2016) headset was worn by viewers while playing versions of the exergame which featured the immersive condition. The lighting, environmental texturing and models were on par with commercial video games, the standard in which gamers and non-gamers alike expect while playing a video game (Lew et al, 2011). The fact that enhanced immersion generated increased physical output validates the contribution high-end visuals make in maximising the potential of user immersion within the realm of exergaming (Cummings & Bailenson, 2016).

In addition to the visual quality generated by the Unreal engine, its integration alongside heart rate and Wattbike created a unique and reliable exergaming experience. In a similar way that Marshall et al. (2011) and Sra et al. (2018) experimented with breath based control, Switching It UP demonstrated that heart rate is a viable means of physiological control in a VR exergame. The heart rate readings were stable and consistent without any dropout, latency or signal noise and while they did provide a physiological measure to experiment with a mild level of user deception, the impact of manipulated physiological data had no significant effect on real or perceived exertion levels. The Wattbike provided a highly accurate means of capturing and recording detailed exertion transfer. One noticeable flaw was the system’s lack of dynamic resistance. In comparison to the Wahoo Kickr in Chase or Be Chased, the manual resistance in Switching It Up prevented adaptive game mechanics and, as is discussed in Chapter Five, is a possible explanation as to why resistance failed to increase user exertion. Having discussed the technical contributions of Switching It Up, the following study will discuss the prototype that was developed in Feeling Virtual Worlds.

3.3.2 Feeling Virtual Worlds

Feeling Virtual Worlds was an exploratory study undertaken over an eight-month period (September ‘17 - June ‘18) to see whether wheel friction could be used as a reliable means to generate dynamic resistance in a virtual environment. The basic premise was to design a system to generate a heightened sense of realism while undertaking physical activity within an immersive environment by tightly coupling virtual and kinaesthetic experiences. A VR system was designed which incorporated a moveable tangible interface that overlapped seamlessly with a 3D counterpart in the virtual world. The user could interact with the virtual environment by pushing the physical avatar, which simultaneously controlled the virtual one. The system design enabled the user to interact with the virtual environment by pushing a physical interface, which simultaneously controlled a virtual counterpart. Objects were placed in the virtual environment that once collided with by the virtual interface triggered force feedback by incrementally adjusting the level of brake friction on the physical interface. Participants could engage in an immersive environment and simultaneously appreciate the tactile qualities of virtual objects and interactions through a combination of passive haptics and automated resistance.

VR researchers have sought to add extra 'reality' into their immersive experiences by taking a more holistic approach. Projects have emerged which have explored beyond the exclusive use of visual and aural modalities to achieve a more embodied interactive experience (Volpe, 2016) and heightened stimulation (Lopes et al., 2017). Influential research was drafted from a number of different domains within HCI research, including immersive environments (Cheng et al, 2015), tangible user interface design (Follmer et al., 2013) and haptic feedback (Sodhi et al, 2013).

Research has been conducted that explored aspects of responsive tactile hardware in an attempt to add enhanced realism into tangible interfaces (Lee et al., 2011; Tennent et al., 2017) and interactive simulations (Brederson et al., 2000). However, there was increasing attention from the research community moving beyond utilising haptics solely dedicated to real world conventions and instead incorporating their usage into more immersive scenarios (Ziat et al., 2014).

Seamlessly overlapping a virtual and physical interface was not an area that many people were researching. Araujo et al.'s Snake Charmer study featured a robotic arm that aligned physical surfaces to virtual objects (Araujo et al., 2016). Although the system could dynamically render texture, temperature, and physical weight the interface was not fully mobile and the level of resistance it generated was not sufficient to withstand full body contact or force. The area was also being explored by the entertainment sector (The Void, 2017), however, the overlapping was limited to large static props or small handheld objects but there was no work being pursued that involved large mobile interfaces. Having discussed related work in this field, the following section will address the development of the interface.

The first aspect of the implementation involved the integration of real-time variable and automated resistance. Initially I experimented with a bomb disposal robot which had been offered on loan from an electronic engineering department. The idea being that users would push the robot forward while leaning against a pressure sensor. Force on the pressure sensor would in turn release the robot brakes. However, the robot was not designed to move at a fast speed and the associated latency made it impractical.

Subsequent tests experimented with several types of linear actuator and stepper motor to control the handbrakes on a bicycle, although some of these devices could generate the required force they moved too slowly to generate resistance at a sufficient latency, making this hardware unsuitable. The last experiment used high torque servos with 30kg per cm torque (Figure 3.10) powered by a golf cart battery. This combination had sufficient power and speed to adjust the servos incrementally without noticeable latency. It was decided to use this method of resistance as it allowed the use of predefined levels of resistance, which could be generated consistently on a wheel.

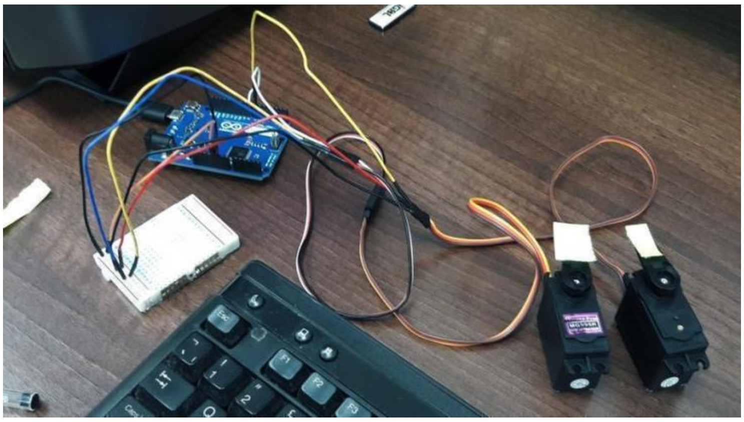

Figure 3.10 High torque servos being tested with an Arduino.

The overall look and feel of the tangible user interface evolved during the implementation process and changes were made as result of the array of technologies explored while attempting to fulfil the design criteria. Initial explorations led me to consider the use of a cube, based on its simplistic form. However, the necessity to integrate wheels into the final physical design influenced the use of a more common wheel-mounted object. Thus, a wheelchair was chosen as it offered the user the ability to engage tactically through the simple combination of reach, touch, grasp and push. Two high torque servos were mounted alongside the wheels on servo brackets bolted to the aluminium tubing and servo arm attachments connected with the brake levers (Figure 3.11). By varying the amount of servo rotation, it was possible to rapidly adjust brake friction allowing the game engine to emulate cart weight in the controller.

Figure 3.11 Wheelchair with repositioned brake lever and servo mounted and connected to repositioned brake lever.

The next phase involved synchronising the position of a virtual model and real world object. The virtual environment would be created in the Unreal game engine and viewed through a HTC Vive VR HMD (HTC, 2022). The Vive had been launched in April 2016 and was the first commercially available HMD to feature hand tracking peripherals (Figure 3.12). The Vive can track the rotational and positional data of the HMD and controllers. Motion tracking within each Vive Controller was made possible by a combination of a single six-axis inertial measurement units (IMU) as well as multiple IR photodiodes, which can detect light emitted from either of the two Vive lighthouses.

Figure 3.12 HTC Vive controller.

The trackers had initially been developed by Vive for hand based virtual interaction however they were soon adapted by the HCI community and used to track and move the virtual position of various XR peripherals (Son et al., 2018; Strasnick et al., 2018). This use is discussed in more detail in the literature review (Chapter 2.4.1 & 2.4.2). Feeling Virtual Worlds made use of this hardware to enable real-time tracking in a pre-calibrated space (Figure 3.13 G & Figure 3.13 H). A prototype was developed and tested using an office chair and a virtual representation of this chair. In the Unreal Game Engine (2015) a motion controller tag was placed onto the centre of the virtual chair, in addition the physical Vive controller was secured in place on the matching location of the physical chair. When tested, the user could move the physical chair and view the corresponding virtual chair move in real-time without latency, generating a tightly coupled interface.

Synchronisation was achieved by connecting a Vive hand controller onto the hand rest of the wheelchair, attaching the virtual wheelchair model to the virtual hand controller and then reverse engineering the size and location of the virtual wheelchair model so as to overlap with its physical counterpart.

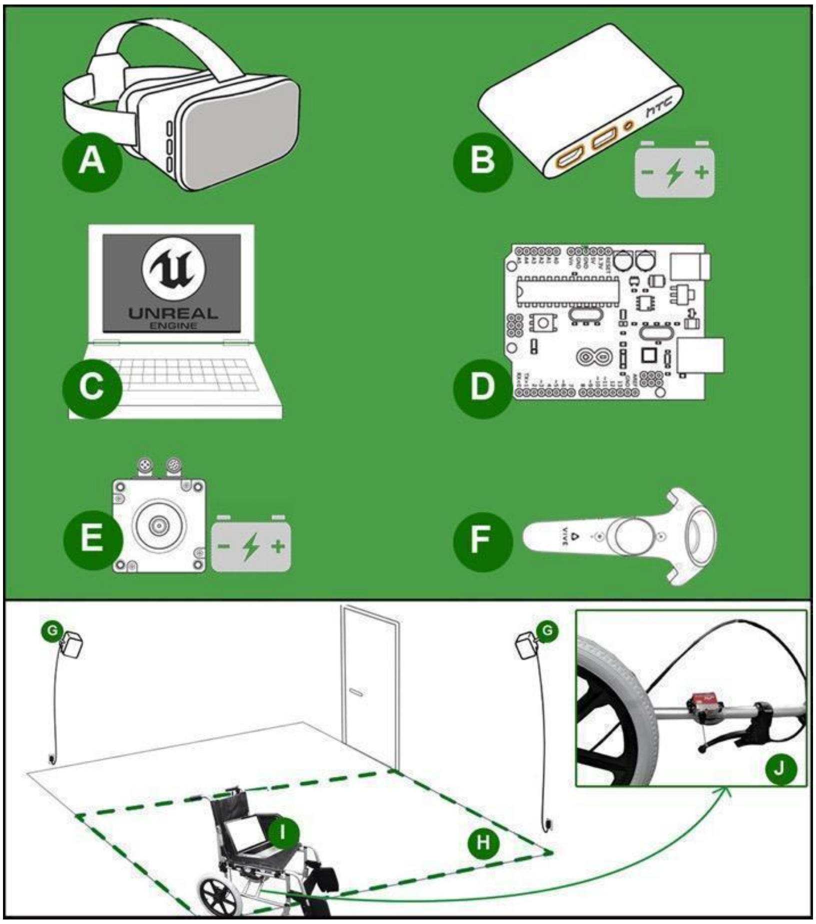

Figure 3.13 Embodied Tangible-Virtual Interface system design. (A) VR HMD, (B) Battery operated link box, (C) Laptop running Unreal Game Engine, (D) Arduino, (E) Battery powered high torque servo, (F) Vive controller, (G) Vive tracking station, (H) Pre-calibrated space, (I) Wheelchair and laptop, (J) Close up of mounted servo attached to brake lever.

Resistance was dynamically adjusted to simulate real world collisions with virtual obstacles. This was done using an Arduino microprocessor (Figure 3.13 D), high torque servos (Figure 3.13 E), the Unreal game engine (Figure 3.13 C) and the UE4Duino plugin. UE4Duino facilitated two way communication between the Arduino sensors and the Unreal engine. A setup such as this allows real world activity to influence virtual environments and virtual interaction to influence real environments. For example real environmental data from an Arduino light sensor could be used to adjust a video games ambient lighting and similarly virtual daylight settings in a game engine could be replicated in the real world by adjusting the power of a dimmer switch connected to a lightbulb. These types of interactions are made possible with blueprint scripting which is a node based language used in the Unreal engine (Figure 3.14).

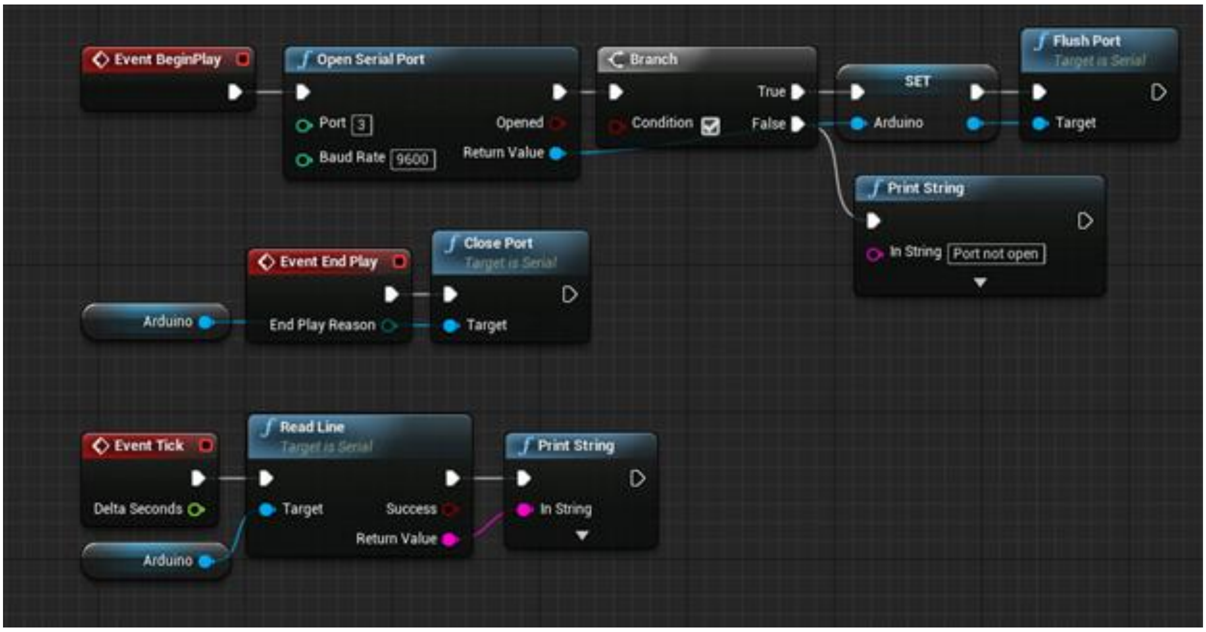

Figure 3.14 Unreal Blueprint code.

In Feeling Virtual Worlds, the virtual layout was designed using the Unreal engine. Three virtual props were located in an empty room. A sphere, a cube and a doorframe. Invisible ‘triggers’ were overlaid on the virtual props. Triggers are regularly used in game design to detect when an avatar is in a particular location or to detect specific collisions between different objects. In this case the triggers were being used to detect when the virtual wheelchair collided with one of the three props. Virtual collision detection between the interface and the props adjusted the servo controlled friction. When the virtual wheelchair collided with one of these triggers, it would cause the servo arms to rotate which would in turn tighten the brake handles and generate force feedback.

Testing was done on the resistance to ensure that the brake friction was sufficient to prevent the wheels on the wheelchair rotating when maximum body force was applied. Once this level of friction was applied its corresponding servo rotation value was noted. This value was then manipulated to generate varying resistance values relative to virtual objects within the environment. Colliding with a sphere model triggered 30% of the maximum brake power whereas a cube model (which was more rigid) triggered a brake power of 70%. When both objects were collided with simultaneously or if the wheelchair collided with the doorframe, the brake power was set to 100%. It should be noted that this was a proof of concept, the incremental braking ratios were based on servo handle rotation and not linearly accurate representations of true force.

Another key requirement was to allow the tangible interface to be as mobile as its virtual equivalent. At present in 2022 there are various options for untethered VR. However, in 2017 the only available devices offering untethered VR were the Samsung VR (Samsung, 2019) and Google cardboard (Google, 2022) headsets. Neither of these headsets were suitable as they both lacked real-time position tracking. The HTC Vive required mains power which meant that its location was limited to the proximity of a power point.

An extension lead could have been used but it would have obstructed the interface and physical environment. Powering the HTC Vive without a mains connection required a unique hardware setup involving custom cabling and batteries. This was achieved by powering the Vive's linkbox using a 12V battery (Figure 3.15) and substituting the desktop with a laptop mounted on the tangible interface.

Figure 3.15 Powering the Vive's linkbox using a 12V battery.

A tightly coupled tangible mobile interface was developed which featured passive haptics as well as force feedback. Its physical counterpart controlled the avatar's position and resistance based on collisions encountered within the immersive environment was replicated in the real-world using wheel based friction.

In total, 12 participants took part in the study (aged 20 to 42, 6 male). Users were able to engage in an immersive environment and simultaneously appreciate the tactile qualities of virtual objects and interactions through a combination of passive haptics and automated resistance (Figure 3.16). The preliminary exploration showed a link between presence and mobile embodied immersive interaction as well as the potential effectiveness of a dually tangible mixed reality.

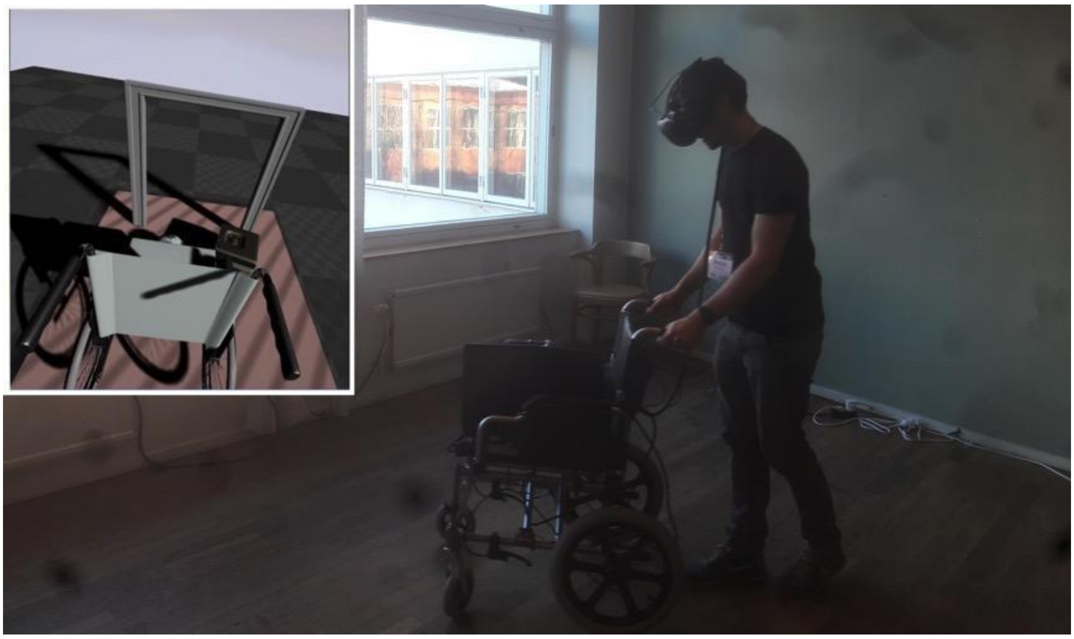

Figure 3.16 The tightly coupled tangible mobile interface.

The use of bespoke hardware demonstrated that a HTC Vive could be powered by battery power and in doing so facilitate fully untethered interaction on a fully mobile interface. At the time this was the first HCI study to have done this. The prototype also demonstrated that friction could be used to successfully implement real-time dynamic resistance capable of withstanding full body force on a mobile interface. The combination of an untethered mobile interface, as well as active and passive haptics demonstrated that virtual collisions could be replicated and experienced in a room based physical and virtual environment.

The integration of dynamic resistance within a virtual environment had provided an interface that allowed resistance-based compensation to be measured more effectively thus fulfilling the technical requirements of this feasibility study. The possibility of replicating virtual collisions in the real world provided an interface in which compensation, proprioception, and real-time posture feedback could be fully explored. This will be discussed in the following section.

3.3.3 CartRight

The proof of concept developed in Feeling Virtual Worlds had been successful and facilitated a focal shift towards postural compensation measurement during resistance-based tasks. In a similar vein to Switching It Up (Chapter Five), CartRight examined the impact of augmented resistance on enhancing physical output, but rather than enhancing the quantity of output the emphasis of this exploratory study would be on the quality of the output. The aim of the study was to examine the relationship between posture and adaptive resistance while replicating a common musculoskeletal task within a virtual environment. This was achieved by replacing the virtual environment used in Feeling Virtual Worlds with that of a supermarket interior where the user was tasked with collecting virtual boxes of groceries (Figure 3.17).

Figure 3.17 Screenshot from users point of view within HMD.

In addition to the physical interface used in Feeling Virtual Worlds, CartRight also featured a user harness which was worn by each participant. The harness consisted of a Vive hand controller attached to a wearable back harness which was adjusted for each user so that the tip of the control unit was flush with their C7 (7^{th} Cervical Vertebra) located at the base of the neck.
This spinal location had been chosen as a reference point for prior upper trunk posture studies (Wong & Wong, 2008).

Real-time postural data was measured and relayed to the user in visual format on the HMDs heads-up display. The visual data was used to alert the user using binary based widgets to what was deemed to be a correct or incorrect posture when performing a resistance based task. For a more detailed description on how incorrect and correct posture was defined for this study please refer to Chapter Six. The postural data was also recorded by a piece of third-party software called Brekel for use in post-test analysis (Figure 3.18) (Brekel, 2018). This recorded the positional and rotational information of the upper body posture at 60 frames per second. Tracked data was recorded in .fbx and .txt formats, which facilitated post-test analysis in 3D Studio Max, SPSS and Excel.

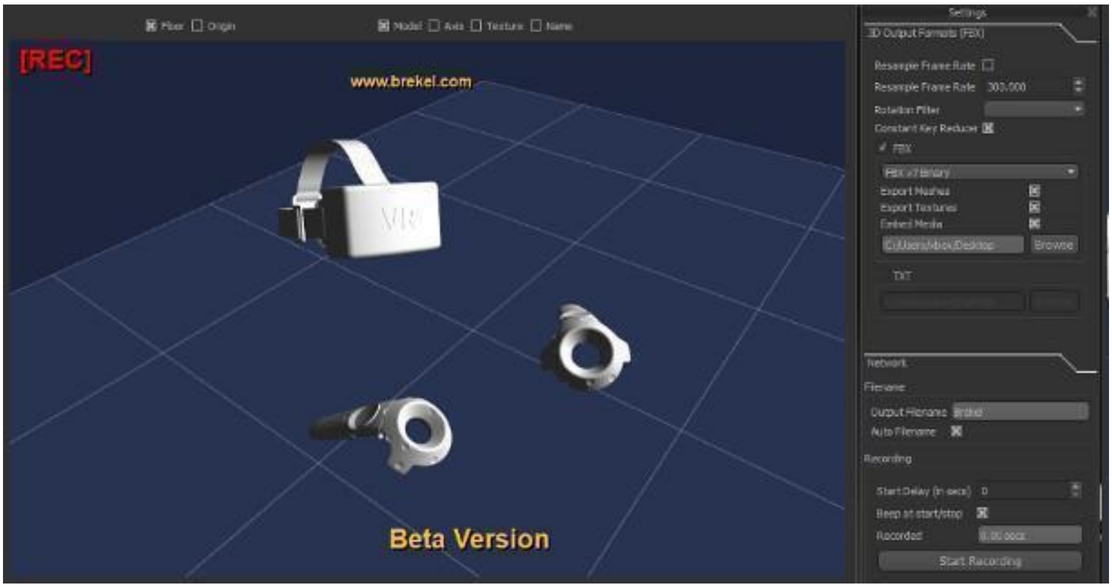

Figure 3.18 Live VR data being displayed within the Brekel application.

Motion tracking within each Vive Controller is made possible by a combination of a single six axis inertial measurement unit (IMU) as well as multiple IR photodiodes, which can detect light emitted from either of the two Vive lighthouses. The Vive can track the rotational and positional data of the HMD and controllers. However, occlusion, reflection and sunlight can cause signal loss and impede precision (Niehorster & Lappe, 2017). To address these limitations, the lab was darkened to eliminate glass reflections and connected both Vive towers with an optical sync cable. For the purposes of this study a floor space measuring 8m x 4m was calibrated. To prevent any potential offset from distorting user coordinates the physical lab space and Vive setup was configured multiple times until the tracking was robust and tracked all of the components consistently. Tracking coverage was optimised by placing lighthouses at either end of the physical space on which the virtual shopping aisle was aligned. As well as preventative measures a quality control system was implemented by replaying the recorded Brekel .fbx files and manually looking for glitches in the graph editor and in each of the animated VR component models.

Prior research by Hoang et al. (2016) had demonstrated the merits of using visual feedback to provide postural guidance. However, a particular design challenge lay in correctly displaying concurrent physiological data in a VR context.

A known phenomenon in VR design is the nausea generated when standard 2D heads-up display data is composited as a static layer in a 3D environment (Ohyama et al., 2007). To prevent this occurring the augmented visual feedback was attached to the virtual trolley as a 3D widget (Figure 3.19).

Figure 3.19 Postural feedback relayed to the user on the VR HUD.

The experience situated users in a virtual supermarket environment where they were asked to partake in the exertion based task of grocery shopping, a typical activity that disturbs posture in everyday settings. The adaptive haptic platform created for the Feeling Virtual Worlds study was seamlessly overlapped with a virtual shopping cart. Participants collected virtual grocery boxes by moving and colliding the virtual shopping cart with them. Collecting the virtual groceries caused the boxes to transfer from the shop floor into the virtual cart and altered the level of wheel friction in the physical cart. Dynamic cart weight was simulated by means of adjustable brake friction relative to the quantity of virtual groceries collected. It was not possible to use an off the shelf game for this user test therefore the virtual supermarket was developed with various gamified interactions using the Unreal Engine over a period of six months between January ‘18 - June ‘18). For detailed information relating to the CartRight study please refer to Chapter Six.

The majority of the hardware used for the CartRight interface had been developed while working on Feeling Virtual worlds however a significant technical contribution was the method in which the HTC Vive’s inertial measurement unit (IMU) data was captured to relay user posture in real-time. When used in conjunction with the Brekel application, the inertial measurement unit data provided a reliable means in which to effectively monitor, record and analyse postural data. This was less expensive, less complicated and less constrained than availing of a Motion Capture or Gait Analysis Lab. Having discussed the technical contributions of the various studies, the following section will reflect on these findings as one concise unit.

3.4 DISCUSSION

Applying user research in a domain that requires exploratory technical work as a necessary precursor involves developing prototypes that involve bespoke hardware and software. This is time consuming when you are working as an independent researcher. Iterative prototyping can be delayed by weeks while waiting on a component such a sensor or battery to arrive from overseas and progress can be reliant on a forum response which may take minutes or weeks to arrive. In some instances, findings demonstrated that a particular technology or interface was unsuitable, inefficient, or unreliable and that continuing with an expanded version of the interface was not an option. Designing interfaces for emerging technologies means that often there are no manuals to consult, if there were it would no longer be a niche research area. All of these aspects make time and project management extremely hard to gauge.

At present, there are far more options for HCI developers to avail of when developing virtual interfaces than there are for customising their physical counterparts. Game engines, modding tools and SDK’s all provide developers from novice to professional with the resources needed to recreate an immersive experience. Although various Arduino, raspberry pi and introductory electronics kits can be customised to an extent, the limitations of this technology become apparent when you want to generate haptics with a force greater than a vibrotactile motor. Such a dearth necessitated exploring alternatives.

The studies conducted between 2015-2018 involved creating unique physical interfaces as no commercial alternatives existed. Although resistance was introduced in different methods during the first and second studies it was not without its drawbacks. EMS actuation proved difficult to calibrate and tended to distort the muscle input signals being read by the flex sensors on the forearm. EMS was found to be a suitable method to generate limited limb actuation but was not deemed to be powerful enough to replicate robust kinaesthetic feedback in a resistance based exergame. Equally the manual use of resistance in Switching It Up was functional but the inability to alter its resistance level in real-time through the game engine placed limits on the creative aspect of exergame design. A key finding from the Feeling Virtual Worlds study was the way in which servo-controlled brake friction could be used to replicate dynamic resistance capable of withstanding full body force. This was something that had not yet been applied on a mobile mixed reality interface.

In relation to human activity recognition, commercial developments over the duration of the research have caused a movement away from expensive gait analysis labs and provided researchers with an affordable alternative without being constrained to a specific pre-calibrated location. The combination of the HTC Vives hand tracking units powered by a bespoke mobile interface facilitated fully untethered interaction on a fully mobile interface. The combination of Brekel and HTC Vive inertial measurement unit data, demonstrated an affordable alternative to create a mixed reality interface and effectively monitor and record real-time postural data.

When the various studies are examined chronologically the timeline reveals a focal shift from customising hardware to customising software. By the time of the final study in 2021, hardware that facilitated dynamic resistance (Wahoo Kickr) was commercially available, yet the software platforms used with these interfaces could not be modified. In an ideal world manufacturers would develop and provide open source universal communication platforms and plugins for physical interfaces. This does happen, as is the case with peripherals such as Leap Motion (Leap Motion, 2016) and Microsoft Kinect (Microsoft, 2021), however, manufacturers are often reluctant to offer the API or SDK to their device as they want to constrain customers to using proprietary platforms. If a researcher wants to use commercial hardware in an unorthodox way, they are reliant on a group or individual with significant coding experience to decompile the firmware and enable open communication between the hardware and various development tools. This is how the Wahoo Kickr device came to be used with the GTAV game. The developer in question was a cycling enthusiast and a computer programmer who felt that the existing gaming options were limited and decided to use his Wahoo Kickr in a manner unintended by the Wahoo corporation.

The proliferation of screen based media and its associated advertisements have passively made mankind sophisticated consumers of digital content. The volume of professionally made content that we interact with on tablets, phones, laptops and kiosks has created a visual standard we expect and in doing so provided us with an ability to rapidly critique low quality aesthetics design when we see it. This is neither opinionated nor anecdotal but a fact that has previously been demonstrated by Lew et al. who wrote that ‘a lack of realism in an interface’s appearance or content signals participants that they are being tested. This can influence participants’ mindsets by reducing their interest or pleasure.’ Visual fidelity and aesthetic design are equally as important in the realm of video game design. HCI experiments involving interactive games should present users with an experience at a standard equivalent to other interactive and immersive activities that they are used to performing (Lew et al., 2011). The merits of these aspects are described in greater detail in Chapter 2.3.2.

The reason the developer created the GTBike V plugin and why the virtual cycling community chose riding together virtually in ‘Los Santos’ instead of Zwift or Peloton was based on the higher visual fidelity provided by the GTAV game engine. This justifies the findings of Cummings and Bailensons (2016) in their study on the impact visual quality has on immersion and gaming and backs up prior statements by Robertson & Good (2005) who maintains gamers should be given the experiential quality and visual fidelity they are used to.

The games in all of my studies used high quality visual content. The environments in Carrot or Stick, Switching It Up, Feeling Virtual Worlds and CartRight were designed using the Unity and Unreal game engines. The fact that enhanced immersion generated increased physical output in Switching It Up demonstrates the value detailed graphic fidelity can bring to the exergaming experience.

The Chase or Be Chased environment was created using a modified version of the commercial video game GTAV. Using a mod obviously doesn't have a commercial appeal, but for academics interested in exergames, it has significant value. Modding provides the research community with powerful tools particularly those that may lack prior game design knowledge. Although the meta-analysis provided by Elson and Quandt (2016) has provided detailed information on the legacy of modding in user studies, all of the mods referenced in their analysis were created using simulators or SDK's. These applications had been developed with customisation in mind where content could be created using 'drag and drop' design. Chase or Be Chased falls into a different category as the modification features a commercial game title that was never designed to be customised in any way.

It is paramount that studies investigating real exertion from real people are conducted in a research environment that provides real experiences. To do so requires high fidelity graphical environments comparable to commercial games, and hardware that can provide variable and/or adaptive resistance. This can be done the hard way: building bespoke hardware and developing virtual worlds of sufficient fidelity using games engines; or the easier way: using off the shelf hardware and game mods, or SDKs if they become available.

The hard way relies on intensive work, but even so can never meet the quality standard of commercial systems. The easy way can save development time however commercially available interfaces only generate particular types of feedback which can restrict creativity. The way research is in a continual dynamic with the state of the art in the commercial world is reflected in the way that commercial interfaces such as the Kinect, Wii and Oculus influence HCI publications in the months following their release (Ann & Theng, 2014; Cummings & Bailenson, 2016; Tripette et al., 2017). I argue that there is a common ground which can save development time and still provide creative control. The combination of the Wahoo Kickr and the modified GTAV is an example of how commercial hardware and software can be utilised to save time without having to compromise on the interface quality. Other developers could build on this approach by leveraging off commercially available hardware and software but also be open to exploring unconventional methods to help exploit these technologies to their maximum benefit. A closer relationship between research and industry would facilitate this dynamic. There has been some progress in this area with environmental legislation forcing manufacturers to facilitate consumers 'right to repair' (Hanley et al., 2020). At present some companies are beginning to provide schematics, API's, and machine diagnostic kits. A grassroots sustainability movement could be the catalyst needed to break the creative constraints imposed by industry and in doing so help further research in the HCI domain.

3.5 CONCLUSION

The technical contributions and limitations of the combined studies are as follows.

Contributions

In relation to the area of resistance, brake friction was found to be suitable for implementing dynamic resistance capable of withstanding full body force. This method of resistance also facilitated a novel mobile interface which could replicate virtual collisions in the real world. Smart trainers were very effective at generating adaptive resistance and the dynamic resistance offered far more opportunity to develop exertion enhancing game mechanics than it had when applied manually in Switching It Up.

From a visual perspective, Chase or Be Chased demonstrated how commercial video games can be modified to suit the needs of a study rather than designing a game from the very beginning. In addition to providing an alternative to using a traditional game engine it provides users with a high-end immersive experience. The fact that enhanced immersion generated increased physical output in Switching It Up demonstrates the importance visual and interaction quality plays in exergame design.

In relation to human activity recognition, the combination of Brekel and HTC Vive inertial measurement unit data, demonstrated an affordable alternative to effectively monitor and record real-time postural data. The use of bespoke hardware demonstrated that a HTC Vive could be powered by battery power and in doing so facilitate fully untethered interaction on a fully mobile interface.
Finally, in terms of resistance and haptic interface design, this work has demonstrated the time saving benefits of maximising adaptation in commercial technology through unconventional means.

Limitations

The exploratory work conducted in the Carrot or Stick study suggests that EMS may not be suitable for applications where significant kinaesthetic feedback is required, however, more focused work is necessary to confirm this. Although the exergame was functional, there were limitations in the amount of force generated by the EMS. Users could feel the sensation of the impeding and supporting body actuation. This sensation was enough to add a degree of limb support during the study but the level of power generated was not enough to force downward arm movement during the Stick game. To conduct an exergame such as ‘Carrot or Stick’, a more robust form of actuating technology would be required such as a robotic exoskeleton.

This concludes the technical methodology and contribution. These findings will support future developers in designing exertion based immersive experiences. The following Chapter will discuss how incentivised and de-incentivised game mechanics were applied using electromagnetically controlled dynamic resistance.

CHAPTER 4: EXPLORING THE IMPACT OF UNAUGMENTED RESISTANCE ON THE QUANTITY OF EXERTION

4.1 INTRODUCTION

The research question in this chapter investigates whether physical output can be increased when the task intensity of an exergame is automated relative to a user's performance. Integrating resistance as a game mechanic in this manner aligns with increasing physical output which forms part of the main research question.

The research in Chapter Three documented the workflow and iterative design process that led to the generation of the bespoke interface designs featured in all of the user studies. Each of the exergames described in Chapter Three uses high fidelity visuals and has the ability to adjust task intensity at specific moments. The prototypes have enabled a series of studies which examine the relationship between resistance and physical exertion.

A lack of automated task control within exergame design has meant that exercise intensity and output is reliant on human motivation rather than mechanised intervention. This chapter addresses this issue by removing the user from the decision process and allowing the computer to dictate the level of task intensity expected from the user. The chapter investigates whether user output can be increased when task intensity is automated relative to the user's performance. Chase or Be Chased adjusts the resistance on a smart trainer relative to the user's performance while they play an exercycle game. Task intensity is generated in this exergame using dynamic resistance by means of electromagnetics. A study is conducted which investigates whether incentivised game mechanics can be used to encourage enhanced physical output. If a user is working below a specified threshold, resistance on the physical interface increases, hindering their game performance. Correspondingly, if a user's output level is above a predefined benchmark, resistance decreases, facilitating task completion. Mechanised intervention in this manner has the potential to improve the quality and efficiency of home based training, assist cycling enthusiasts reach stamina targets and reduce costs associated with third party instructors such as spinning classes and personal trainers. In addition to its application in the commercial health and wellness sector, results from this chapter will provide the HCI community with unique research findings relating to the areas of exertion, dissociation, motivation, enjoyment, immersion and loss aversion.

Exergames increase enjoyment, dissociation and physical output by distracting participants from real world exertion using goal oriented immersive gameplay (Beat Saber, 2021; Konami, 2019). Prior research by Glen et al. (2017) compared psychological and physiological output during interactive and non-interactive exercycle activity and demonstrated that dissociation and enjoyment are higher when playing the exergame. Dissociation from the physical aspects of these games has increased in recent years brought about by improvements to both visual fidelity and human activity recognition.

Advances in GPU design and game engine technology (Unreal, 2015) provide realistic environments that can be presented through a variety of virtual media. According to Mäyrä & Ermi (2011), sensory experiences such as these support the engagement process by leading players to forget about the sensory input from the real world and focus on the sensory input from the virtual world.

In addition to visual improvement, the evolution of exergame control hardware has also helped to dissociate users from the physical aspect of the exercise. Physical control that once consisted of basic hand gestures now involves whole body interaction (Konami, 2019; Beat Saber, 2018) which according to Nijhar et al. (2011) enhances the sense of immersion.

Embodied interaction coupled with the dissociative attributes of immersion can increase physical output during exergame activity (Monedero et al., 2015), however, motivating users to complete repetitive and monotonous physical tasks still remains a challenge in exergame design. Cycling simulators such as Zwift (2019) and Peloton (2018) motivate enhanced exertion from participants through a variety of gamification techniques. Time trials are provided whereby a user's previous best score is displayed on screen providing the cyclist with a feed forward mechanism to try to either maintain or beat their existing record. Virtual rewards in the form of virtual jerseys or access to hidden levels may also be earned with the accumulation of points relative to distance and calorific expenditure. The popularity of the existing gamified exercycling model is reflected in membership rates of the various online communities (Reed, 2021). However, although these simulators do facilitate fitness training for millions of virtual cyclists (Peloton Investor Resources, 2021), the exercise intensity of the training session is reliant on human motivation. This chapter investigates whether user output can be increased when the game rather than the player dictates task intensity through game mechanics that rely on variable resistance.

Conventional video games often employ the metaphor of loss and gain through use of virtual energy levels. Energy levels may decrease when an avatar gets injured or increase when a powerup is collected. The studies in this chapter physicalise this metaphor through the use of incentivised and disincentivised exertion. Task intensity is generated on smart trainers using dynamic resistance by means of electromagnetics. At present, trainer resistance within the various exercycle environments is relative to the slope and surface of the virtual terrain the virtual cyclist is cycling in. Chase or Be Chased intends on altering the trainer resistance relative to the virtual terrain but also relative to the user's real-time performance. For example, if a user is working below a specified threshold, resistance on the physical interface increases, hindering their game performance. Correspondingly, if a user's output level is above a predefined benchmark, resistance decreases, facilitating task completion.

Two conditions were compared to investigate whether incentivised and disincentivised game mechanics can be used to encourage enhanced physical output. In each condition the user was tasked with moving a virtual car over a distance of 1.5km. The speed of the virtual car was synchronised with the speed of the smart bike trainer. In the first condition, 'Chase', users race against an AI car. Resistance is automatically reduced for five seconds every time the user overtakes the AI car. In the second condition, 'Be Chased', users are chased by an AI car.

If the speed of the user's car drops below a predefined speed the chasing car rams the player's car causing resistance to automatically increase for five seconds.

The two closest studies which used a similar concept and involved physical activity are by Finkelstein et al. (2008) and Patel et al. (2016). Finkelstein et al. sought to test if financial incentives for walking could increase physical activity among sedentary older adults. Their study demonstrated that incentives motivated increased walking among adults aged 50 years and older over a four week time period. It should be noted that this study only involved financial gain and did not feature financial loss. In Patel et al.'s study overweight adults who achieved daily exercise goals were given a payment of $1.40, while participants who failed to reach the daily target of 7000 steps were fined $1.40. In contrast to the findings of Finkelstein et al., Patel et al. demonstrated that financial incentives framed as a loss were most effective for achieving physical activity goals. Patel et. al.'s study is based on Kahnemans' loss aversion theory which states that people will work harder to avoid losing a small deposit than they will to win an equal amount (Kahnemann et al.,1991). The authors in question discovered that monetary incentives framed as a loss were most effective in achieving physical activity goals. Taking Kahneman's theory and Patel et al's findings into account, it is currently unknown whether participants will work harder to avoid increased resistance in the Being Chased condition than they will to earn decreased resistance in the Chase condition or whether either of these game mechanics might motivate additional effort from participants.

4.2 BACKGROUND

A common theme in all exergames involves the use of biofeedback loops, whereby a user's physiological output is directly affected by their awareness of their own real-time corporal data. The Chase or Be Chased system design is based on the concept of the biofeedback loop but one that features adaptive game mechanics relative to user performance.

Two prior studies have adjusted aspects of real-time game play relative to the user's physiological data. Masuko & Hoshino (2006) designed a heart rate controlled 'boxercise' video game where the in-game contents were actively adjusted based on real-time physiological feedback. The motivation behind the game design was to motivate participants to exercise at a predefined optimal level. Stach et al. (2009) also adjusted virtual game attributes in a multiplayer exergame with a view to minimising disparity between the competitors' physical strength. The authors of this study ranked avatar attributes in real-time relative to the user's fitness level rather than the user's power. Although the study did implement a fairer system of inter-player competition it did not focus on enhancing physical output. The fact that both games adjusted aspects of game difficulty relative to the users' physiological readings were of interest, however, the system designs of both studies lacked any form of dynamic resistance.

Bicycles are often used as a medium in exergame design to bridge the real and the virtual. Barathi et al. (2018) focused on intrinsic motivation by creating a system that consisted of a virtual third person cyclist viewed through a HMD (Head-Mounted Display) and controlled by the real world cadence of a stationary bike. Users achieved rapid improvement in performance by competing against 'virtual self models', which showed previously unachieved performance levels. Bolton et al.s' PaperDude' (2014) also used a bicycle interface to recreate a 1980s arcade classic in VR. This was one of the first studies to have combined smart trainers with HMD technology. Although the physical interface does utilise a Wahoo Kickr (Wahoo, 2021) to replicate the speed of the virtual bicycle, slope resistance from the game engine is not replicated on the physical device.

Other studies focus less on the experience and more on output measurement. Two separate studies by Warburton et al. (2007) and Monedero et al. (2015) compare physical output generated when cycling in an exergame and when cycling on an exercise bike. The only time that resistance features in Warburton et al.'s. study is when users are asked to manually adjust the cycle ergometer; however it is not implemented dynamically based on in-game performance. Monedero et al.'s (2015) system design features components from a Velotron ergometer in addition to a speed sensor and steering mechanism from a CatEye GameBike. Two way feedback was not established between the ergometers resistance mechanism and the virtual slope gradients within the game. The only variable passed from the physical interface to the videogame was the cyclists' rate of cadence. Both studies effectively show that immersion and gamification do motivate increased output, however, resistance does not feature in any way as a game mechanic.

Farrow, et al.'s (2019) exercycle study measured user output but also integrated resistance to see if intensity could be increased without impacting the users' level of enjoyment. Their study demonstrated that resistance can be increased by 10% without impacting on the user experience. In their study, intensity was raised by adjusting the ergometers' resistance, however, the rate of resistance was not dynamic and had no correlation with the virtual terrain viewed by the user.

Michael & Lutteroth's (2020) study Race Yourself combined competition with dynamic resistance and enabled participants to race and compete against 3D representations of their estimated fitness potential. Resistance did feature as a game mechanic, however, player performance had no bearing on the degree to which it was implemented. Dynamic resistance is also featured in Haller et al.'s (2019) study 'HIIT the Road'. The exergame involved cycling through a virtual environment in which there are props that trigger contrasting results when hit. Colliding with an 'obstacle' caused extra resistance on the physical interface whereas collecting a 'reward' lowered its resistance. There are definite similarities in the way Chase or Be Chased and HIIT the Road feature resistance as rewards and penalties; however Haller et al.'s study examined the impact of virtual spectator applause on user performance and did not measure the impact of resistance on user output.

This section has referenced exercycle games that have used various strategies to motivate the way in which participants exercise. Although some of the studies have featured dynamic resistance, none have used resistance to coerce or entice enhanced output. The way that Chase or Be Chased adjusts dynamic resistance relative to user performance is unique in exergame design. This game mechanic should offer new findings to both the HCI community and commercial exergame designers as it has the potential to increase levels of physical fitness without the need for a personal trainer.

4.3 HYPOTHESES

The hypotheses are as follows:

H1: That physical output will be higher and completion times will be faster for both 'Chase' and 'Being Chased' relative to those of the control condition. This hypothesis is being made on the basis that the dynamic resistance associated with the chase based game mechanics will increase levels of immersion and dissociation which Glen et al. (2017) have demonstrated can increase physiological output. The fact that the control condition lacks any chased base game mechanics will reduce immersion and dissociation leading to reduced player exertion.

H2: That enjoyment levels for both 'Chase' and 'Being Chased' conditions will be higher than the levels of the control condition. This hypothesis is being made on the basis that the dynamic resistance associated with the chase based game mechanics will increase levels of immersion and dissociation which can have a positive impact on psychological output (Glen et al., 2017). The fact that the control condition lacks any chased base game mechanics will reduce immersion and dissociation leading to reduced player enjoyment.

H3: That a majority of participants will play an optional game rather than take a sports drink. This is a behavioural measure to see if participants find the game more enjoyable than a small reward: its purpose is to measure something more objective than self-reported measures.

H4: Of those who choose to play an optional game, more will choose to play Being Chased than Chased. I envisage that a greater number of participants will avoid potential increases in resistance in 'Being Chased' than those that will seek reductions in resistance when overtaking in the 'Chase' condition. This is made on the basis of Kahneman's loss aversion theory, whereby loss is perceived by individuals as psychologically or emotionally more severe than an equivalent gain.

H5: That completion times will be faster, physical output will be greater and enjoyment results from the Paces scale will be higher in 'Being Chased' than the 'Chase' condition. Similar to hypothesis four, I anticipate that participants will avoid potential increases in resistance in 'Being Chased' than those that will seek reductions in resistance when overtaking in the 'Chase' condition. This hypothesis is also made on the basis of Kahneman's loss aversion theory.

4.4 METHODS

4.4.1 Participants

The experiment was conducted with 30 volunteers (six female), average age: 41± 7.7 years, weight: 75±12.5 kg, height: 1.75± 0.09 m and BMI: 24.2±2.5 kg/m2). A confirmation procedure ensured that participants had no underlying health conditions and that they engaged in regular exercise at least once a week. The criteria for defining regular weekly exercise was either running 5km, cycling 15km or swimming 800m.

4.4.1.1 Ethics Approval

Ethics approval which involved conducting a thorough risk assessment was obtained prior to the study. Each participant was thoroughly briefed and asked to provide informed consent prior to taking part in the study. Participants were also informed that they could withdraw from the experiment at any stage they wished.

4.4.2 Design

4.4.2.1 Materials

A Wahoo Kickr Core smart trainer was purchased as was a 10-speed gear cassette which was attached to the trainer. A ‘Giant Rapid’ bicycle was sourced, its rear wheel was removed and swapped in place with the smart trainer (Figure 4.1). The bike’s chain was attached to the gear cassette on the trainer and then calibrated over a Bluetooth connection with the wahoo fitness app on an iphone 10. A copy of the video game Grand Theft Auto Five (GTAV) was purchased and installed on a Windows 10 PC with a Gforce GTX970 Graphics Card. ScriptHookDotNet (2022) was installed in the GTAV folder which enabled customised scripts or mods to be run parallel with the main GTAV.exe system file.

Figure 4.1 Giant Rapid’ bicycle mounted on Wahoo Kickr.

It should be noted that this GTBike V mod (Matas, 2021) does not support Bluetooth but instead communicates with the Wahoo Kickr using ANT+ technology. There were some initial proximity related issues with ANT+ as the hardware dongle has a limited distance of 3 metres. This caused some confusion during setup as there was intermittent signal loss between GTAV and the trainer. This issue was rectified using a USB extension cable to bring the ANT+ closer to the Wahoo Kickr resulting in consistent connectivity for the remainder of the study.

The GTAV mod ‘Map Editor v2.13’ (Figure 4.2) was used to map out a 1.5km route on the northern highway of the virtual isle of *Los Santos*. This 1.5km virtual route equated to 1.5km real world units and the same route was used in all of the user study conditions. The virtual terrain was highway asphalt so it would not provide any excess friction for the rider, however increases and decreases to the slope gradient over the route led to changes in the trainers’ resistance. A heads-up display on the right of the screen provided the user with real-time feedback relating to wattage output, bike cadence, distance covered, accumulated time and slope gradient. A more detailed account of the technical development and game modification can be read on Chapter Three.

Figure 4.2 The 1.5km route mapped on the virtual island of ‘Los Santos’.

While the GT Bike V mod menu provides the user with a selection of cyclists and bikes to choose from, I decided that it would be more in line with GTAV gameplay if the avatar vehicle took the form of a car. An equal ratio mapping between smart trainer speed and virtual car speed was maintained. To simplify the task, steering was not required as the car always followed a predefined path between the start and the finish line (Figure 4.3). The path kept the route consistent for each player and each condition. A start banner is placed at the beginning of the course and a green luminous beacon is placed at the 1.5km marker.

Fluctuating AI generated traffic has the potential to introduce bias within gameplay. A build-up of virtual traffic on the highway or a crash for example could slow one users’ avatar down in one condition and not for another. To eliminate this possibility the volume of traffic is adjusted so that vehicles other than those necessary for game play disappear once within a 300m radius of the avatar vehicle.

Figure 4.3 Chase or Be Chased starting and finishing points.

4.4.2.2 Experimental Design

A within-subjects repeated measures design was used, so each participant participated in all three riding conditions. The sequence of conditions was counterbalanced to mitigate learning effects or fatigue.

Each subject was assigned an anonymous identification number for data analysis. All experimental data were recorded using the anonymous id number alone. On reaching the finishing line performance data relating to duration, distance, wattage and speed were recorded as a .fit file for use in the post test analysis.

After each condition participants had a five minute rest period during which they could sit down, rehydrate and complete a Borg Scale questionnaire as well as an adjusted Physical Activity Enjoyment (Paces Scale) questionnaire (Figure 4.4). The Borg scale measures Rate of Perceived Exertion (RPE) and the Paces scale measures data relating to levels of enjoyment, interest, like, absorption, stimulation and fun. Completion times, energy expenditure, perceived exertion and enjoyment were recorded in order to understand the impact the differing game mechanics had on performance.

Item	**Rating 1-7**
Enjoy / Hate	
Bored / Interested	
Dislike / Like	
Absorbed / Not Absorbed	
No Fun / Fun	
Not Stimulating / Stimulating	

Figure 4.4 Paces Scale.

4.4.2.3 Design Study 01: Control Condition

This condition featured the 1.5km route and had no additional A.I. vehicles.

4.4.2.4 Design Study 02: Being Chased Condition

The course features a pink jeep which appears at the starting line and is programmed to ‘shadow’ the avatar vehicle by following parallel to it on the left hand side (Figure 4.5 top left image). Prior to playing any of the conditions, participants selected a speed threshold from a choice of five speeds during a pretest session. If the avatars’ speed dropped below this predefined threshold the chasing car performed a U-turn to alert the participant that it was going to attempt to ram them (Figure 4.5 top right image). During the following five seconds, if the participant increased their output and accelerated to above the chosen speed threshold the chasing car would drive parallel to the player and continue to shadow them (Figure 4.5 top left image). However, if the participant failed to increase output following the U-turn the chasing car would aggressively ram into the back of the player’s car (Figure 4.5 bottom left & bottom right images). Ramming generated extra resistance on the smart trainer for a period of five seconds. If rammed, a five second grace period was factored in before the chasing car could execute any subsequent ramming maneuverer. This was to prevent a vicious circle occurring.

Figure 4.5 Repercussions for pedalling too slow.

The chasing car and its ramming properties were added as a supplementary script to the GT Bike V mod. The extra classes were coded in C# and merged with the existing code using the DNSpy (2021) application to decompile and repackage the plugin. Code was also used to move the third person camera mounted on top of the player vehicle twenty metres behind the car model so as to allow the player to gauge how close the chasing car is, if and when it attempts to ram from behind.

The following code sets the chase behaviour of the chasing car to ‘1’ which equates to ‘Aggressive ramming of suspect’ whenever the players’ speed drops below 35kph:

```
if (Bike_Speed <= 35)
{
Function.Call(GTA.Native.Hash.SET_TASK_VEHICLE_CHASE_BEHAVIOR_FLAG,
Globals.chase_ped,1, true);
}
```

This script checks if the players’ car is above the predefined threshold of 36kph and if true it sets the chasing vehicle to ‘escort’ the players’ car whereby it drives parallel to the player at the same speed:

```
if (Bike_Speed >= 36)
{
Function.Call(GTA.Native.Hash.TaskVehicleEscort, Globals.chase_ped,
Globals.chase_car, Game.Player.Character, 1, 32F, 786944, 3F, 1, 4F);
}
```

The following script determines if the chasing car has rammed with the player car and if it has it increases the smart trainer resistance:

```
if ((Function.Call(GTA.Native.Hash.IS_ENTITY_TOUCHING_ENTITY,
Game.Player.Character.CurrentVehicle, Globals.chase_car)) == true);
{
ANT_Receiver.SetBasicResistance(60);
}
```

4.4.2.5 Design Study 03: Chasing Condition

This game also featured a pink Jeep, however rather than pursuing the avatar car it automatically drove on the predefined path assigned to the avatar car. The speed of this AI car was the same speed as that chosen by the participant in the benchmark pretest. If the participants’ car overtook the AI vehicle, resistance on the smart trainer was temporarily reduced for five seconds. The following script determines if the players’ car has overtaken the AI car and if it has it decreases the smart trainer resistance:

```
if (Game.Player.Character.CurrentVehicle.Position.X >
Globals.competition_car.Position.X)
{
ANT_Receiver.SetBasicResistance(0);
}
```

4.5 PROCEDURE

The following sections will discuss the pretest which was used to determine an optimum target speed for each of the participants. The subsequent sections will describe the process used in the Control, Chase and Be Chased experimental conditions. The final section relates to the process used for the optional measurement test.

4.5.1 Pretest

Chase or Be Chased investigated whether output can be enhanced when task intensity is adjusted relative to player performance. The Chase exergame temporarily reduced resistance on a smart trainer whenever the participant went above a predefined speed; Be Chased temporarily increased resistance whenever the participant went below a predefined speed. In order to calculate the optimum predefined speed for each participant it was important to find a balance between user exertion and user enjoyment. Prior research has demonstrated that enjoyment levels do start to decrease once user intensity is around the lactate threshold (Ekkekakis et al., 2011). This occurs when lactate builds up in the bloodstream during physical exercise to a level that is higher than resting values. Lactate threshold was not being measured in this study but it could be approximated by referencing Borg scale values. A study by Scherr et. al (2013) involving 2560 athletes has indicated that RPE can be used to gauge lactate-threshold training effort, equating it to 13 on the Borg scale. Keeping the exertion level below 13 ensures that the user remains within their lactate threshold and in doing so prevents their enjoyment levels from decreasing.

In order to define the optimum target speed for each participant they were asked to cycle for one minute keeping the trainer at a constant speed of 15kph followed by a five minute rest. During this time they were not controlling any exergame, all that was displayed on the screen was their bike speed. During the resting period participants had to quantify their RPE by selecting a number between 6 and 20 on the Borg scale. These steps were repeated four more times at 20kph, 25kph, 30kph and 35kph. Of the five RPE values provided by each participant, the speed corresponding to the highest value that was greater than 6 but less than 13 was selected as their speed threshold. On completion of the pretest participants were given a five minute break to rest and rehydrate.

4.5.2 Interface Familiarisation

Following the post pretest resting period, participants were given a one minute trial controlling the player car within GTAV so as to familiarise themselves with the on screen heads-up display data and to select a suitable starting gear on the bicycle.

4.5.3 Procedure: Control

For the control condition participants were tasked with moving the avatar' vehicle over a distance of 1.5km from the starting line to the finishing beacon. The speed at which the participants cycled was entirely up to themselves and no verbal motivation was given at any stage.

4.5.4 Procedure: Chase

Once this game was initiated an AI car was generated and automatically driven at the speed of the participants' pretest threshold along the predefined path between the start and finish line. The players' car was placed parallel to the AI car on the starting line and participants were tasked with pedalling the smart trainer so as to move the avatar vehicle to the finish line at their own pace and were also given the option to race against or overtake the AI car if they wanted to. Each time the participant's car overtook the AI vehicle a bonus was given in the form of a five second reduction in wheel resistance. Upon completion as with other conditions, performance data was saved and questionnaires were given to participants to complete during the resting period.

4.5.5 Procedure: Being Chased

For this condition, the avatar car was placed at the starting line of the 1.5km route and participants were tasked with getting the car to the virtual finish line by means of pedalling the smart trainer. This condition also featured an AI vehicle that was programmed to ram the players' car should the participants' bike speed drop below their chosen pretest threshold. Each time a collision was detected between the chasing car and the avatar a penalty was given in the form of a five second increase in wheel resistance. If the players' car remained greater than or equal to their chosen pretest threshold the chasing car would shadow the players car by driving parallel to it. Once the finish line was reached the steps of saving performance data, resting and questionnaire completion were repeated.

4.5.6 Optional Measurement (Drink Or Extra Game)

On completion of the third condition participants had the option of either receiving a bottle of Lucozade sport or else partaking in a choice between the Chase Condition or Being Chased condition. If participants decided to replay one of the conditions they were given a five minute rest break before doing so.

4.6 ANALYSIS

Repeated-measures analyses of variance (ANOVAs) were used to compare the corresponding means, with Average Speed, Average Watts, Maximum Speed, Completion Time and RPE as factors. Significant measures were subjected to post-hoc analyses by means of paired sample, two tailed t-tests using Bonferroni corrected alpha values ($\alpha = .05$). Finally, for the optional game, a chi-square test was used.

Data relating to levels of enjoyment, interest, like, absorption, stimulation and fun was gathered by means of an adjusted Paces scale. Likert results were subject to a non-parametric Friedman test and significant results were followed up with a post-hoc analyses using a Wilcoxon signed-rank test with Bonferroni-adjusted alpha level of .017 (0.05/3).

4.7 RESULTS

Average Watts

Mauchly's test indicated that the assumption of sphericity had been violated, χ^2 (2) = 0.7356, p = 0.0136, therefore Greenhouse-Geisser corrected tests are reported (ε= 0.79). The results show that there was a significant effect of the riding condition on the Average Watts value $F(2, 58) = 8.88$, $p < 0.01$. Post hoc tests using Bonferroni correction revealed significant differences ($p<0.05$) between the average wattage output while playing Being Chased (M = 200.56, SE = 13.54) and Chase (M = 206.4, SE = 13.82) relative to the wattage output while playing the Control condition (M = 171.77, SE = 14.6), but no significant difference between the Being Chased and Chase conditions ($p>.05$).

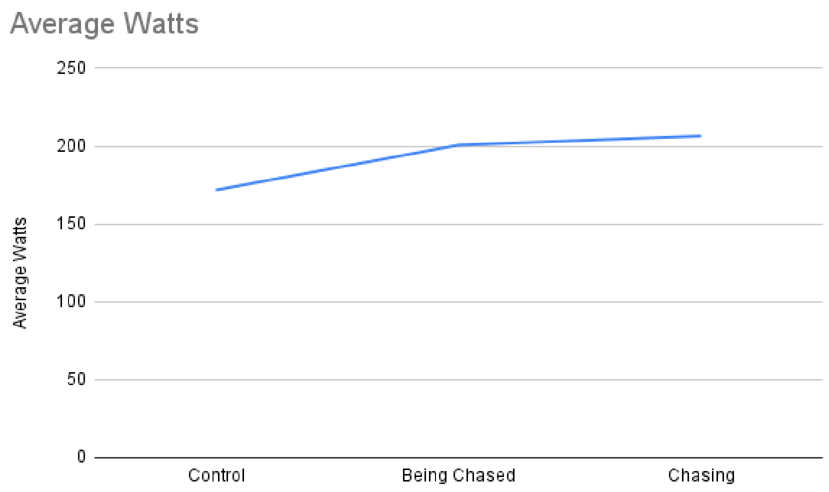

Figure 4.6. User Data Relating to Average Watts.

Duration of Ride

Mauchly's test indicated that the assumption of sphericity had been violated, $\chi^2(2) = 0.9499$ p = 0.4867, therefore Greenhouse-Geisser corrected tests are reported (ε= 0.95). The results show that there was a significant effect of the riding condition on the trial Duration, $F(2, 58) = 3.76$, $p < 0.05$. Post hoc tests using Bonferroni correction revealed significant differences ($p<0.05$) between completion times while playing Being Chased (M = 153.47, SE = 5.86) and Chase (M = 152.9 SE = 5.3) relative to the Control condition (M = 164.7, SE = 5.74), but no significant difference was found between the Being Chased and Chase conditions ($p>.05$).

Rate Of Perceived Exertion

The results show that there was a significant effect of the riding condition on RPE, $F(2, 58) = 10.5$, $p < 0.05$. Post hoc tests using Bonferroni correction revealed significant differences between RPE while playing Being Chased (M = 14.06 SE =0.3) and Chase (M = 14.13 SE = 0.3) relative to the Control condition (M = 12.6, SE = 0.4), but no significant difference was found between the Being Chased and Chase conditions ($p>.05$).

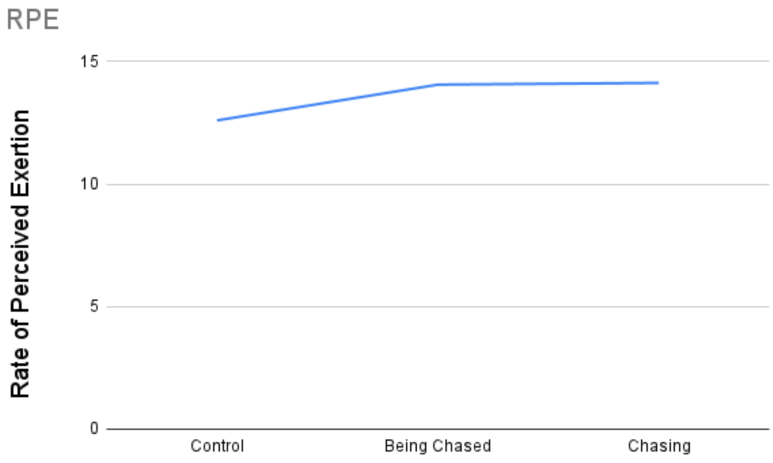

Figure 4.7. User Data Relating to Rate of Perceived Exertion.

Maximum Speed

The results show that there was no significant effect of the riding condition on the Maximum Speed, ($p > .0504$).

Average Speed

The results show that there was no significant effect of the riding condition on the Average Speed, ($p > .067$).

Enjoy/Hate

A Friedman's ANOVA showed that there was a significant effect of condition on recorded enjoyment levels, $X^2r(2)=22.2$, $p < .001$.

Post-hoc tests using a Wilcoxon signed-rank test with Bonferroni-adjusted alpha level of .017 (0.05/3) showed that participants enjoyed playing Being Chased (Mdn = 1) more than they did playing Control (Mdn = 3), T= 246.5, Z = -3.3 p<.01

Post-hoc tests using a Wilcoxon signed-rank test with Bonferroni-adjusted alpha level of .017 (0.05/3) showed that participants enjoyed playing Chase (Mdn = 1) more than they did playing Control (Mdn = 3), T= 356, Z = -4.01 p<.00001.

Comparable data between Being Chased and Chase was not significant ($p > .017$).

Bored/Interested

A Friedman's ANOVA showed that there were significant differences between levels of interest recorded by participants across the Chase, Being Chased and Control conditions, $X^2_r(2)=26.6$, $p < .001$.

Post-hoc tests using a Wilcoxon signed-rank test with Bonferroni-adjusted alpha level of .017 (0.05/3) showed that participants were more interested in playing Being Chased (Mdn = 7) than they were playing Control (Mdn = 5), T= 9, Z = -4.02 p< .00001.

Post-hoc tests using a Wilcoxon signed-rank test with Bonferroni-adjusted alpha level of .017 (0.05/3) showed that participants were more interested in playing Chase (Mdn = 7) than they were playing Control (Mdn = 5), T= 0, Z = -4.29 p<.00001.

No differences in levels of interest were found between the Being Chased and Chase conditions (p > .017).

Dislike/Like

A Friedman's ANOVA showed that there were significant differences in the extent to which participants liked playing the Chase, Being Chased and Control conditions, $X^2_r(2)=37.9167$, p < .001. However, post-hoc tests using a Wilcoxon signed-rank test with Bonferroni-adjusted alpha level of .017 (0.05/3) did not find significant differences between the three conditions (p > .017).

Fun

A Friedman's ANOVA showed that there were significant differences between the levels of fun recorded by participants while playing the Chase, Being Chased and Control conditions, $X^2_r(2)=35.15$, p < .001.

Post-hoc tests using a Wilcoxon signed-rank test with Bonferroni-adjusted alpha level of .017 (0.05/3) showed that participants found playing Being Chased more fun (Mdn = 7) than playing the Control condition (Mdn = 5), T= 10, Z = -4.3949 p< .00001.

Post-hoc tests using a Wilcoxon signed-rank test with Bonferroni-adjusted alpha level of .017 (0.05/3) showed that participants found playing Chase (Mdn = 6) to be more fun than playing the Control condition (Mdn = 5), T= 27, Z = -4.0078. p<.00001.

No differences were found in the levels of fun reported between the Being Chased and Chase conditions (p > .017).

Absorbed

A Friedman's test showed significant differences between how absorbed participants' reported being while playing the Chase, Being Chased and Control Conditions, $X^2_r(2)=17.15$, p < .001.

Post-hoc tests using a Wilcoxon signed-rank test with Bonferroni-adjusted alpha level of .017 (0.05/3) showed that participants found playing Being Chased more absorbing (Mdn = 2) than playing the Control condition (Mdn = 3), T= 244, Z = -3.8147 p< .01.

Post-hoc tests using a Wilcoxon signed-rank test with Bonferroni-adjusted alpha level of .017 (0.05/3) showed that participants found Chase more absorbing (Mdn = 2) than playing the Control condition (Mdn = 3), T= 120, Z = -3.4078 p<.01.

No differences were found in how absorbed participants reported between the Being Chased and Chase conditions (p > .017).

Stimulating

A Friedman's test showed an effect of riding condition on how stimulated participants reported being while playing, $\chi^2_r(2)=40.0667$, p < .001.

Post-hoc tests using a Wilcoxon signed-rank test with Bonferroni-adjusted alpha level of .017 (0.05/3) showed that participants found playing Being Chased more stimulating (Mdn = 6) than playing the Control condition (Mdn = 4.5), T= 0, Z = -4.703 p < .00001, Chase more stimulating (Mdn = 5) than playing the Control condition (Mdn = 4.5), T= 8, Z = -3.9539 p < .01, and Being Chased (Mdn = 6) more stimulating than Chase (Mdn = 5), T= 296.5, Z = -3.6055 p<.01.

4.8 RESULTS: OPTION OF PLAYING AN EXTRA GAME

A Chi-Square test was carried out to test whether participants were more likely to play an extra game featuring one of the Chase conditions (N=21) or if they would choose to receive a sports drink (N = 9) after completing the study. The results were significant, (p < 0.05).

A Chi-Square test was carried out to test whether the Chase condition (N=13) had been more popular than the Be Chased condition (N=8) amongst the participants who chose to replay an extra game instead of the sports drink. No significant difference was found, $\chi^2(2)=1.19$, p > 0.05.

4.9 DISCUSSION

The aim of the study presented in this chapter was to test five hypotheses relating to the motivational effects of resistance-based feedback within an exercycle video game. This section summarises the results and observations, discussing various aspects of the game. The main findings were the significant effect chase based game mechanics had on average watts, completion times, RPE, enjoyment, fun, stimulation, level of interest and how absorbed users felt. The following section will discuss the findings of this study in more detail.

Hypothesis one stated that chase based game mechanics will motivate greater physical output and faster completion times than the control condition. This hypothesis was supported; there was a significant effect of physical output and ride duration for both ‘Chase’ and ‘Being Chased’ relative to the control condition.

Hypothesis two stated that Paces scale results for both ‘Chase’ and ‘Being Chased’ conditions will be higher than the control condition. This hypothesis was correct; relative to the control condition, ‘Chase’ and ‘Being Chased’ had a significant effect on average watts, completion times, RPE, enjoyment, fun, stimulation, level of interest and how absorbed users felt.

Hypothesis three stated that a majority of users will play an optional game rather than take a sports drink. The results showed that participants were more likely to play an additional game than to receive the small reward of the sports drink.

Hypothesis four stated that of those who chose playing an optional game, the majority would select playing Being Chased. 62% of those who opted for the game over the drink, chose to play the Chase condition however there was insignificant data to verify its popularity over Being Chased.

Hypothesis five stated that avoiding potential disincentivised game mechanics in ‘Being Chased’ will generate greater physical output than the incentivised based aspect in the ‘Chase’ condition. This hypothesis was false. No significant differences were recorded relating to average watts, duration of ride, RPE or maximum speed between the Being Chased and Chase conditions.

The significance of the first and second hypotheses demonstrate that it is logistically possible to automate task intensity using dynamic resistance. The use of EMS was not robust or reliable enough for an interface involving exertion and generated distorted data in the Carrot or Stick study (Chapter Three). In contrast the resistance generated by the smart trainer was more than capable of limiting limb movement when necessary and did so in a consistent and reliable manner.

This use of dynamic resistance as a game mechanic has enabled the game rather than the user to dictate the task intensity. The fact that automated task intensity can be used to generate enhanced output and that smart trainers are a viable way of integrating dynamic resistance within HCI projects are two things that were unknown prior to the study. These findings will benefit game designers, fitness enthusiasts and the HCI community.

The fact that 70% of participants chose to replay the game rather than accepting payment in the form of an energy drink highlights the appeal of the experience. The decision to replay the game may have been influenced by the high visual fidelity and individualised speed thresholds. Chase or Be Chased modified the video game GTAV which provided the user with state of the art graphics. According to Mayra & Ermi et al. (2011), enhancing dissociation leads players to forget about the sensory input from the real world and focus on the sensory input from the virtual world. The study also individualised participants’ speed thresholds to try to prevent user lactate levels from reaching threshold levels. Ekkekakis et al. (2011) have highlighted the importance of remaining below lactate threshold in order to enjoy the experience and remain dissociated from the physical task.

The logic from both authors is that enjoying the activity and focusing more on the game and not the exertion generates greater output than a game that is less enjoyable. Although there were no comparable immersive or lactate threshold measures I believe the choice to replay the game may have been attributed to the combination of enhanced visual fidelity and the lactate limiting strategy.

Farrow, et al. (2019) have previously demonstrated that intensity can be increased by 10% during a VR exercycle game without impacting on the users' level of enjoyment. In their study resistance was manually adjusted before each condition, the experiments did not implement any lactate limiting strategy and cycling was limited to a duration of sixty seconds, nonetheless their findings are still of interest. A future study in this area could yield interesting results by investigating the main effects of reduced lactate threshold and visual fidelity on output and enjoyment levels in addition to studying the interaction effects of both. I would propose doing a longitudinal study where the focus would be on using resistance based game mechanics, immersive environments and real-time physiological data with a view to maximising user engagement, exertion and enjoyment.

Incentivised and disincentivised exertion did motivate enhanced physical output. The hypothesis (H5) had been that avoiding potential punishment in 'Being Chased' would generate greater physical output and enjoyment than the reward based aspect of overtaking in the 'Chase' condition. Wattage and completion times compared between the chase based conditions were not significantly different and therefore this hypothesis could not be verified as data differences were too low. This theory had been based on Kahneman's theory which states that people will work harder to avoid a financial loss than they will to gain an equivalent financial reward.

Hypotheses one and two did demonstrate the benefits of including chase based game mechanics within exergame design and could be utilised in future research. A subsequent study could yield interesting results by investigating how altering between both chase states can impact on maintaining engagement during long term exergame activity.

4.10 CONCLUSION

There was no relevant data to differentiate between the benefits of penalising or reward based resistance as game mechanics. However, the study demonstrates that chase based game mechanics can be used to motivate enhanced physical output through the medium of an exergame without diminishing the enjoyment aspects of gamified physical activity. Chase or Be Chased demonstrates the potential of enhancing physical output through adaptive interface design. The ability to fully automate predefined levels of physical exercise could open up infinite possibilities for physical training, skill acquisition and rehabilitation. Understanding to what extent human motivation can be replaced by mechanised exertion would require a longitudinal study with a more complex system design and is worth considering for future work. This concludes the section that has been dedicated to unaugmented resistance. The following chapters (Chapter Five & Chapter Six) will examine enhancing physical output using augmented resistance.

Contributions

Smart trainers are a viable way of integrating dynamic resistance within HCI projects.
It is logistically possible to automate task intensity using dynamic resistance.
Automated task intensity can be used to generate enhanced output.
Chase based game mechanics can be used to motivate enhanced physical output.
Incentivised and disincentivised resistance does motivate enhanced physical output.

Limitations

The advantages of applying Kahneman's theory as a game mechanic to enhance exertion remain unanswered. Continuing with a subsequent study involving higher numbers of participants would more than likely yield an effect size offering limited practical value. However, the advantages of applying Kahneman's theory as a game mechanic to enhance exertion remain unanswered and could yield interesting results using an alternative game design.

CHAPTER 5: EXPLORING THE IMPACT OF AUGMENTED RESISTANCE

5.1 INTRODUCTION

The research question in this chapter asks whether varying display immersion, manipulated physiological data and augmented resistance can be used to enhance user output during exergame play. Exploring how these three conditions can be used to optimise physical output answers a core part of the broader research question: ‘creating exergame mechanics to increase physical output’.

The research in Chapter Four successfully demonstrated that incentivised game mechanics involving dynamic resistance can be used to enhance physical exertion through the medium of an immersive exergame. While the Chase or Be Chased study focused on motivating physical exertion through the exclusive use of variable resistance mechanisms embedded into simple game mechanics, the subsequent chapters broaden this inquiry and investigate whether physical activity can be improved further by combining resistance with other elements to create additional game mechanics.

One of the key focuses in this study is the effects of relinquishing control, for example if people are willing to relinquish ‘task’ control to a fitness coach such as CrossFit, BootCamps or Personal Trainers, would they also be willing to relinquish ‘physical’ control to a coach during a resistance based exergame.

Chase or Be Chased has demonstrated that relinquishing task intensity to a virtual coach through chase based game mechanics can enhance physical output. Switching It Up also features relinquished control as a game mechanic, by allowing a third party to manually adjust task intensity at specific moments. In addition to augmented resistance, the study design investigates how other factors in VR known to influence exercise output - varying display immersion and manipulated physiological data - might interact with variable resistance. By developing and user testing more complex exergames I aim to provide the exergame development community with new findings that can be used to motivate enhanced physical output.

This chapter is particularly interested in how interfaces might adapt and intervene in the user’s exercise routines to provide definite outcomes. Within the realm of exergaming, coaches and trainers lack the ability to increase task intensity at specific times during customer workouts. This study addresses this issue by focusing on factors that can be included in exergaming interfaces to support high intensity exercise. Prior research has shown an effect of immersion on motivation (Plante, 2003), however, it is not clear what resistance would bring to this space. This study aims to build on this knowledge by examining the relationship that immersion has on physical output during a resistance based exergame. Users participate by playing two versions of an exergame, one in which basic user data is displayed on a monitor and another which features a fully interactive VR environment.

In addition to examining differing relationships between output, resistance and immersion, physiological data is also introduced as a game mechanic. The user's own real-time physiological data is displayed on the interface HUD.
However, in certain conditions the displayed data will be altered without informing the participant until after all the experiments have been completed. Deception has recently emerged as a common, practical approach to manipulate key variables during exercise. Stone et al. (2012) demonstrated that secretly augmenting an exercycle game with information from a prior workout enables participants to complete a 4km time trial quicker than they had done with accurate feedback.

In several commercial and research based exergame projects the virtual character or vehicle is controlled by the cadence or speed of the real-world exercise machine (e.g. rowing machine, turbo trainer, treadmill, exercise bike). Using a setup like this enables a smooth crossover for the user – the faster they operate the real-world machine, the faster their virtual machine or character moves on screen. A decision was made to control the exercycle interface in Switching It Up using the user's heart rate rather than the user's cadence as it allowed for a more subtle method of manipulating their displayed physiological data. If cadence had been altered, proprioceptive awareness could have alerted participants to discrepancies between physical cadence and virtual avatar speed.

To elaborate on this point, cyclists can approximate their cadence rate due to the voluntary nature of the activity whereas the involuntary nature of heart rate allows a more discreet method of physiological deception. For this reason a decision was made to control the virtual cyclist using the user's heart rate. BPM (Beats Per Minute) has a direct link with Wattbike pedal speed and its utilisation within the system maintains a connection, albeit an indirect one, between that of the physical bike interface and the virtual cyclist. No prior work had manipulated heart rate data to encourage enhanced output during exergame play. This was a unique research topic which had the potential to provide new findings to the HCI community.

Having provided a brief synopsis of the motivation behind this study the following paragraphs provide a detailed account of how I explored linkages between motivating enhanced exertion and augmented resistance.

5.2 BACKGROUND

The following section will discuss related work focusing on the areas of immersion in exercise, physical bicycle interfaces, gaming physiology and deception.

5.2.1 Immersion in Exercise

Morgan et al. (2008) studied the cognitive strategies of marathon runners, proposing two key categories: association where runners focus on their own bodies, and dissociation in which attention to the environment distracts from the body. They found that associative approaches were dominant in elite marathon runners, while amateur runners used a dissociative strategy.

Modern coaching techniques attempt to enhance the associative strategy, for example by training meditative techniques to take the athlete's attention away from audiences or the environment and onto their own embodied process.

Based on the role dissociation and distraction play cognitively amongst non-elite athletes, linkages are expected between dissociation, immersion and motivation that could be influenced by immersive techniques such as VR. Prior academic studies have examined the influence sensory stimuli have had on dissociation while exercising: Razon et al. (2009) conclude that "external stimuli may serve as mediating agents in diverting attention away from internal and painful stimuli. This distraction may likely contribute to the pleasantness of the exercise experience, ultimately leading to increased exercise participation". Similarly Karagoris & Priest (2012) describe the relationship between music and physical exercise, suggesting that its positive impact magnifies motivation and performance.

Existing research has also examined the impact of immersion on physical output within the realm of VR. Studies to date examining exertion and VR have typically used projected virtual environments rather than immersive HMDs. Finkelstein et al.'s (2009) exergame 'Astrojumper' is one other such example (Finkelstein et al., 2009). Their study demonstrates that VR exergames can effectively motivate children and adults to exercise through immersive VR.

Studies relating to exertion and bicycles have demonstrated that VR cycling experiences effectively motivate exercise. Warburton et al. (2007) discovered that "a training program that links interactive video games to cycle exercise results in greater improvements in health related physical fitness than that seen after traditional cycle exercise training". Monedero et al. (2015) found that "a single bout of Interactive Cycling Video Game resulted in a significantly higher rate of energy expenditure than a bout of conventional cycling". Mestre et al. (2011) also conducted an exercycle study to measure the impact of VR on cycling performance, however its primary focus was to enhance the exercise experience rather than the exercise output. In each of these exercycle studies VR is viewed on a monitor or projector screen and not through a HMD.

The VR version of Switching It Up places an emphasis on the aesthetic and interactive qualities by using Unreal game engine technology (2015) (as outlined in Chapter Three). By enhancing the visual stimuli I aim to increase the user's sense of dissociation from the physical task. The decision to do so is influenced by the work of Razon et al. (2009) who have demonstrated the effect visual stimuli have on enhancing dissociation and physical output. Levels of true energy expenditure will be recorded and compared between the VR and non-VR task. I expect that VR immersion will generate enhanced output (H2). I also hypothesise that interaction effects of immersion and resistance will motivate greater output than they will as individual conditions (H4).

5.2.2 Gaming Physiology

Previous exergames have used physiological data such as heart rate to control virtual game elements. Mokka et al. (2003) used immersion in the form of a projected virtual environment; while the project did measure heart rate, the BPM measure was not used to control the virtual character. Nenonen et al.'s (2007) exergame study, featured heart rate as a game mechanic, however, the BPM readings had no impact on game difficulty.

Heart rate has been used as an effective tool to vary the level of exertion required in certain exergame studies. Masuko & Hashino's interactive boxercise game actively updates the gameplay based on real-time cardio data (Masuko & Hoshino, 2006). Stach et al. (2009) also introduce customised exergame activity through the use of heart rate scaling, a mechanism where players' in-game performance is based on their effort relative to their fitness level. These examples make use of heart rate with and without resistance-based activity, however, none of the studies manipulate displayed user data in an attempt to increase output.

5.2.3 Deception

Previous publications have examined the topic of disinformation and its application to the realm of physical exertion. Valins (1966) made use of real-time physiological feedback to demonstrate that physiological reactions can serve as a source of information that influences emotional behaviour. While not strongly linked with exertion, his study is one of the first to involve temporary user deception with physiological feedback. Hutchinson et al.(2008) provided participants with false positive/negative feedback on completion of certain tasks. This study correlated exertion and physical tasks, although the feedback given was neither real-time nor physiologically based.

Löchtefeld et al.'s (2016) exercycle study 'Deceptibike' demonstrated that user output could be increased when the natural mapping between the physical bike cadence and the virtual avatar speed was altered. The illusory game mechanic coerced users to pedal faster without realising they were being duped, with some participants generating a 15.2% increase in user speed. It should be noted, that at the time of developing and user testing this study (September 2015 - June 2016), Deceptibike had not yet been published.

Stone et al. (2012) demonstrated that secretly augmenting an exercycle game with information from a prior workout enables participants to complete a 4km time trial quicker than they had done with accurate feedback. While the results were significant, resistance was not altered at any stage during the game play and the interface was projected rather than being viewed through a VR HMD (two aspects which Switching It Up feature).

I anticipate that a reduction in displayed heart rate data will motivate increased physical output [H3], and expect that interactive effects during conditions involving deception and resistance will increase output compared to that of the output generated by the effect of those conditions individually [H5].

5.3 HYPOTHESES

Resistance has been previously implemented as a game mechanic in the Chase or Be Chased study where it has proven to be effective in motivating physical output. This study was designed to explore whether exertion can be enhanced further in combination with other intervention techniques that might be used to develop more sophisticated game mechanics.

It aims to motivate enhanced physical output by augmenting resistance into a study of performance with a high-end exercise bike. It's important to differentiate between the methods of resistance used in Chased or Be Chased and Switching It Up, the former used ANT+ technology to generate dynamic resistance whereas the latter features the manual adjustment of a Wattbike magnetic resistance lever. In addition to augmenting resistance the study also features varying levels of immersion and manipulated physiometric readings. Although this research was primarily exploratory, hypotheses were made that:

• [H1] Resistance interventions will affect physical output (increase in resistance will increase power, RPE (Rate of Perceived Exertion), and Nasa TLX Physical Demand and Effort measures). This hypothesis is a reasoned estimate that increased task intensity will require greater physical output.

• [H2] HMD immersion will affect actual and perceived exertion levels (use of HMD will increase power, RPE). This hypothesis is made on the basis of prior work by Razon et al. (2009) who have previously demonstrated the positive influence visual stimuli have on perceived exertion during a physical task.

• [H3] Falsified physiological data will affect actual and perceived exertion levels (decreasing the users displayed BPM will increase power, RPE and Nasa TLX Physical Demand and Effort measures). This hypothesis is made on the basis of prior research by Stone et al. (2012) who demonstrated that user performance could be enhanced through user deception.

• [H4] Resistance and immersion combined will have a larger effect than their combined main effects (as interaction effects of resistance will enhance the experience of the other). This hypothesis is made on the basis that increasing task intensity during the immersive condition will require greater physical output than that of the immersive condition without added resistance; and that the dissociative benefits of immersion (Razon et al. 2009) combined with the resistance condition will generate greater output than the resistance condition without any dissociative stimuli.

• [H5] Resistance and deception combined will have a larger effect than their combined main effects (as interaction effects of resistance will enhance the experience of the other). This hypothesis is made on the basis that increasing task intensity during the deception condition will motivate greater physical output than the deception condition without added resistance; and that the influence of user deception on physical output (Stone et al., 2012) combined with the resistance condition will motivate greater output than the resistance condition without any use of deception.

• [H6] Resistance, immersion and deception combined will have a larger effect than their combined main effects (as interaction effects of resistance will enhance the experience of the other).

This hypothesis is made on the basis that the combination of increased task intensity with enhanced immersion and user deception will motivate greater physical output than than the combined output generated by the dissociative merits of immersive stimuli (Razon et al. 2009) and the demonstrated impact of user deception (Stone et al., 2012).

5.4 METHOD

Richer immersive environments viewed through HMDs and interactions based on real-time physiological feedback have paved the way for fresh studies in the field of HCI and physical exertion. The design approach uses these advances to discover if it is possible to motivate the performance of intense physical activity through adaptive interventions combining physical resistance, immersion and manipulated physiological data.

5.4.1 Design

Switching It Up addresses these issues by motivating players to surpass the low levels of physical exertion associated with traditional exergames (Lanningham-Foster et al., 2006). A VR cycling game was developed in which the avatar's speed and distance covered are controlled by the user's heart rate while pedalling a stationary Wattbike. Speed was dictated by the user's heart rate and steering was controlled by a standard gamepad. The goal of the game is to cover as much virtual distance as possible in a predefined time frame. Seeing as the task had to be repeated eight times with varying conditions a decision was made to limit the duration of the activity to sixty seconds. In hindsight this was not a sufficient length and will be reflected on in the discussion. The following section describes the use of resistance and how it was augmented alongside immersive gameplay and manipulative physiological feedback.

5.4.1.1 Resistance

It should be noted that this method of dynamic resistance differs to the method used in the previous chapter, Chase or Be Chased. The system design used in Chase or Be Chased automated bike resistance relative to task performance allowing the game rather than the player to dictate the required exertion. Switching It Up also removes the user from the decision process but rather than automating the exertion level, task difficulty is dictated by a third party such as a coach or trainer. Chase or Be Chased demonstrated how dynamic resistance could generate enhanced output.

The Wattbike includes a magnetic resistance dial or 'climb' lever with seven incremental settings which could be adjusted to alter the exertion levels required to turn the bike's pedals. The lowest setting '1' generated the resistance of a level road and the highest setting '7' simulated resistance to that of a very steep gradient. For the game condition that featured both resistance and the HMD, resistance was adjusted using the dial.

During the resistance and non-VR conditions, the climb lever was adjusted using a pulley system whose controlling system had been placed beneath a desk and out of the participants view.
In all of the games involving resistance alteration, the lever was changed from 'level 5' to 'level 7' on the magnetic resistance at exactly thirty seconds throughout each sixty second game. The dial remained static at 'level 5' in all other games.

I anticipate that involuntary resistance changes will generate enhanced physical output (H1) and that the interactive effects of resistance will also play a role in enhancing the impact of immersion (H4), deception (H5) and immersion and deception (H6) during the respective user tests.

5.4.1.2 Immersion

For comparing immersion, there were two separate game modes, fully immersive and screen based. The fully immersive game was viewed in a HMD and consisted of a virtual cyclist on a highway which ran through a rural environment. The game environment and cyclist avatar (Figure 5.1) were created using the Unreal Game Engine and rendered for output through an Oculus Rift HMD (Oculus, 2016). For feedback purposes it was necessary to design a Graphical User Interface that displayed heart rate, virtual distance, bike gear and remaining time. As layered 2D status bars within a HMD can make users nauseous (Ohyama et al. 2007), a Heads Up Display element was attached to the avatar using a 3D widget. This reduced any virtual sickness and kept the important feedback in a prominent location.

Figure 5.1: (1) Heart Rate, (2) Virtual Bike Gear, (3) Virtual Distance Covered, (4) Timer Countdown (5), Virtual Cyclist.

The screen based mode consisted of the heads-up display data and did not feature any 3D graphics or avatar (Figure 5.2). The aim of increasing the visual stimuli in the fully immersive version was to increase the user's sense of dissociation from the physical task.

Levels of true and perceived energy expenditure were recorded and compared between the VR and non-VR task. I hypothesise that the VR version will motivate enhanced output than the screen based non-immersive version (H2).

I also expect interaction effects from increased resistance during immersive game play will generate greater output than that of immersion on its own (H4).

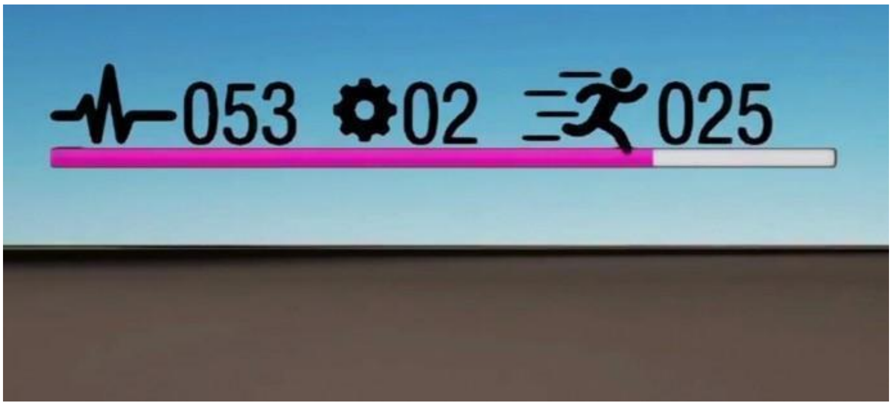

Figure 5.2: Non-Immersive GUI.

5.4.1.3 Physiological Control

Switching It Up features manipulated physiological data as a game mechanic and examines its relationship with energy expenditure. In all but one of the bicycle based exergames described in the related work section, bike cadence was mapped to the character's virtual performance and speed. Mapping the user's pedalling with that of the virtual cyclists would have lent to a greater sense of interactive 'connection'. However, the increased synchronisation between machine and body would have made it increasingly harder to deceive the user. Instead of using cadence, Switching It Up mapped output indirectly to the virtual bike speed through the user's heart rate.

Figure 5.3: (1) Wattbike, (2) Arduino Wireless Heart Rate Receiver, (3) Oculus Rift, (4) Gamepad, (5) Resistance Pulley, (6) Wattbike Display Unit, (7) Resistance Dial.

A mapping system was developed in order to dynamically adjust the virtual bike's speed based on the incoming heart rate data. There were 12 gears on the virtual bike (1st gear being the slowest speed and 12th being the highest); a BPM reading of between 40-50 would activate 1st gear, 50-60 2nd gear, 60-70 3rd gear, up to 170+ 12th gear.
Thus BPM was relative to gear speed, which was relative to distance covered. The virtual bike's gear system, speed and distance covered were all relative to the incoming sensor readings. This meant that a user who was unfit could in theory cover a greater virtual distance than a fitter user exerting a greater force. Taking this into account a Wattbike was selected as it could measure energy expenditure in addition to distance.

5.4.1.4 Falsification

Tenenbaum & Hutchinson's (2007) exertion model maintains that above a given effort threshold, physiological cues dominate attention focus and at this point an associative attention focus is almost unavoidable. According to Tenenbaum there is a limit as to how long distractions can enable people to remain in a dissociative state; there is a cut-off point when the task intensity gets so high that users become unable to take their mind off the physical task and they begin exercising in an associative state. Once people begin exercising associatively they are more aware of their own physiology. I was interested in whether users moving from a dissociative to an associative state would pay greater attention to their on screen heart rate and if so could false physiological feedback be used to motivate increased physical exertion.

I could find no prior study that used altered cardio feedback within an exergaming context so no optimum level of heart rate exaggeration existed. A pilot test was conducted to establish an appropriate percentage range that the user's visible heart rate could be altered by during game play. Seven variations were created where the user's visible heart rate would be changed by +10%, +20% +30%, 0%, -10%, -20% and -30%. A single user was asked to play these seven games (chosen in random order) with a two minute break between each game, and asked to give feedback on the system. The user did not notice when their BPM was raised by any amount but when it was reduced below 20% they commented that they thought there might be inaccuracies with the heart monitor. Based on this feedback, displayed heart rate reduction was 'capped' at a level of 20%. I hypothesise that decreasing the visible BPM will motivate greater physical exertion (H3). Interaction effects are also expected between deception and resistance (H5), with greater physical and perceived output expected when resistance and deception are combined rather than used as individual game mechanics.

5.4.2 Measures

Two main measures were used: Power Output and RPE. The first dependent variable generated by the user was 'absolute' power measured in Watts and recorded by the Wattbike for each trial. Absolute power percentage for each condition were manipulated to calculate a 'relative' power value, measuring the performance in that condition as a ratio of that participant's average performance across all trials, to factor out outliers in individual performance. RPE was measured for each user. This is a psychophysiological 15 point scale defined by Borg (1962) in his original studies on how individuals adjust to physical effort and exercise.

Finally, a short form NASA Task Load Index questionnaire (Hart & Staveland, 1988) was administered following each ride in order to discover issues of changing workload across the trials. This is a workload assessment tool which allows users working with various human-machine interface systems to provide feedback on aspects of a task which are rated on a 20 point scale. Questions asked were on Mental Demand, Physical Demand, Temporal Demand (being hurried or rushed), Performance, Effort and Frustration.

The experiment was conducted as a within-subjects study with 12 participants (six female, six male). Their ages ranged from 20 to 30 years. Participants were recruited by email and were required to be relatively fit (exercising twice a week for 20-25 minutes on a regular basis) without any health conditions or disabilities. The six male and six female participants were asked to sign a consent form and were informed that they could withdraw from the experiment at any stage they wished. While the participants would be recorded playing the games, their personal data and video/audio recording were retained only for analysis. Participants received an incentive to take part in the form of a €100 gift voucher which was randomly assigned after the study.

As participants were experiencing falsified information under conditions that could be stressful, the proposed study was approved by the University of Bristol Engineering Ethics committee.

5.4.3 Participants

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As participants were experiencing falsified information under conditions that could be stressful, the proposed study was approved by the University of Bristol Engineering Ethics Committee [CT 2050].

5.4.4 Procedure

An experiment was organised based on the previous game design to explore the three key adaptive interventions, immersion (conditions VR headset or flat screen), resistance (conditions gear actuation or no actuation) and deception (conditions true BPM and false BPM) and their interactions.

A partial latin square was used to generate counterbalanced condition orderings for eight games, each embodying a unique permutation of the three independent variables.

Isbister & Mueller (2015) suggest that active management of fatigue is critical in studying exergames, and this experiment was no exception. The study attempted to prevent fatigue and 'over familiarisation' for participants by keeping the eight games one minute long, and also providing five minute rests between each game. During the resting period participants had to quantify their perceived rate of exertion by selecting a number from the Borg scale as well as filling out a NASA TLX questionnaire. Verbal feedback based on participants' comments during and after each game were also recorded and typed up for supporting analysis.

Participants were provided with a heart rate monitor to attach in a separate private room prior to beginning the user test. Once ready they were asked to play a demo game in order to adjust the bike saddle, the HMD and the heart monitor. The demo game also gave participants a chance to become familiar with being in a VR environment and steering an avatar using a gamepad. As shown in Figure 5.1 and Figure 5.2 real-time data items on the in-game heads-up display were brought to the participants attention before the user tests began: Heart Rate, Bike Gear, Virtual Distance Covered and Timer Countdown.

Participants were told that the object of each game was to cover as much virtual distance as possible within a sixty second period. The order of the games varied for each participant depending on the counterbalancing. Tests were documented with a video and audio recording of the participants cycling as well as screen capturing their virtual performance.

Participants were informed at the end of the last game that their visible heart rate had been altered in four of the eight games. None of the participants were upset by this alteration and only one of the twelve said that they had suspected there may have been some manipulation of the data.

5.4.5 Analysis

A repeated measures three-way factorial ANOVA was conducted over each dependent variable to identify any main effects of immersion, resistance or deception and any interaction effects. The test was also mirrored over the NASA TLX data, which showed a sufficiently Gaussian distribution to enable ANOVA analysis.

5.5 RESULTS

5.5.1 Immersion

Immersion had a significant effect on Absolute Power, Relative Power and Mental Workload.

The results show that there was a significant effect of Immersion on Absolute Power, $F(1, 11) = 6.301$, $p < 0.05$. Post hoc tests using Bonferroni correction revealed significant differences ($p < 0.05$)

between wattage output while playing in the immersive condition (M = 177.542 SE = 21.244) and non-immersive condition (M = 159 SE = 19.115).

The effect of Immersion on Relative Power was significant, $F(1, 11) = 8.21$, $p < 0.05$. Post hoc tests using Bonferroni correction revealed significant differences ($p < 0.05$) between distance in metres recorded by the Wattbike while playing in the immersive condition (M = 559.396 SE = 25.493) and non-immersive condition (M = 532.167 SE = 25.688).

The effect of Immersion on perceived mental workload was significant, $F(1, 11) = 6.833$, $p < 0.05$. Post hoc tests using Bonferroni correction revealed significant differences between Nasa TLX Mental ratings while playing in the immersive condition (M = 7.271 SE = 1.61) and non-immersive condition (M = 4.229 SE = 1.211).

Immersion had no significant effect on perceived exertion, RPE ($p = 0.257$) , NASA TLX physical ($p = 0.2$), NASA TLX Effort ($p = 0.274$) or on NASA TLX Temporal Demand ($p = 0.08$), NASA TLX Frustration ($p = 0.175$) or NASA TLX Performance ($p = 0.247$).

5.5.2 Resistance

The results show that there was a significant effect of Resistance on perceived time pressure, $F(1, 11) = 7.871$, $p = 0.017$. Post hoc tests using Bonferroni correction revealed significant differences ($p < .05$), between Nasa TLX Temporal rates while cycling with augmented resistance (M = 9.792 SE = 1.168) and without augmented resistance (M = 8.479 SE = 1.08).

Resistance had no significant effect on Absolute Power ($p = 0.521$), Relative Power ($p = 0.437$), Perceived Exertion: RPE $p = 0.4$), NASA TLX Physical ($p = 0.315$), NASA TLX Effort ($p = 0.243$), or on NASA TLX Mental Workload ($p = 0.892$), ($p = 0.711$) or Nasa TLX Performance ($p = 0.38$).

5.5.3 Deception

There was no significant effect of Deception on Absolute Power ($p = 0.4$), Relative Power ($p = 0.306$), Perceived Exertion: RPE ($p = 0.458$), Nasa TLX Physical ($p = 0.391$), Nasa TLX Effort ($p = 0.526$), or on Nasa TLX Mental Workload ($p =1$), NASA TLX Temporal Demand ($p = 0.8$), frustration ($p = 0.18$) or Nasa TLX Performance ($p = 0.476$).

5.5.4 Interaction Effect Of Resistance & Immersion

There were no significant interaction effects of Resistance & Immersion on Absolute Power ($p = 0.51$), Relative Power ($p = 0.518$), Perceived Exertion: RPE ($p = 0.286$), Nasa TLX Physical ($p = 0.561$), Nasa TLX Effort ($p = 0.66$), or on NASA TLX Mental Workload ($p = 0.108$), NASA TLX Temporal Demand ($p = 0.565$), NASA TLX Frustration, ($p = 0.727$) or NASA TLX Performance ($p = 0.928$).

5.5.5 Interaction Effect Of Resistance & Falsification

There was no significant interaction effect of Resistance & Falsification on Absolute Power (p = 0.966), Relative Power (p = 0.664), Perceived Exertion: RPE (p = 0.253), Nasa Physical (p = 0.524), Nasa Effort (p = 0.074), or on NASA TLX Mental Workload (p = 0.145), NASA TLX Temporal Demand (p = 0.283), NASA TLX Frustration (p = 0.742) or NASA TLX Performance (p = 0.661).

5.5.6 Interaction Effect Of Immersion & Falsification

There was no significant interaction effect of Immersion & Falsification on Absolute Power (p = 0.357), Relative Power (p = 0.95), Perceived Exertion: RPE (p = 0.957), Nasa TLX Physical (p = 0.378), Nasa TLX Effort (p = 0.261), or on NASA TLX Mental Workload (p = 0.915), NASA TLX Temporal Demand (p = 0.555), NASA TLX Frustration (p = 0.541) or NASA TLX Performance (p = 0.353).

5.5.7 Interaction Effect Of Resistance, Immersion & Falsification

There was a significant interaction effect of Resistance, Immersion & Falsification on perceived time pressure, $F(1, 11) = 12.407$, $p < 0.01$. Post hoc tests using Bonferroni correction revealed significant differences ($p < .05$), between Nasa TLX Temporal rates when resistance was increased while cycling without using user deception in the non-immersive condition (M = 11.583 SE = 1.495) compared to when resistance was increased while cycling without using user deception in the immersive condition (M = 8.583 SE = 1.033), (Figure 5.4).

There were significant differences ($p < .05$), between Nasa TLX Temporal rates when resistance was increased while cycling without using user deception in the non-immersive condition (M = 11.583 SE = 1.495) compared to when resistance was not increased while cycling without using user deception in either the immersive condition (M = 8.083 SE = 1.209) or non-immersive condition (M = 7.917 SE = 1.443), (Figure 5.4).

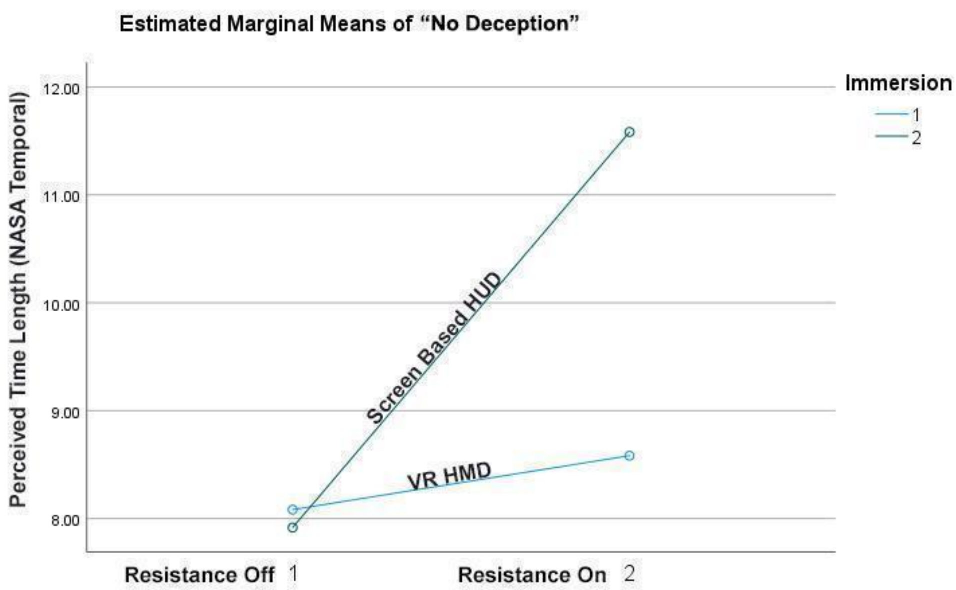

Figure 5.4 Interaction effect of Resistance, Immersion and Unmanipulates User Data.

There were significant differences (p < .05), between Nasa TLX Temporal rates when resistance was increased and user data was manipulated in the immersive condition (M = 9.5 SE = 1.264) and when resistance was not increased and user data was manipulated in the immersive condition (M = 9.917 SE = 1.368), (Figure 5.5).

There were significant differences (p < .05), between Nasa TLX Temporal rates when resistance was not increased and user data was manipulated in the immersive condition (M = 9.917 SE = 1.368) and when resistance was not increased and user data was manipulated in the non-immersive condition (M = 9.917 SE = 1.368), (Figure 5.5).

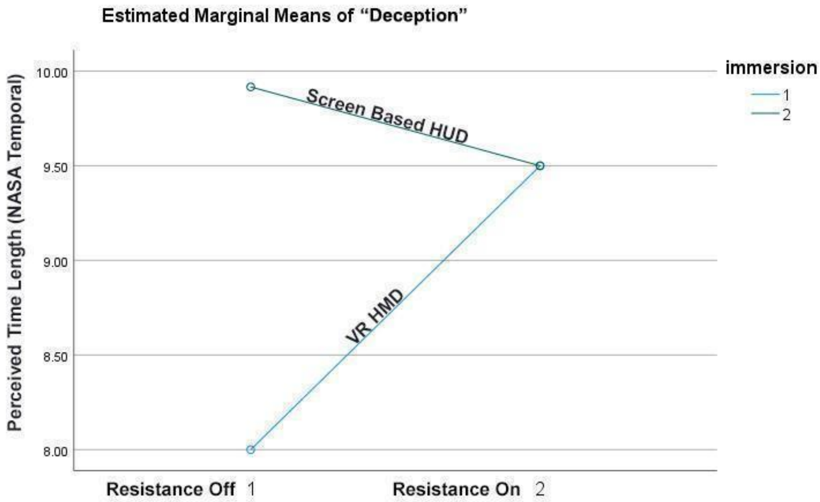

Figure 5.5 Interaction effect of Resistance, Immersion and Falsified User Data.

There were no significant interaction effects by the three conditions on Absolute Power (p = 0.768), Relative Power (p = 0.949), Perceived Exertion: RPE (p = 0.502), Nasa TLX Physical (p = 0.362), Nasa TLX Effort (p = 0.897), or on NASA TLX Mental Workload (p = 0.547), NASA TLX Temporal Demand (p = 0.283), NASA TLX Frustration (p = 0.687) or NASA TLX Performance (p = 0.455).

5.6 DISCUSSION

This section summarises the results and observations, discussing various aspects of the game. The main finding was the significant effect of immersion on performance. The most surprising results were the lack of evidence for increased power when resistance increased, the lack of evidence for increased power when heart rate was falsely decreased and a lack of interaction effect generated by resistance on immersion and deception respectively and combined. The next two subsections explore these variables in turn.

5.6.1 Resistance

Chase or Be Chased and Switching It Up separated user autonomy from task intensity, however, whereas the former used technology to *simulate* a virtual coach the latter uses technology to *facilitate* a physical coach. Doing so, allows a third party such as a trainer to manually adjust the task intensity at specific moments.

The effect of Temporal Demand data on increased resistance suggests that participants felt hurried or rushed when resistance was increased, however, there was insufficient evidence to support Hypothesis One. The use of resistance in Switching It Up had no main effect on perceived or real exertion levels and yet it had done so in the previous study. Could this issue relate to the manner in which resistance was implemented i.e. automated in Chase or Be Chased and manual in Switching It Up ?

Before any conclusions are drawn it's important to examine differing aspects in both user studies. This study had fewer participants and less recorded play time than Chase or Be Chased. The latter involved thirty participants with an average play time of 153 seconds per condition. In comparison, Switching It Up involved twelve participants with each condition lasting exactly sixty seconds; during conditions involving resistance only 30 seconds of each sixty second game involved an increase in resistance. The game mechanics in this study were also meaningful and perceptible to the participants, whereas in Switching It Up, they weren't interactive, meaningful, or perceptible: they just increased at a set point.

It is true to say that resistance can be effective in motivating additional effort; however a lack of statistical power makes it impossible to determine how resistance implementation influences user output. In the words of Mark Bolas, “Presence has to go both ways. The world has to acknowledge that you’re in it” (Stein, 2016). If gear resistance on the actual bike could have been linked with in-game performance, perhaps two-way feedback would have had more of an impact on performance in the study. However, at present there is insufficient data to detect a real effect and therefore a future study with greater participants and longer duration lengths is necessary.

Other design considerations to take into account are the manner in which manual resistance is controlled. I was confident that resistance was being adjusted without drawing the user’s attention, however participants may or may not have been aware of the resistance changes. There is no way of knowing this as it was not documented in any questionnaire. In hindsight, participants should have been asked if they had sensed resistance manipulation and to what extent. These are aspects that currently prevent a definitive conclusion regarding a preferable method in which to apply resistance within exergame design.

5.6.2 Immersion Motivates Performance

Immersion was found to have a significant effect on absolute power, relative power and perceived mental workload. This provides evidence for Hypothesis Two, that immersion has a significant main effect, and is a strong result to encourage increased interplay between VR and exergaming. Studies such as Glen et al.'s (2017) have shown that immersive video game cycling leads to higher energy expenditure. However, the immersive environments in these studies were generated using projectors or monitors. At the time of this study (2016) measuring the impact of a HMD on physical output was a unique aspect in exergaming.

There was insignificant data to provide evidence for Hypothesis Four that the interaction effects between resistance and immersion would generate greater output than those variables would when trialled independently. One possible explanation may have been due to the way in which resistance was altered during game play. The automated task intensity used in Chase or Be Chased generated enhanced output in comparison to Switching It Up, however, Chase or Be Chased did not feature immersion as a measured condition. In order to determine the interaction effect between immersion and resistance it would be necessary to conduct a new study.

5.6.3 Deception

I did not find any evidence to support Hypothesis Three, that manipulated data increases performance, nor any interaction between manipulation and increasing the resistance (Hypothesis Five). One explanation for this could be attributed to task duration and the impact it has on physiological awareness. According to Morgan et al. (2008) users in a dissociative state are less aware of their own physiology than those in an associate state. Users enter an associative state when task intensity gets so high that they are unable to take their mind off the physical task. Hutchinson, J. C., & Tenenbaums model (2007) states that physiological awareness is greater in an associative state than a dissociative one. Whether users within this particular study entered into an associative state in such a short time frame is unlikely. Had the participants cycled for longer periods and entered associative states, a greater sense of physiological awareness may have resulted in a different outcome for this condition. This is something that should be explored in future work.

In hindsight more than one participant should have been used to determine the optimum falsification rate during the pilot study. However, the fact that only one out of twelve participants became suspicious of the data manipulation is encouraging and would lead one to believe that 20% was a credible reduction rate.

5.6.4 Resistance, Falsification & Immersion

There was a significant interaction between resistance, immersion and deception which impacted on the participants' perception of time pressure. When there were no adjustments made to resistance, and displayed player heart rate was manipulated the users in the non-immersive condition perceived that the exercycle task was more rushed than it had done when viewed through the HMD.

When resistance was increased and displayed heart rate was true, the users perception of time pressure in the non-immersive condition was much higher than it had been in the immersive condition. When deception and augmented resistance were used simultaneously, perception of temporal demand of those using the HMD became closer to the ratings provided during the non-immersive condition. In addition to validating the dissociative benefits of visual stimuli (Kim, & Biocca, 2018) these findings also suggest that immersion and data manipulation can be used independently to reduce the perceived time pressure in an exertion based task, however when used simultaneously they nullify the dissociative benefits of enhanced immersion.

A strong interaction effect between all the variables in this Temporal Demand measure is seen, supporting Hypothesis Six, suggesting that the effect of feeling rushed when heart rate is manipulated increases in the non-immersive and unaugmented resistance conditions. Therefore, this effect may be especially the case when other physical or visual distractions from the physiological data are not present.

5.7 Conclusion

This chapter presented the design of Switching It Up: an immersive cycling based exergame, together with the results and observations from testing the game. The study showed that players demonstrated increased exertion in one of three game interventions (immersion) and that while adaptive resistance control and manipulated physiological data had little impact on output intensity, subtle compensations were actively at play in both mental and physical performance. The use of manipulated physiological data had been an exploratory phase of this body of work and on the basis of the insignificant results relating to physical output a decision was made to discontinue featuring it any further study.

A significant effect of immersion was found and this suggests that virtual fitness applications would benefit from increased visual immersion to enhance both training and performance. While physical and physiological manipulations did not result in significant measures, this work suggests that there will be compensation effects in both these areas, which will be important for future work to measure and underpin explanations for these surprising outcomes. The findings strongly indicate that immersive interventions can have positive effects on adapting user behaviour, and that further adaptive interventions may also support marginal performance enhancements for athletic training and exercise.

I have also demonstrated the wider principle that immersive, physical and physiological gaming interventions can be incorporated into virtual exergaming agents in ways which underpin performance and support increased training capacity. Being able to compare findings from Chapters Four and Chapters Five also provides the exergame development community with a greater understanding of resistance-based game mechanics and intervention aspects that are more fruitful and less time consuming than others.

This chapter explored whether augmented resistance could be used to increase the *quantity* of output during an exergame. The next chapter expands on this augmentation and examines whether it can be used to improve the *quality* of output during an immersive exertion based task.

Contributions

The study showed that a VR HMD could be used to enhance physical output during resistance based exergame play. In addition to validating the dissociative benefits of visual stimuli, the findings also suggest that immersion and data manipulation can be used independently to reduce the perceived time pressure in an exertion based task, however when used simultaneously they nullify the dissociative benefits of enhanced immersion.

Limitations

At the time of conducting this study in 2016, there was no prior work that had manipulated heart rate in an exergame and therefore no optimum level of heart rate exaggeration existed. A pilot study was conducted with one participant to establish a proposed level of BPM reduction. In hindsight more than one participant should have been used to determine the optimum falsification rate during this pilot study.

The use of resistance in Switching It Up had no main effect on perceived or real exertion levels and yet it had done so in Chase or Be Chased. This may have been due to the statistical power which may have increased the possibility of incorrectly accepting the null hypothesis. Switching It Up had twelve participants with each condition lasting exactly sixty seconds; during conditions involving resistance only 30 seconds of each sixty second game involved an increase in resistance. Chase or Be Chased had thirty participants with an average play time of 153 seconds per condition. The time length of participant activity in exergame studies and the limiting impact it may have on user data has previously been raised by other researchers (Mueller et al., 2016). The length of these conditions could be increased in a follow up study and could consider reaching out to the online cycling community to partake in a longitudinal study.

Levels of perceived immersion were not recorded in this study. Having done so in this study and in all of the other studies would have provided a way to compare the impact of various HMD and game engine combinations on immersion, dissociation and exertion. This would have also enabled comparisons between Chase or Be Chased and Switching It Up relating to the resistance style (i.e. dynamic or manual) and user exertion.

Another design limitation to take into account in Switching It Up was the manner in which manual resistance was controlled. I was confident that resistance was being adjusted without drawing the user’s attention; participants may or may not have been aware of the resistance changes. There is no way of knowing this as it was not recorded in any questionnaire. In hindsight, participants should have been asked if they had sensed resistance manipulation and to what extent.

CHAPTER 6: EXPLORING THE IMPACT OF AUGMENTED RESISTANCE ON THE QUALITY OF EXERTION

6.1 INTRODUCTION

The research questions asked in this chapter are whether adaptive haptics affect user posture and if real-time visual feedback can be used to improve user posture during an exertion based task. By focusing on the quality rather than the quantity of user output the questions align with the aspect of postural improvement in the main research question.

The following chapter introduces the third and last of three exploratory studies in the area of exertion based gaming. Before continuing, it is important to summarise the outcomes of the first two studies. Chapter Four demonstrated that incentivised game mechanics involving dynamic resistance can be used to enhance physical exertion. Chapter Five broadened this inquiry by investigating whether physical activity can be improved further by combining resistance with manipulated user data and varied immersion. Although the use of manipulated user data showed no significant effect, the study did demonstrate how Virtual Reality can be used as a medium to increase energy expenditure during exercycle activity. The following chapter continues with the theme of augmented resistance. However, unlike *Switching It Up,* which focused on enhancing the *quantity* of physical output, the current chapter examines enhancing the *quality* of the task performance.

Enhancing the quality of a physical task through a virtual medium is an underexplored area which has the potential to improve people's physical health. Home based immersive physical activity is a rapidly expanding commercial sector with millions of users subscribing to virtual training platforms (Reed, 2021; Peloton Investor Resources, 2021), however, they do so without knowing how efficiently their body is being put to use.

C*artRight* is an immersive exergame based around the day-to-day activity of grocery shopping. The interface features a type of ‘hybrid reality’ design whereby physical resistance can be replicated in the real world based on the user’s virtual interactions. Resistance is generated using an adaptive haptic platform which seamlessly overlaps with a virtual shopping cart. Two experimental studies are conducted to explore whether adaptive haptics affect user posture, and determine whether real-time feedback on posture can increase a user’s ability to be mindful of their postural choices. The aim of this chapter is to investigate whether haptic and visual game mechanics can be used to enhance the qualitative performance of an exertion based task.

Virtual Reality (VR) systems have long-standing challenges with physical ergonomics, such as additional weight of HMDs on the head and neck muscles, display latency, and collision with invisible physical features of the real-world during periods of immersion.

While haptic feedback devices have a long history, increasingly VR is coupled with adaptive haptic feedback (CyberGrasp, 2018; Realwalk, 2018) which aligns variable forces on the user's body with the properties of the interactions, environment, or even other users. Although these challenges exist, commercial VR exergames focus entirely on motivating output and in doing so they ignore the qualitative aspects of the physical activity. Games such as Audioshield (2022) and Thrill of the Fight (2021) can motivate players to burn an average of between 10.66 kcals to 11.85 kcals per minute and 9.74 kcals to 15.32 kcals per minute respectively. However, no data is collected on how well the tasks are performed, or how the user engages ergonomically.

Exertion based virtual activity is predicted to increase over the next five years driven by Facebook's desire to get its 2.9 billion subscribers embracing the Metaverse and playing the exergames they have been actively acquiring (Heater, 2021; Kelly, 2022). Given the surge in exergaming and the lack of emphasis on task quality, users are putting themselves at risk of injury by participating in virtual activities without any feedback on the quality of their physical movement. Providing real-time postural feedback during exergame activity has the potential to improve physical performance and counteract any threat of physical strain on the body.

6.2 RELATED WORK

The work presented in this study examines the relationship between posture and adaptive resistance while replicating a common musculoskeletal task within a virtual environment. The following summarises the most directly related works in the areas of biomechanical loading, haptics, visual feedback and activity recognition.

6.2.1 Biomechanical Loading

CartRight is a user study which replicates the task of grocery shopping within a virtual environment. As the task involves pushing a wheeled object with varying resistance loads it was necessary to explore related work involving the manual handling of wheeled objects. The reason for this is twofold, firstly to understand any associated postural risks and secondly to investigate if any recommendations or improvements had been introduced in this area.

Universal health expenditure associated with physical exertion in the workplace are a cause for concern amongst employers and employees alike. The National Institute for Occupational Safety and Health reported that 20% of injury claims for lower back pain (LBP) involved pushing or pulling loads. According to Pope et al. (2002), LBP is one of the most important disabling health problems facing industrialised societies.

Several studies have been undertaken in an attempt to alleviate the risks and negative consequences linked with moving wheeled objects. Hoozemans et al. (1998) studied the risk factors and noted the role of pushing and pulling loads as a key causal factor of LBP. In their paper the authors created guidelines to help prevent musculoskeletal disorders associated with pushing and pulling heavy objects such as containers and wheelchairs. Glitsch et al. (2007) also investigated pushing and pulling wheeled objects but specifically amongst flight cabin crew. Their findings demonstrated a connection between varying cabin aisle inclination and cabin crew posture issues when moving refreshment trolleys in flight. Although this study went to great lengths recreating a cabin aisle in a lab setting and conducting in-flight studies, they do not identify or explore any interventions.

In an attempt to alleviate injury and back pain, certain studies have taken a different view and have focused on adjusting the wheeled device rather than the method in which it is pushed. In their paper 'Postures adopted when using a two-wheeled cylinder trolley', Okunribido & Haslegrave (2003) experimented with various handle types to improve posture when pushing a two-wheeled cylinder trolley. Similarly, Jung et al. (2005) made a number of ergonomic design recommendations to alleviate problems associated with the movement of hand trucks.

These studies do recommend manual handling guidelines and ergonomic improvements yet none have considered the merits of improving technique and posture by means of activity recognition and real-time feedback. Considering that lower back pain has associated costs in excess of 80 billion dollars per annum in the USA (Pope, 2002) and that expenses related to musculoskeletal disorders in the EU have been estimated to be between 0.2% and 5% of GDP (Buckle & Devereux, 2002), this is an area where technical intervention could be used to improve workplace health and safety and reduce health expenditure.

At present these statistics are of concern to workers in the non-virtual workplace, however, taking market forecasts into account regarding 'digital twin' development models in the manufacturing sector, they may soon be an issue that employers will have to contend with in the virtual world (Digital Twin Market Size, 2022). Having discussed biomechanical loading, the following section will discuss the area of adaptive haptics and how it can be used to assist human ergonomics and skill acquisition in both the physical and virtual world.

6.2.2 Haptics

This study focuses on the use of haptics as a potential method of providing participants with postural feedback. The following paragraphs will examine the use of haptics under the headings of haptic feedback, haptic guidance, tactile feedback and kinaesthetic feedback.

Studies relating to human posture have integrated concurrent extrinsic feedback through various modalities to improve sensory-motor performance. One such modality is haptic or vibrotactile feedback. The following examples show how it has been used to improve posture, physical performance and skill acquisition.

Zheng & Morrell (2012) used tactile haptic feedback to notify users of poor sitting posture. An ergonomic office chair was modified with seven force-sensitive resistors for posture detection and six vibrotactile actuators for haptic feedback. When the chair detected that a subject was not sitting in the desired posture, one or more tactors vibrate, directing the subject towards or away from a certain position. The feedback improved user posture and also led to postural improvement when the haptic feedback was disabled without the subject's knowledge.

In addition to postural improvement, haptic guidance has also been used to improve physical performance in sport and recreation. Spelmezan et al. (2009) used haptic technology along with a variety of pressure and inertial sensors to improve student-instructor communication during snowboarding lessons. Instructors were able to remotely monitor their student’s postures and when necessary guide students to an improved stance using tactile cues.

Haptics have also been utilised to assist with virtual training in an artistic context. Van Der Linden et al.’s Good Vibrations (2009) and MusicJacket (2010) studies combine vibrotactile feedback and motion capture to assist novice students learn the violin. Their system features an Animazoo motion tracking system which captures player posture and bow position while a separate vibrotactile system provides user feedback relative to their bow movement. Their primary study, Good Vibrations, explored a variety of metaphors to effectively relay haptic feedback relating to the quality of the user’s bow trajectory. These metaphors are based on real world practice, for example some music teachers hold a kitchen roll insert and ask the student to play the violin bow without the bow hitting the edge of the cardboard insert. This method is replicated using haptics which are triggered if and when the user’s bow collides with an invisible virtual tube. Tactile haptics have also been used to aid more advanced music students. An application called Mobile Music Touch by Huang et al. (2010) demonstrates how wireless haptic controllers inside fingerless gloves can help teach users to play piano melodies even while they are performing other tasks away from the piano.

These findings suggest that vibrotactile feedback can be an effective means of communicating musculoskeletal commands to the human sensory-motor system, especially in the area of motor training. These results were of interest, however all the above studies had been applied in the physical world as opposed to the virtual. The following paragraphs explore to what extent haptics have been employed within virtual worlds specifically in relation to embodied interaction.

Strasnick et al. (2018) developed ‘Haptic Links’: electro-mechanically actuated physical connections that can generate varying levels of tension between two VR handheld controllers. The connections between the handheld controls have the ability to adjust the perceived force(s) between the user’s hands and in doing so enable kinaesthetic feedback within several pre-designed virtual scenarios.

Actuating technologies have also been used to generate a greater sense of immersion by rendering real world surfaces on a user’s finger tips relative to the virtual object which is being touched. Whitmore et al. (2018) developed ‘Haptic Revolver’ a handheld virtual reality controller that renders fingertip haptics during virtual interaction. Haptic Revolver consists of a motorised wheel that rotates beneath the user's finger to render a variety of virtual surfaces. As the user's finger moves over a virtual surface, the device rotates under the fingertip generating dynamic tactile sensations.

Glove-worn exoskeletons are another form of hardware used to facilitate haptic rendering. Products such as FinGAR (Yem et al., 2016) and Dexmo (Gu et al., 2016) utilise haptic feedback to render contact and pressure as a user grasps a virtual object.

The various technologies used to facilitate haptic rendering have demonstrated their effectiveness in adding tangible aspects to a virtual experience. However the system designs used in all of the examples were limited to hand based/digital sensations which offer limited resistance. In order to study the linkages between exertion and real-time feedback in a virtual environment it was vital that participants were provided with an interface robust enough to withstand full body exertion. The lack of suitable hardware necessitated a fresh design approach to create a suitable tangible user interface. Dynamic resistance was generated on a wheeled object using brake friction (described in detail in Chapter Three).

Alternative forms of feedback were explored with a view to providing participants with real-time postural guidance. The following paragraphs explore to what extent visual feedback has been employed within real and virtual environments specifically in relation to embodied interaction.

6.2.3 Visual Feedback

Augmented or extrinsic feedback is defined by Schmidt et al. (1991) as information that cannot be elaborated without an external source such as a trainer or display mechanism. Inversely, intrinsic feedback is the proprioceptive sensation felt by a performer as they engage in physical movement. While the dynamic resistance and passive haptics within the CartRight system design does generate intrinsic feedback this study is more concerned with the application of extrinsic feedback and how it can be used to improve user posture. The following section discusses related work involving the use of visual feedback in both real and virtual environments.

Augmented feedback has previously been used to examine the influence of real-time postural feedback to participants involved in manual tasks in a real environment. Vignais et al. (2013) used a see-through head mounted display to notify participants about their posture. The environments used in CartRight and Vignais study are technically mixed reality however the latter study does not feature an adaptive task and this is a gap that CartRight addresses. However, Vignais' research demonstrates how real-time ergonomic feedback can significantly decrease the risk of musculoskeletal disorders and optimise worker performance.

Two exertion based studies involving embodied interaction within virtual environments were of interest. Hoang et al's. Onebody provided users with remote posture guidance during physical training, and showed support for immersive real-time posture feedback (Hoang, 2016).

Postural guidance is provided by showing the instructor's skeletal posture. The instructor's avatar is rendered in place of their own body, providing the user with a first person perspective of the movement instruction. Comparable studies demonstrate that user posture matching accuracy was greater using OneBody than with pre-recorded video or third person VR. The authors in this study do not consider adaptive forces and although real-time feedback is visible to the user it is reliant on their instructor being present i.e.. no study is conducted to see whether the improvement or skill acquisition has been memorised by the participant.

Michalski et al. (2019) utilised augmented visual feedback within a VR game ('Getting Your Game On') to investigate whether such a medium would be viable for improving skill acquisition among table tennis players. Findings from their study demonstrated that real-world table tennis performance significantly improved after VR training compared to no training. Their results also showed that concurrent feedback improved and accelerated learning technical playing styles but also outlined how improvements in motor tasks could be retained when augmented visuals were removed. These findings align with the work of Ruffaldi et al. (2011) who maintains how real-time feedback is a "fundamental feature for developing the training scenario and it is the natural choice in the context of Virtual Environment technologies".

There are definite similarities between CartRight and 'Getting Your Game On', such as the way skill acquisition is applied within an extended reality. The system designs in both studies generate haptic and passive feedback; whereas Michalski et al.'s system implements tactile haptics, CartRight generates resistance using kinaesthetic feedback.

6.2.4 Activity Recognition

Having discussed interventions used to improve posture while engaged in physical activities, the following paragraphs discuss the areas of optical motion cameras, motion capture suits, inertial measurement units and how changes in these technologies are influencing exertion based research.

Optical motion capture systems such as Vicon use multiple infrared cameras, which are used to track the movement of body-worn retro-reflective markers in order to recreate the movement pattern in a real-time 3D application. Disadvantages associated with this type of motion capture are the time required to calibrate the cameras, the necessity to conduct user tests in a pre-calibrated lab and the hardware expense linked with the camera equipment.

A more mobile and affordable option for motion capture which does not restrict research to specific locations is a Mocap suit. These are wearable suits which have multiple sensors located at specific joint locations and have the capability to transmit real-time postural data wirelessly. Pasch et al. used a Gypsy 6 motion capture suit (Gypsy, 2022) to assist them with user analysis during exergame play (Pasch, 2008). Although this study did involve exertion and posture it was focused towards identifying various playing strategies rather than improving technique or posture.

IMUs (Inertial Measurement Units), such as accelerometers or gyroscopes have facilitated a less constrained and lighter affordable means of activity recognition. Smaller, portable and more affordable IMUs require little or no calibration, have low power requirements, and enable untethered activity tracking over prolonged periods. Khan et al. (2010) was able to use a single accelerometer to recognise multiple states and activities in user's daily lives over a four week period with an average accuracy of 97.9%. In an effort to establish the reliability of IMUs, Wong & Wong (2008) simultaneously recorded human activity data from a Vicon system and a sensor based posture monitoring system. Users participated in a series of daily tasks and posture data was found to be highly correlated and reasonably close in magnitude to those of the motion analysis system. Similarly, Gleadhill et al. (2016) demonstrated how IMUs monitor movement patterns more accurately than visual observation by experts and with as much confidence as camera based motion capture for timing measures in resistance exercise.

Bulling et al. (2014) suggests that the pervasive use of IMU's has been influenced by a necessity to recognise activities in unconstrained daily life settings. Examples of inertial measurement unit usage can be seen in sports: accelerometers worn by professional and amateur athletes and the ubiquity of the fitbit. In addition to being as reliable and affordable as more expensive mocap systems, IMU's have facilitated a shift in focus within the domain of exertion based research from a quantity to quality based approach. The following paragraphs will discuss this aspect in more detail looking at how IMU's have been applied in physical rehabilitation and physical exercise.

In their research paper ' Project Star Catcher', Elor et al. (2018) used a combination of low cost motion capture and immersive gameplay to assist with upper limb rehabilitation. IMU's within the HTC Vive hand controllers (HTC, 2022) capture motion tracking data to assist with offline analysis. The findings demonstrate how virtual reality can be used to increase patient motivation during physiotherapy sessions and generate higher adherence rates compared to traditional forms of therapy. What differentiates Project Star Catcher from CartRight, is its focus on upper limb movement rather than body posture and the lack of dynamic resistance in its system design. Nonetheless, the fact that the authors could leverage inertial measurement unit data from the Vive's hand controller was impressive as this would be the same form of motion capture CartRight would utilise. Having discussed qualitative recognition in the rehabilitative sector, the following paragraphs will focus on the use of activity recognition applied to exertion based activities.

The Virtual Reality Institute of Health and Exercise (VRIHE, 2018) is a commercial laboratory situated within San Francisco State University's Kinesiology department whose mission statement is 'to assess the potential energy expenditure of different VR and AR experiences'. The institute generates revenue by grading commercial VR exergames with an average calorific expenditure, which are calculated by measuring participant oxygen consumption during game play. In addition to its commercial activities, the institute supports research that investigates the exercise intensity of active virtual reality games (Ortiz-Delatorre ET AL., 2020).

Studies such as those conducted by the institute measure physical outcomes such as performance increases but do not analyse the quality of the activity or its proprioceptive benefits.

The work of Eduardo Velosso examines ‘qualitative activity recognition’ during physical activity, where the focus is not on the quality of the experience but on the quality of the physiological interaction. Velosso maintains that conventional activity recognition is concerned with recognising which activity is performed, while qualitative activity recognition is concerned with assessing how well the activity is performed. Velloso et al. developed a system called MotionMa which could automatically extract a model of movements demonstrated by a trainer and use this model to assess the performance of trainees (Velloso et al., 2013).

In a separate collaborative publication Velloso et al. (2013) demonstrated how sensors can be used to determine how well a weightlifter executes a unilateral dumbbell biceps curl by measuring and recording skeletal pose rather than the number of repetitions completed. In addition to grading the quality of physical actions the system was able to provide feedback to the user on how to improve their movements. Velosso’s studies benefit those interested in bodybuilding and strength and conditioning; however, the feedback on task quality only applies to real world exercise.

Given the growth in virtual fitness (Heater; 2021; Reed, 2021; Sutrich, 2021) it makes sense that real-time feedback is provided to participants who engage in exertion based activities within virtual environments. Engaging in physical activity with real-time feedback in VR has the potential to increase exercise efficiency, reduce injury and provide a means to measure the acquisition of skill and strength. At present there are applications which provide postural feedback while performing physical tasks in Virtual Environment’s but they lack any form of dynamic resistance. Similarly there are products for posture and rehabilitation which use adaptive forces but are only applicable to real environments. To date no commercial or academic entity has utilised available technology with a view to improving postural wellness through the medium of resistance based virtual exercise. CartRight addresses this gap through the virtual simulation of an embodied physical task using robust force feedback.

6.3 HYPOTHESES

Resistance and immersion have previously been implemented as game mechanics in Chapters Four and Five where they have proven to be effective in motivating physical output. This study expands on these intervention techniques and explores whether a VR system can be used to convey how well a user is optimising their body movement during an immersive exergame.

Although this research is primarily exploratory, hypotheses are made that:

(H1) Pushing hindered by dynamic haptic interventions will increase the likelihood of incorrect or poor posture. This hypothesis is based on the work of Glitsch et al. (2007) who made a connection between varying cabin aisle inclination and cabin crew posture issues when moving refreshment trolleys in flight.

(H2) Concurrent visual feedback will lead to an improvement in posture. This hypothesis is being made on the basis of prior research by Vignais et al. (2013) in which augmented visual feedback was successfully used to reduce ‘hazardous posture’ during manual tasks.

(H3) Improved posture will remain after the feedback is removed. This hypothesis is based on the work of Michalski et al. (2019) which demonstrated how skill acquisition was maintained following a period of training in a virtual environment.

(H4) Pushing hindered by dynamic haptic interventions will increase perceived exertion and decrease perceived performance. This hypothesis is also based on the work of Glitsch et al. (2007).

6.4 METHOD (STUDY 01)

6.4.1 Participants

18 volunteers (nine females, average age: 31.7± nine years, weight: 70±11.4 kg, height: 1.73± 0.08 m and BMI: 23.3±2 kg/m2) undertook both this and the second study. The study aimed to include individuals with diverse characteristics in terms of gender, age, height, weight, and health conditions (Lara & Labrador, 2012). Seven participants did not have any prior VR experience, other than viewing 360° video with devices like the Google Cardboard, four participants were industry based VR developers. Two participants were having or had previously had physiotherapy for back related injury issues. A confirmation procedure ensured that participants had no underlying back or postural issues and that they had pushed a shopping cart with groceries at least once a month over the previous twelve months.

6.4.2 Design

A within-subjects repeated measures design was used so that each participant encountered all of the conditions. The sequence of conditions was counterbalanced using a latin square ordering permutation to mitigate learning effects.

6.4.3 Materials

6.4.3.1 Design Study 01: Adaptive Haptic Effects

A wheelchair was fitted with a HTC Vive hand controller (Figure 6.1 J), which enables real-time tracking in a pre-calibrated space. The motion controller’s virtual counterpart is attached to a 3D shopping cart model within the Unreal game engine (2015).
To match the physical affordances of the virtual cart, a horizontal pole was attached to the wheelchair’s handgrips. The user could move the physical avatar and simultaneously move the virtual shopping cart, creating a tightly coupled tangible platform.

To allow the cart controller to be as mobile as its virtual equivalent some alterations were made to the regular hardware setup so as to provide the user with an untethered immersive experience. DC power on the Vive HMD (Figure 6.1 B) was substituted with a 12V 15000 mAh Lithium Ion Battery and the initial system desktop was replaced with an Alienware Laptop (Figure 6.1 C) mounted on the wheelchair. This created a portable hardware setup that was fully integrated within the motion control platform. The development of this interface can be read in detail in Chapter Three.

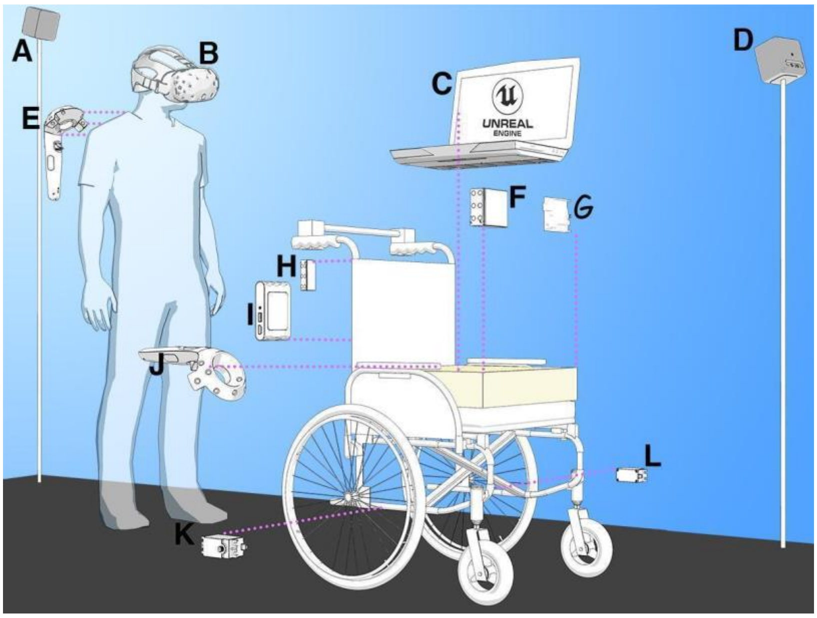

Figure 6.1 Motion platform system design. (A) Vive tracking station 1, (B) Head-Mounted Display, (C) Laptop running Unreal Game Engine, (D) Vive tracking station 2, (E) Vive controller 1, (F) 12V servo battery, (G) Arduino, (H) 12V link box battery, (I) Vive link box, (J) Vive controller 2, (K)(L) Battery powered high torque servos.

Literature on ergonomics and human biomechanics was researched to identify an optimum back angle (Pope, 2002; Buckle & Devereux, 2002; Dael, 2016; Jung, 2005; Okunribido & Haslegrave, 2003). In order to prevent injury, it is recommended that a straight back is maintained while pushing heavy objects, regardless of the object's weight. So, in the presence of adaptive resistance, ideally correct upper body posture would be maintained while the changing load is compensated for by musculoskeletal exertion.

While it is possible to keep a neutral upper trunk pitch rotation, in reality maintaining a precise posture under load is impractical due to the non-rigid nature of human biomechanics. To ascertain the amount of curvature or 'Optimum Range of Sagittal Plane Flexion' (Figure 6.2) that would be permissible before posture was deemed to be incorrect, I consulted relevant literature regarding musculoskeletal responses to pushing loads (Glitsch et al., 2007; Hoozemans et al., 1998). The literature does not identify a single threshold, and many contextual factors are at play depending on the specific circumstances of task, apparatus and environment. I consulted with five ergonomics domain experts who confirmed that no general parameters exist and suggested running an adjustment procedure to identify apparatus threshold.

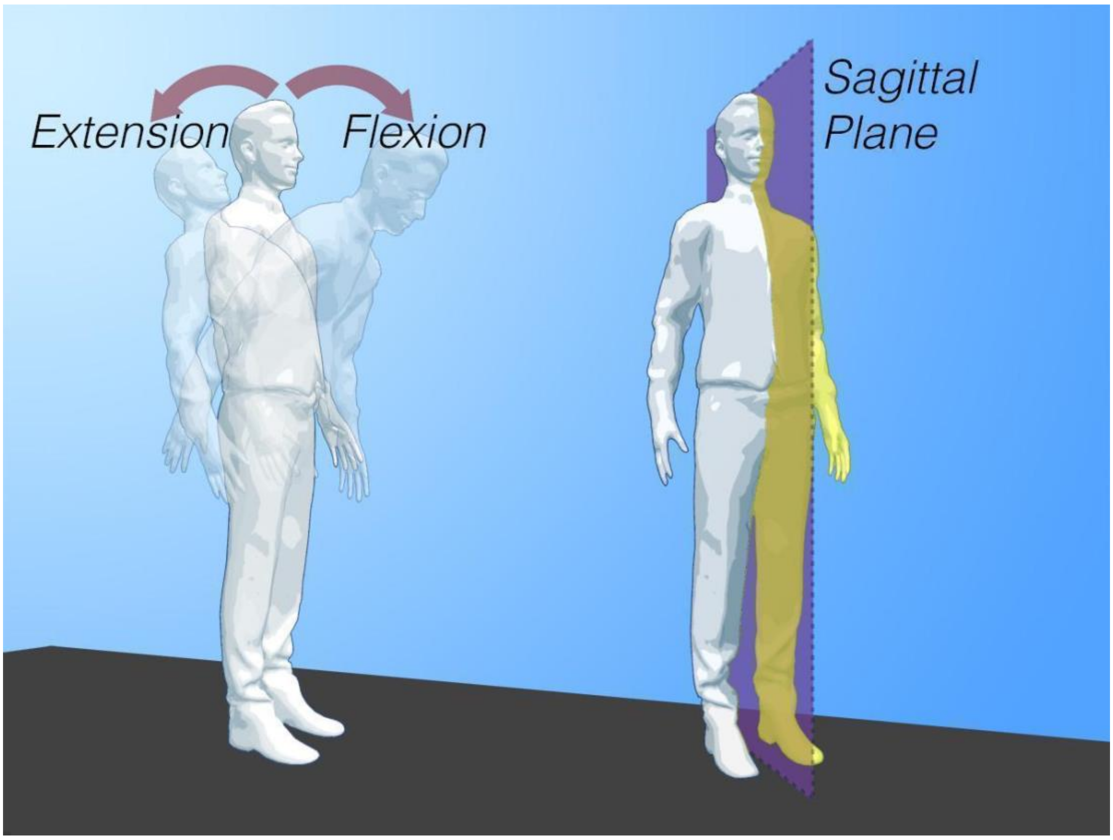

Figure 6.2 Sagittal Plane: Flexion and Extension.

The adjustment procedure asked eight participants to maintain as straight an upper trunk as possible while simultaneously leaning their body weight forwards or backwards to push and pull the wheelchair. Postural data was examined while observing musculoskeletal changes, and the point at which participants would significantly shift their posture into an exertion strategy based on spinal loading was calculated to be nine degrees of flexion.

Once the tangible user interface was developed and tested there was a noticeable physical sensation felt each time the cart collided with the various shopping boxes in the virtual shopping aisle. Unintentionally, haptic rendering had become part of the system design. Seeing as the system now featured dynamic resistance, passive haptics and haptic rendering, a decision was made not to use additional haptics as it may have led to a cognitive overload. Prior research had demonstrated the merits of using visual feedback to provide postural guidance (Vignais et al., 2013), however a particular design challenge lay in correctly displaying concurrent physiological data in a VR context. This seems to be an ongoing debate within the VR community and one in which there is no industry wide best practice. A known phenomenon in VR design is the nausea generated when standard 2D heads-up display data is composited as a static layer in a 3D environment (Ohyama et al., 2007). Oculus discourages the use of traditional HUDs, and instead encourages developers to embed information within the environment (Yao et al., 2014). Taking this advice into account the augmented visual feedback was attached to the virtual trolley as a 3D widget.

Early prototypes displayed real-time information relating to the angle of the user's head within a virtual display widget (Figure 6.3). However, early testing demonstrated that the effect of the HMD weight when glancing at the widget or other complex visualisations excessively impacted the user posture data, and continuous head and upper trunk pitch data led to cognitive overload and lack of attention to the physical task. It was decided to simplify the feedback widget significantly in size and style, settling on a binary visualisation of good or poor posture of the spine.

Figure 6.3 heads-up display prototype featuring feedback relative to HMD pitch.

The Vive’s real-time positional tracking data made it possible to bring posture data into the game engine for recording and analysis. A Vive controller (Figure 6.4 B) was attached onto a wearable harness (Figure 6.5 C) and an adjustable Velcro patch allowed the controller to be calibrated so the tip of the accelerometer was always level with the user’s C7 (7th Cervical Vertebra) (Figure 6.5 A). Postural data was recorded using a 3rd party software application ‘Brekel OpenVR Recorder’ (2018). This application recorded the positional and rotational information of the upper body posture at 60 frames per second. Tracked data was recorded in .fbx and .txt formats, which facilitated post-test analysis in 3D Studio Max, SPSS and Excel. Brekel also provided audio recordings of the user tests, which were used for qualitative feedback. This spinal location was chosen as a reference point for prior upper trunk posture studies (Wong & Wong, 2008). Postural quality was calculated per user per task by annotating posture data with correct or incorrect posture threshold as determined by the spine sensor.

To moderate any issue of fatigue, a two minute break was taken between each task and during this time users were asked to complete a Borg Scale document (1962) as well as a Nasa Task Load Index questionnaire (Hart & Staveland, 1988). Both questionnaires are standardised assessment tools to establish and quantify rates of perceived exertion and perceived workload respectively from the user's perspective.

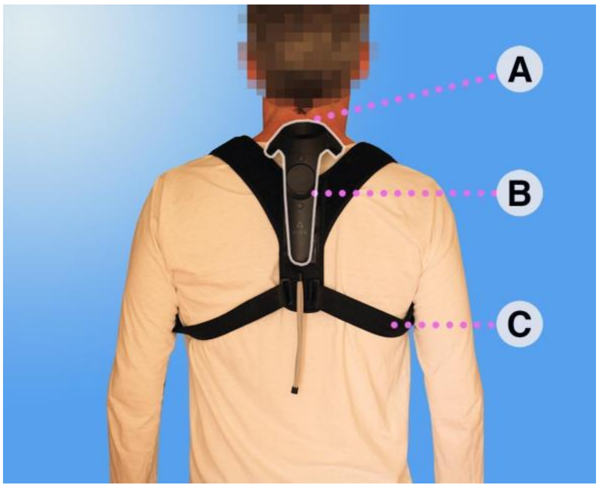

Figure 6.4 A. C7 Vertebra. B. Vive controller. C. Harness.

6.4.4 Procedure

At the start of each task the pitch of the harness worn controller was calibrated so that the pitch reading from the controller would be relative to the amount of extension or flexion in the participant's sagittal plane. The participant stood still with their back against a stadiometer in an upright position for the first two seconds of the measurement as an initial reference period in order to initialise the inclination angle and offset the reading of the sensors. Unreal engine allowed for this real-time pitch data to be brought into the game engine via the Steam VR application. While a virtual 'chaperone' was visible in the virtual environment to prevent participants walking into any real world surfaces, a physical start and end point was also marked on the floor space to keep the distance of each user task consistent.

For this study participants were asked to push the virtual cart the length of the virtual shopping aisle three times. For each iteration, a different level of resistance was applied, based on how full their shopping cart was.

A. Minimum resistance (pushing an empty cart the length of the virtual aisle with the brake friction turned off).

B. Maximum resistance (pushing a full cart the length of the virtual aisle with the brake friction at its maximum).

C. Adaptive resistance (different resistances are triggered when the virtual trolley collides with virtual boxes within the virtual aisle). Collecting one box of virtual groceries generated 40% of the maximum brake power, two boxes 65% and three boxes 100%.

Orientation readings taken from the starting position accelerometer from tasks A and B were used to establish a min/max baseline for each participant which could be used as a reference relative to the level of resistance during the adaptive task (task C). The nine degree optimal sagittal plane flexion outlined in the design was used as a reference for this analysis.

The experiment lasted around five minutes for each participant to complete all three counterbalanced conditions, not including any resting and questionnaire breaks.

6.4.5 Analysis

The independent variable was the Resistance Level (conditions Minimum, Maximum or Adaptive), and the dependent variable was Posture, measured by posture angle data sampled at 60fps over three trials per participant. Volume of data depended on time to complete each trial, but the overall mean was 577 posture data points per trial per person (31,148 data points in total). NASA TLX measures were recorded to compare the impact of resistance against performance, effort and physical demand.

6.4.6 Results

The results show that there was a significant effect of resistance level, $F(2, 34) = 7.1$, $p < 0.01$. Post hoc tests using Bonferroni correction revealed significant differences ($p<.01$) between minimum resistance ($M = 76.95$ $SE = 6.49$) and maximum resistance ($M = 47.82$ $SE = 6.91$) and between adaptive resistance ($M = 64.85$ $SE = 7.02$) and maximum resistance ($M = 47.82$ $SE = 6.91$), but no significant difference between minimum and adaptive resistance, ($p>0.05$).

NASA TLX measures showed an effect in the Mental subscale ($F(2,34)=7.7$, $p<0.01$). Post hoc tests using Bonferroni correction revealed significant differences ($p<0.05$) between the Mental subscale during the Minimum ($M = 1.833$ $SE = .2177$) and Adaptive ($M = 5.05$ $SE = 1.115$) conditions, but no significant difference between Minimum and Maximum ($p>0.05$) or between Adaptive and Maximum ($p>0.05$).

NASA TLX measures showed an effect in the Physical subscale ($F(2,34)=20.41$, $p<0.01$). Post hoc tests using Bonferroni correction revealed significant differences ($p<0.01$) between the Physical subscale during the Minimum ($M = 2.055$ $SE = .2967$) and Adaptive conditions ($M = 7.667$ $SE = 1.0322$), Minimum ($M = 2.055$ $SE = .2967$) and Maximum conditions ($M = 6.0556$ $SE = .9717$) but no significant differences between Adaptive and Maximum conditions, ($p>0.05$).

NASA TLX measures showed an effect in the Temporal subscale ($F(2,34)=5.95732$, $p<0.01$).

Post hoc tests using Bonferroni correction revealed no significant differences between the Temporal subscale in any of the conditions, ($p>0.05$).

NASA TLX measures showed an effect in the Performance subscale ($F(2,34)=5.7$, $p<0.01$). Post hoc tests using Bonferroni correction revealed significant differences between the Performance subscale during the Minimum (M = 2.111 SE = .278) and Adaptive conditions (M = 3.72 SE = 0.68), but no significant difference between Minimum and Maximum ($p>0.05$) or between Adaptive and Maximum ($p>0.05$).

NASA TLX measures showed an effect in the Effort subscale ($F(2,34)=10.2$, $p<0.001$). Post hoc tests using Bonferroni correction revealed significant differences ($p<0.01$) between the Effort subscale during the Minimum (M = 1.94 SE = .248) and Adaptive conditions (M = 6.055 SE = 1.058), but no significant differences between Minimum and Maximum or between Adaptive and Maximum conditions, ($p>0.05$).

NASA TLX measures showed an effect in the Frustration subscale ($F(2,34)=4.3$, $p<0.05$). Post hoc tests using Bonferroni correction revealed no significant differences between the Temporal subscale in any of the conditions, ($p>0.05$).

The Borg Scale also showed an effect of resistance level on perceived exertion ($F(2,34)=13.7$, $p<0.001$). Post hoc tests using Bonferroni correction revealed significant differences on RPE between Minimum (M = 6.94 SE = .205) and Adaptive conditions (M = 9.83 SE = .617), ($p<0.01$), between Minimum (M = 6.94 SE = .205) and Maximum conditions (M = 9.111 SE = .587), ($p<0.05$) but no significant differences between Adaptive and Maximum, ($p>0.05$).

6.5 DISCUSSION (STUDY 01)

In this study resistance directly influenced posture negatively, with greater resistance leading to poorer posture. Perhaps unsurprisingly, there was a significant difference in posture between Minimum and Maximum conditions, with posture significantly worse when there was an increased resistance. TLX and RPE (Rate of Perceived Exertion) data also demonstrated that participants felt it required more effort and was physically harder to push the cart. This provides evidence for the first hypothesis H1, as increased resistance also increased poor posture.

Differences in perceived exertion and perceived performance were found between Minimum and Adaptive conditions. Participants' perceived exertion in both RPE and NASA TLX Physical, Nasa TLX Effort and Nasa TLX Mental Demand increased, and NASA TLX Performance decreased in the Adaptive condition relative to the Minimum resistance condition. This provides evidence for the fourth hypothesis H4, suggesting that adaptive haptics provides an increased challenge for user posture.

Finally, a significant difference was found between Adaptive and Maximum conditions. This result is somewhat surprising and requires careful attention. Participants actually performed with worse posture in the Maximum condition than in the Adaptive condition. This implies that high resistance was more problematic than variable resistance, in terms of its effect on user posture, although no significant differences were found in the corresponding workload or perceived exertion data. When compared to high levels of resistance, unpredictable haptic effects are perhaps not as strenuous as had been expected. This issue will be elaborated on in the final study discussion. Given the clear effects of haptics on posture, the second study explored the use of visual feedback in correcting poor posture.

6.6 METHOD (STUDY 02)

The second study investigates hypotheses two and three, that concurrent visual feedback will lead to an improvement in posture and that user posture will remain corrected after the feedback is removed.

6.6.1 Participants

Participants were the same as those who had participated in the first study, however this study was conducted on a separate day.

6.6.2 Design

A within-subjects repeated measures design was used so that each participant encountered all of the conditions. The sequence of conditions was counterbalanced using a latin square ordering permutation to mitigate learning effects.

6.6.3 Materials

6.6.3.1 Design: Real-Time Feedback

The same hardware apparatus was used as the first study, but some changes were made to the software and task. In the first and fifth tasks no visual feedback was presented. However in the second, third and fourth tasks the participants received concurrent augmented visual feedback based on the curvature of their upper trunk. In these middle tasks, sagittal plane data was used to alter the VR heads-up display visual widget (Figure 6.5A & Figure 6.5B) based on whether the posture was deemed to be correct or incorrect.

Figure 6.5 Visual Feedback Relative To Correct Or Incorrect Posture.

User posture was recorded using a third party application Brekel OpenVR Recorder which output the Vive controller and HMD coordinate data as both a 60fps animated .fbx model and a 60fps text file. This data facilitated the recording and post analysis of user posture data for each of the five tasks. It also meant that postural data from the first and fifth tasks could be compared to understand if postural feedback in the second, third and fourth tasks had been effective in improving user posture. RPE and NASA TLX scales were also recorded per user per task.

6.6.4 Procedure

Participants were required to complete five adaptive haptic tasks whereby dynamic resistance was relative to the number of virtual boxes collected. As with the previous study, collecting one box of virtual groceries generated 40% (Minimum) of the maximum brake power, two boxes 65% (Medium) and three boxes 100% (Maximum). Posture quality between the 1st and 5th task was compared to see whether heads-up display posture feedback from iterations 2-4 facilitated an improvement in user posture. The pre-test-post-test study design measured whether concurrent visual feedback could be used as a training tool to improve user posture during a task involving adaptive resistance. Posture performance was measured in the fifth task without the feedback to determine whether any short-term posture learning had taken place.

6.6.5 Analysis

The independent variables were the Resistance Level (conditions were Zero, Minimum, Medium, Maximum) and Feedback Intervention (conditions were Pre- and Post-Intervention), and the dependent variable was Posture measured by posture angle data sampled at 60 frames per second over five trials per participant. Within-subjects repeated measures design was used and each participant encountered all conditions. Counterbalancing was not implemented in this study, as it was designed to facilitate postural improvement through learning. Volume of data depended on time to complete each trial.

6.7 RESULTS (STUDY 02)

The data were tested with a repeated measures ANOVA, and where there were significant differences identified, contributing condition pairings were used. Where the ANOVAs were significant at $p<0.05$, post-hoc analyses were carried out using three paired sample, two tailed t-tests using Bonferroni corrected alpha values ($\alpha = .05$).

The results show that there was a significant effect of Resistance Level on Posture $F(3,51)=20.49$, $p<.01$, during the pre-feedback conditions. Post hoc tests using Bonferroni correction revealed significant differences ($p<.01$) between zero resistance (M = 5.874 SE = 1.83) and maximum resistance (M = 22.56 SE = 3.64), between minimum resistance (M = 6.36 SE = 1.37) and maximum resistance (M = 22.56 SE = 3.64), and between adaptive resistance (M = 5.33 SE = 1.17) and maximum resistance (M = 22.56 SE = 3.64) but no significant differences ($p>0.05$) between zero and minimum resistance, between zero and adaptive resistance or between minimum and adaptive.

There was a significant main effect of Resistance Level on Posture F(3,51)=6.38, p<0.001, during the post-feedback conditions. Post hoc tests using Bonferroni correction revealed significant differences (p<.01), between zero resistance (M = 1.59 SE = 0.73) and maximum resistance (M = 13.5 SE = 3.96), but no significant differences between zero and minimum resistance, between zero and adaptive resistance, between minimum and adaptive resistance, between minimum and maximum or between adaptive and maximum resistance.

Cross referencing pre and post feedback data relative to the incremental resistance changes showed an interaction effect between Resistance Level and Feedback (F(3,51)=5.5, p<0.01). Post hoc tests using Bonferroni correction revealed significant differences (p<.05), between zero resistance (pre-feedback) (M = 5.87 SE = 1.83) and zero resistance (post-feedback) (M = 1.59 SE = .73), and between maximum resistance (pre-feedback) (M = 22.56 SE = 3.64) and maximum resistance (post-feedback) (M = 13.5 SE = 3.96).

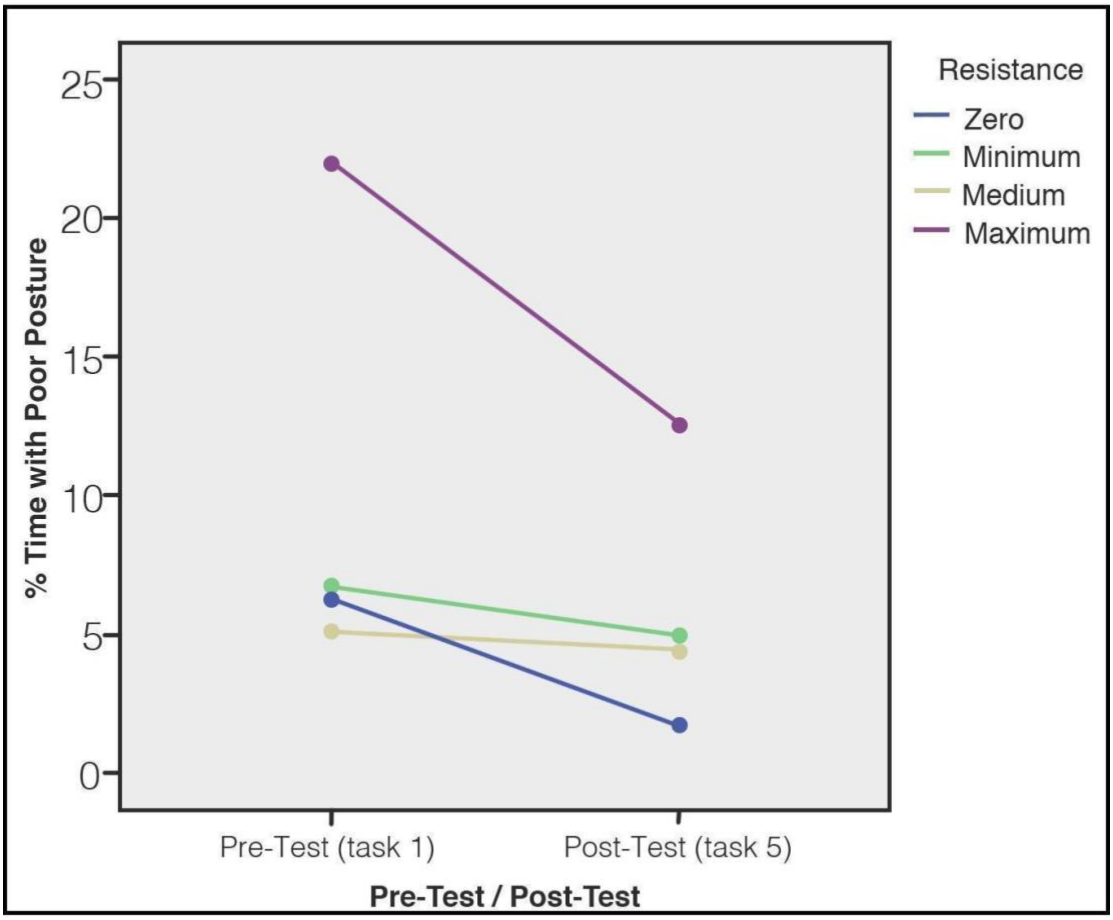

Figure 6.6: Real-Time Feedback Results.

6.8 DISCUSSION (STUDY 02)

It was found that Feedback Intervention directly influenced posture positively (Figure 6.6) with post-tests (task 5) significantly improving in posture over pre-tests (task 1), despite the withdrawal of visual posture feedback in task 5. This provides evidence for hypotheses H2 and H3. The improved posture in the presence of feedback shows the value of the intervention, while the enhanced performance during subsequent task 5 when no feedback was present shows the potential for posture learning.

The resistance level remained important, with a significant effect of increasing resistance level on poor posture. Interestingly, in this second study there was only a significant difference between lower levels and the Maximum resistance condition, with intermediate stages lacking significant differences. The reduced effect of intermediate resistance levels may relate to the interaction effect between Intervention and Feedback. In the first study, increasing resistance showed significant differences in posture at all levels. In this study, participants received real-time feedback, so increases in resistance levels had a lesser impact on posture in comparison with the first study.

6.9 DISCUSSION

This concluding study has addressed two pertinent issues:

> The clear design of user awareness relating to in-game adaptive feedback.

> The measurement of physical compensation during an exertion based immersive task.

Results for study one show that increasing resistance increases poor posture, and that the main factor is the level of resistance. Study one also shows that the dynamic variation of resistance, though more challenging for posture than without haptics, does not show dominant problems over the overall intensity of the force itself. This may be good news for those designing adaptive haptic systems, as it may imply that the overall level of resistance is a greater challenge for posture than responding to its dynamic variability. User posture may be better at coping with variable haptics than with sustained high levels of force feedback.

Given this overall challenge, I decided to introduce real-time feedback with a simple indicator for good/poor spinal posture. The second study showed that visual feedback led to a significant improvement in user posture, during and beyond the presence of the visual indicator. While long-term studies would be required to identify the degree of training retention, these initial results demonstrate that this strategy should prove beneficial.

Two of the participants had previously suffered from back injuries. They were acutely aware of their posture, believing it to be generally poor, and did not seem confident about their performance in the studies. However, while not strong outliers, these participants showed among the best levels of performance in study one and the least improvement in study two across the participants.

This would suggest that active attention to posture can further enhance performance, but also that the gains will become more marginal at some increased level of focus. While this evidence is anecdotal at this stage, it is a potential direction that should be explored in future work.

6.9.1 Limitations

The placement of the inertial measurement unit on the user's C7 accurately measured the level sagittal plane flexion, however, it did not measure any amount of trunk curvature. Measuring curvature or bend during the various tasks would have required a second inertial measurement unit placed further down the user's spine.

The second study design implemented no control condition. This should have been considered to prevent learning effects from distorting data. These are limitations in the current system, and ones that need to be considered for future studies. Nonetheless, this was an exploratory study (Klahr & Simon, 1999) that demonstrated how postural improvements could be made during immersive exertion based activities.

6.10 Conclusions

The fact that all three hypotheses were confirmed in this investigation highlights the importance of incorporating postural feedback within haptic VR design. These findings collectively show that iterative feedback can support good postural behaviour patterns while experiencing adaptive haptics. Although a specific haptic task has been chosen, this work could be extended to a range of disciplines covering sport, physiotherapy and physical health, in which VR is increasingly used to improve technique, promote fitness and alleviate pain.

Postural feedback such as this could also prove to be very practical in the near future by preventing injury within hazardous XR manufacturing environments. Industry research has predicted that the use of XR technologies, digital twins and blended reality within industry will see significant growth in the coming decade (Dalton, J., & Gillham, 2009). If changes like this do come into play, there is nothing to prevent poor posture transferring from the physical workplace into its virtual counterpart. In order to prevent this happening it is important that postural feedback and physical task quality are prioritised when designing blended reality systems for use in physical tasks. I expect that these findings will be of interest to designers of haptic VR systems as well as the wider HCI community.

Contributions

Results from the first study revealed that resistance directly influenced posture negatively, with greater resistance leading to poorer posture. Results from the second study demonstrated that real-time feedback improved posture, even under significant dynamic musculoskeletal loading both during and after the presence of the augmented feedback.

Limitations

A limiting factor in this study was the length of the supermarket aisle which restricted the virtual shopping activity. The virtual and physical floor surface measured 8m x 4m which was the maximum space that could be tracked using a HTC Vive (2019). Newer headsets featuring ‘inside out’ tracking would not have such limitations and would enable a much longer shopping aisle. A larger virtual supermarket would mean that longer user studies could be conducted.

During the second study, no control condition was implemented to prevent learning effects from distorting data, this should have been considered. A future study in this area should also consider longitudinal research to identify the degree of training retention learnt from the posture learning.

CHAPTER 7: DISCUSSION

7.1 INTRODUCTION

The main research question in this Thesis is ‘How can variable or adaptive resistance be used to create motivating game mechanics?’. I have answered this question by designing and conducting a series of user studies that tested several exertion-based immersive games which feature novel physiological interface design and adaptive resistance (see Chapters 3,4,5 & 6). Each game altered the exertion levels and challenge required by participants of the studies at key moments, providing several scenarios in which to investigate the relationships that exist between task intensity and user output. A secondary research area (which served the first purpose) was to ensure the immersive games used in these studies would provide participants with graphical fidelity on par with commercial exergames.

The following paragraphs summarise the research gaps and technical contributions identified in Chapter 2, the methods used to explore these gaps and the outcomes of the various studies that were conducted.

Carrot or Stick (Chapter 3) was a feasibility study that explored the potential of EMS in a weightlifting exergame. Findings from the study revealed that the kinaesthetic force generated by EMS could be resisted by participants prohibiting its use in studies involving full human force.

The lack of sufficient force generated by EMS influenced a subsequent study which explored the use of brake friction as a method of generating robust kinaesthetic feedback. Feeling Virtual Worlds (Chapter 3) demonstrated that servo-controlled brake friction could be used to replicate dynamic resistance that was capable of withstanding full body force on a mobile mixed reality interface.
The robust kinaesthetic feedback created in Feeling Virtual Worlds was adapted for use in an exergame, which focused on postural improvement. CartRight (Chapter 6) demonstrated that visual and haptic game mechanics could be used to motivate enhanced physical output during an immersive task involving dynamic resistance.

Whereas the CartRight study focused on enhancing task quality, two further studies, Chase or Be Chased (Chapter 4) and Switching It Up (Chapter 5) utilised resistance as a game mechanic to motivate enhanced physical exertion. The purpose of Chase or Be Chased, was to determine whether incentivised or disincentivised game mechanics generated greater physical exertion. The findings revealed that there was no significant difference between incentivised or disincentivised game mechanics. However, automated task intensity could be used to generate enhanced output. This use of dynamic resistance as a game mechanic in Chase or Be Chased enabled the game rather than the user to dictate the task intensity.

Switching It Up also removed user autonomy from task intensity, but did so manually rather than dynamically. There was no main effect of manual resistance on the participants' physical output, however, an immersive condition was conducted, to examine the relationship between HMD VR immersion and physical output. The data analysed in this study revealed that the immersive medium significantly increased physical output, suggesting that virtual fitness applications would benefit from increased visual immersion to enhance both training and performance. A third and final condition was explored in Chapter 5, which investigated the use of data manipulation as a game mechanic to motivate the participants to increase their levels of output. The findings of this study revealed that there was a significant interaction between resistance, immersion and deception which impacted on the participants' perception of time pressure, although, there was no main effect of deception on either true or perceived energy expenditure.

The games in all of my studies used high quality visual content through the use of bespoke game design, commercial game engines, detailed lighting, materials and modelling, and modifying commercial game titles. While the impact of visual fidelity was not a measured component, I feel that the detailed graphics used in each of the studies contributed to the dissociative attributes of the virtual environments. The following paragraphs will expand on the outcomes of these findings in more detail.

7.2 THE POTENTIAL & LIMITATIONS OF ELECTRO MUSCULAR STIMULATION

In Chapter 3, the 'Carrot or Stick' study investigated whether supporting ('Carrot') or impeding ('Stick') muscle actuation was more likely to enhance physical performance while playing an exergame. Electro muscular stimulation technology (EMS) had previously been used for low level force feedback (Tamaki et al., 2011) but at the time of developing Carrot or Stick (2015) it had never been implemented in an exergame. Tens activated electrodes triggered involuntary bicep and tricep contractions which hindered or assisted bicep curls. Although the exergame was functional, there were limitations in the amount of force generated by the EMS. Users could feel the sensation of the impeding and supporting body actuation. This sensation was enough to add a degree of limb support during the study but the level of power generated was not enough to force downward arm movement during the Stick game.

The purpose of the study was to see if EMS was a viable and practical way to implement limb actuation, and also, whether it was capable of generating sufficient force feedback for use in further studies involving resistance. EMS technology made dynamic resistance possible to an extent, however it was not robust enough to create motivating game mechanics. I found it to be a suitable method for generating tactile feedback and limited kinaesthetic feedback but not for replicating full body force feedback in a resistance based exergame. To conduct an exergame such as 'Carrot or Stick', a more robust form of actuating technology would be required such as a robotic exoskeleton.

Tamaki et al. (2011) have previously shown how to actuate participants' fingers, however, the force required to actuate finger muscles is significantly less than that required to actuate a larger limb such as an arm. Lopes et al. (2013) also used EMS to generate forces equal to those generated by a phantom omni (Silva et al., 2009). Furthermore, they used EMS to try to prevent participants from putting their hands through the walls of a virtual environment (Lopes et al., 2017). They found that the 'repulsion feedback' design made it uncomfortable for people to pass their arms and hands through the virtual walls, but they could not fully restrict this action. This is a limitation of EMS, which I also observed and described in Chapter 3 during the development of 'Carrot or Stick' study. I found that EMS could assist with the weightlifting but if a user wanted to prevent EMS from actuating their limbs they could choose to prevent it from doing so (as was also the case in the Stick condition).

Although EMS was not suitable in this scenario, it could be used as a motivational game mechanic in future exergaming studies if it was applied in an alternative way. EMS has been used at a consumer level to integrate pain and discomfort into video game design. PainStation (2019) consists of a specially made case that gives two people the opportunity of playing a specially adapted version of the video game, Pong. During the game, the players place their left hands on the Pain Execution Unit which serves as a sensor and feedback instrument. EMS is used to generate heat impulses and electric shock. The feedback generated is dependent on the playing process and can increase in its intensity. This type of pain avoidance could also be applied in an exergaming scenario. EMS could be used as a motivational game mechanic to enhance output; the idea being that slight pain would be applied if optimum exertion targets were not being reached.

Having discussed the findings, limitations and alternative application of EMS, the following section will discuss the implementation of kinaesthetic feedback using brake friction.

7.3 APPLYING KINAESTHETIC FEEDBACK USING BRAKE FRICTION

While developing interfaces for the exergames in this Thesis, it became apparent that there were far more options for HCI developers to avail of when developing virtual interfaces than there were for customising their physical counterparts. Game engines, modding tools and SDK's provide developers with the resources needed to recreate an immersive experience. However, advances in haptics had failed to keep pace with audio, visual and interactive technologies, causing, what Benko and colleagues refer to as "a lack of meaningful haptics from conveying a sense of force during immersive interactivity" (Benko et al., 2016). A lack of robust adaptive resistance prevented exergames from dictating user intensity and in doing so, created a reliance on user motivation as the primary game mechanic to improve user output.

In order to study the linkages between exertion and adaptive resistance in a virtual environment it was vital that participants were provided with an interface robust enough to withstand full body exertion. To this end, my explorations with EMS technology during the Carrot or Stick exergame have demonstrated that the forces it could generate were limited.

Previous research has shown (e.g. Strasnick et al., 2018 & Whitmore et al., 2018) that this was necessary due to the lack of any commercial alternative. Interfaces such as these were limited to hand based/digital sensations and offered limited resistance. The interfaces that generated a greater amount of kinaesthetic feedback had issues with latency, weight or movement restrictions which prevented them from being used in a fully mobile exergame. The robotics used in Snake Charmer (Araujo et al., 2016) lacked sufficient force. The air propulsion system used in Thors Hammer (Heo et al., 2016) had too much latency for real-time dynamic feedback.

The lack of suitable hardware necessitated a fresh design approach in order to generate kinaesthetic feedback that was capable of withstanding full body force. This was done using brake friction in the Feeling Virtual Worlds study (Chapter 3). The interface generated robust resistance on a mobile untethered mixed reality platform. The system design enabled the user to interact with the virtual environment by pushing a physical interface, which simultaneously controlled a virtual counterpart. Objects were placed in the virtual environment that once collided with by the virtual interface triggered force feedback by incrementally adjusting the level of brake friction on the physical interface. Participants could engage in an immersive environment and simultaneously appreciate the tactile qualities of virtual objects and interactions through a combination of passive haptics and automated resistance.

One of the main contributions of the ‘Feeling Virtual Worlds’ study (Chapter 3) was the way in which servo-controlled brake friction could be used to replicate dynamic resistance capable of withstanding full body force. This is novel as it had yet to be applied on a mobile mixed reality interface. I believe that this knowledge is a valuable contribution to the HCI community as I have shown how brake friction can be replicated relatively easily. It can also be applied to real and virtual environments, and the fact that Arduino support can be implemented directly or via game engine plugin provides flexibility for researchers and designers. Furthermore, as the interface is untethered, it is beneficial for fully mobile and immersive experiences. Systems such as Pull-ups (Ye et al, 2019) and Realwalk (Son et al., 2018) generate high levels of force, but their reliance on air and power mean that they are tethered which can be limiting for certain applications.

Although the use of friction has been applied in CartRight (Chapter 6) to simulate grocery shopping, it could also be applied in different ways to enhance physical exertion. For example, friction could be applied on a bespoke bench press (an exercise in which a weight is raised by extending the arms upward while lying on a bench). Dynamic friction could be applied to a specialised channel where each end of the barbell is located. This would enable the gap to be tightened or loosened; varying the force required to lift the weight. This would provide an interface to further investigate the use of adaptive resistance as a motivating game mechanic.

7.4 ANALYSING THE RELATIONSHIP BETWEEN VARIED RESISTANCE & PHYSICAL OUTPUT

A lack of automated task control within exergame design had meant that user output was reliant on human motivation rather than mechanised intervention. A game mechanic that was explored over the duration of this Thesis allowed for the game, rather than the user, to control the level of task intensity. The aim of separating the these elements was to motivate the participants to increase their physical output. This concept was applied in two of my studies (Chapter 3 & 4), whereby resistance was applied as a method to dictate task intensity. In Carrot or Stick and Chase or Be Chased, interface resistance was relative to the user's physical output and was used to facilitate or hinder task performance.

Carrot or Stick used EMS to apply supporting or impeding muscle actuation by triggering involuntary limb movement on the user's upper body. The Carrot condition applied EMS to enhance muscle contraction in compliance with the exercise motion thus exaggerating bicep contraction during a bicep flex. The Stick condition applied EMS to counteract muscle contraction in opposition to the exercise motion, activating triceps contraction during a bicep flex. A lack of kinaesthetic force generated by EMS meant that it was unable to fully actuate participant limbs while they were holding 2kg dumbbells.

'Chase or Be Chased' was based on the same game concept as Carrot or Stick, however, the physical output required to control the exergame was generated by pedalling a stationary bicycle and the resistance was generated by a smart trainer (Wahoo, 2021). The objective here was to move a virtual car along a 1.5km route by cycling a smart trainer. Resistance on the smart trainer adjusted relative to the user's performance and the virtual terrain while they played the exercycle game. If a user's output performance was below a specified threshold, resistance on the physical interface increased, hindering their game performance. Correspondingly, if a user's output level was above a predefined benchmark, resistance decreased, which enabled them to complete the task they were given.

I had hypothesised that participants would cycle faster to avoid being rammed during the Be Chased condition in comparison to overtaking the AI competitor during the Chase condition. This had been based on Kahneman's theory (Kahneman, 1991) which states that people will work harder to avoid a financial loss than they will to gain an equivalent financial reward. The closest study that used a similar concept and involved a physical activity was by Patel et al. (2016). In their study financial incentives framed as a loss were most effective for achieving physical activity goals. This finding conflicted with Finkelstein et al.'s (2008) findings that demonstrated modest financial incentives tied to aerobic exercise can be effective at increasing physical activity. However, Finkelstein et al.'s study only featured financial incentives and participants were not faced with financial loss if they did not engage in the activity; they merely received no payment.

My analysis of both of these findings suggests that exercise can be motivated using financial reward, but when financial incentives are based on gain or loss, there is greater adherence to avoiding loss than through earning.

Wattage and completion times for both of the Chase Conditions (Chapter 4) were not significantly different and therefore this hypothesis could not be verified as data differences were too low. The advantages of applying Kahneman's theory as a game mechanic to enhance exertion remain unanswered. Providing a more definitive outcome would provide the research community with interesting data, however such a study would require an alternative interface design than that used in Chase or Be Chased.

My findings in Chapter 4 show how physical output and enjoyment were greater in both Chase conditions than those of the Control condition. These findings demonstrate that chase based game mechanics can be used to motivate enhanced physical output, and also, incentivised and disincentivised resistance does motivate enhanced physical output. Understanding to what extent human motivation can be replaced by mechanised exertion would require a longitudinal study with a more complex system design and is worth considering for future work. A future study could yield interesting results by combining both Chase conditions and investigating how altering between both Chase states can impact on maintaining engagement during long term exergame activity. The physical activity would not necessarily be limited to cycling and could, in theory, be transferred to interfaces such as rowing machines and cross trainers. Collaborating with virtual fitness communities would enable a longitudinal study to be conducted remotely. This would provide a chance to experiment with more sophisticated game mechanics with a view to encouraging long term engagement.

In Chapter 4, I found that when participants were offered the choice of replaying the game or receiving an energy drink, 70% of participants chose to replay the game. Arguably, this highlights the appeal of the game and would suggest that a majority of participants enjoyed the experience. User enjoyment could be attributed to a combination of enhanced visual fidelity and lactate threshold limitation. Prior work has shown that both factors can increase enjoyment during physical activity. Glen et al. (2017) demonstrated that immersive exergames generate greater enjoyment and higher exercise intensity during self-regulated intensity cycling. Similarly, Ekkekakis et al. (2011) posit that remaining below lactate threshold increases user enjoyment and dissociation from the physical task. Research has indicated that "enjoyment of physical exercise is a stronger predictor of long-term activity engagement than actual self-efficacy for physical activity" (Lewis et al., 2016). Taking this into account, any subsequent longitudinal studies would need to ensure that enjoyment is prioritised in the system design. A future study in the area of resistance-based exergaming could yield interesting results by investigating the main effects of reduced lactate threshold and visual fidelity on output and enjoyment levels in addition to studying the interaction effects of both.

In my study ‘Chase or Be Chased’ (Chapter 4) I separated the connection between user autonomy and task intensity by automating task resistance. ‘Switching It Up’ (Chapter 5) also removed user autonomy from task intensity but did so manually rather than dynamically. This provided an interface to examine the impact of manual intensity adjustment by a third party such as a trainer on physical output during exergame activity.

Switching It Up was a physiologically controlled exergame in which the player's exertion influenced their avatar's output. Energy was expended by pedalling a Wattbike, and the particpants heart rate, which increased with cadence, was mapped to the avatar speed. The Wattbike featured a ‘climb lever’, which could generate consistent and reliable magnetic resistance. During the resistance condition, the climb lever was increased at a specific time by a specific amount.

Although both of these studies featured varying resistance and high-fidelity graphics, the game mechanics were implemented in different ways. The game mechanics in ‘Chase Or Be Chased’ were meaningful and perceptible to the participants, whereas in Switching It Up, they weren't interactive, meaningful, or perceptible: they just increased at a set point. The lack of dynamic resistance in the Switching It Up interface was reflected in the user output. The automated task intensity used in Chase or Be Chased generated enhanced output in comparison to Switching It Up. The mechanic in Switching It Up was simplistic and not linked to performance, so resistance may need to be more fundamentally involved in the game play to have a motivational effect.

One way in which the impact of manual task intensity could be reconsidered would be giving the coach or trainer a more prominent role during the exergame. In the same way that personal trainers provide feedback, motivational support and ‘spot’ clients during weight lifting exercises, the exergame could be designed around giving the coach or trainer more control. One hypothetical scenario would be to design an exergame that mimics the timing and intensity of a ‘beep test’. In physical exercise this test involves participants running back and forth between two points positioned 20-meters apart. The participants must maintain a running speed determined by an amplified beep tone, over the duration of the test. The required running speed increases as the test progresses. In the context of an exergame, the user might be on an exercise bike or treadmill. The coach or trainer would control the task intensity of the exergame just as a real-world coach would control a beep test. Heightened participant awareness generated by obvious resistance changes could motivate enhanced output as Farrow et al. have demonstrated.

7.5 ENHANCING VISUAL FIDELITY

Presenting participants with visual experiences that are dated or lower in quality than the graphics they interact with on a regular basis can influence participants’ mindsets by reducing their interest or pleasure (Lew et al., 2011). Providing users with a visual experience on par with a commercial equivalent increases immersion (Cummings & Bailenson, 2016) and enhances dissociation during physical activity (Mestre et al., 2011).

The environments in Carrot or Stick, Switching It Up, Feeling Virtual Worlds and CartRight were designed using the Unity and Unreal game engines; the Chase or Be Chased environment was created using a modified version of the commercial video game GTA V (Rockstar Games). Doing so enhanced the visual and interactive quality of the studies and in doing so supported the resistance based game mechanics in each of the studies.

The fact that enhanced immersion generated increased physical output in Switching It Up demonstrated the value detailed graphic fidelity can bring to the exergaming experience. The combination of the exergame's graphic fidelity viewed through the medium of a VR HMD generated greater output than the non-immersive condition, validating the dissociative benefits of visual content (Glen et al., 2017) and graphical fidelity (Cummings & Bailenson, 2016). This had previously been demonstrated using immersion by means of projection screens and monitors (Monedero et al, 2015; Glen et al., 2017). However at the time of this study (2016) measuring the impact of immersion on physical exertion using a VR HMD was a unique contribution.

Monedero et al. (2015), Farrow et al. (2019) and Glen et al. (2017) have all demonstrated how immersion increases enjoyment during exercycle activity. These examples use visual stimuli to support other motivational game mechanics. This also applies to the bespoke exergames tested in this Thesis; variable resistance is used as the core game mechanic and is supported by enhanced immersion. A possibility for a further study would be to use visual fidelity as the primary game mechanic. This could be done by linking player performance with the quality of the visual display in the exergame. For example, a player could be encouraged to maintain a set workout by being rewarded with a HD Netflix stream, and should the required output drop below a predefined threshold, the display would become pixelated.

The Chase or Be Chased game was developed using a modified version of an existing GTAV mod called GTBikeV (Matas, 2021). The developer created GTBikeV as they preferred the visual quality in GTA V over the graphic fidelity used in mainstream cycling platforms (Zwift, 2019). As of April 2022, there were 1300 virtual cyclists using the GTBike V plugin on a weekly basis. This figure pales in comparison to the three million Zwift accounts generated to date (Reed, 2021), however, it still demonstrates that a minority have chosen to switch cycling platforms on the basis of experiential quality. I believe that conducting a longitudinal study on the relationship between visual fidelity and physical exertion would provide interesting results to the HCI community. Prior studies have compared the relationship between immersion and physical output, but typically the immersive comparisons are 'interactive cycling vs. cycling' (Monedero, 2015; Glen, 2017). If I were to conduct a future study in this area I would look at more specific game elements such as the quality of lighting, rendering and textures, in addition to the age and genre of the title.

In addition to adjusting the quality of the visual content, a similar experiment could also be conducted with the quality of the immersive medium. Cummings & Bailenson, posit that stereoscopic width has a greater impact on immersion than visual fidelity. One could explore the possibility of developing a dynamic headset capable of altering stereoscopic width in real-time. With such a device it would be possible to study the relationship between stereoscopic quality and physical output during a resistance based task.

7.6 ANALYSING THE IMPACT OF DYNAMIC RESISTANCE & VISUAL FEEDBACK ON MOVEMENT GUIDANCE IN VR

My decision to focus on exertion from a qualitative approach was influenced by prior research by Velloso et al. (2013) and Kowsar et al. (2016). Both of these studies had examined weightlifting activities, although, neither of them related to exergaming in any way. While Velloso's study demonstrated that visual feedback could improve weightlifting technique, it had never been applied in VR.

Enhancing the quality of a physical task through a virtual medium is an underexplored area which has the potential to improve people's physical health. Providing real-time postural feedback during exergame activity has the potential to improve physical performance and counteract any threat of physical strain on the body. Virtual Reality has been used to relay postural instruction (Hoang, 2016) and tactile haptics have been used to improve sitting posture (Zheng, 2010). However, kinaesthetic feedback has never been used during a virtual activity to improve postural quality. Carrot or Stick, Chase or Be Chased and Switching It Up used resistance to motivate the quantity of physical output, CartRight demonstrated that adaptive resistance combined with visual feedback could be used as a game mechanic to motivate the quality of physical output.

In Chapter 6, CartRight compared pre and post postural data recorded when participants were engaged in an immersive task involving dynamic resistance. Results from the first study revealed that resistance directly influenced posture negatively, with greater resistance leading to poorer posture. Results from the second study demonstrated that real-time feedback improved posture, even under significant dynamic musculoskeletal loading both during and after the presence of the augmented feedback. These results align with Velloso et al.'s findings that real-time visual feedback can improve the quality of an exertion based task (Velloso et al., 2013).

A limiting factor in this study was the length of the supermarket aisle which restricted the virtual shopping activity. The virtual and physical floor surface measured 8m x 4m which was the maximum space that could be tracked using a HTC Vive (2019). Newer headsets featuring 'inside out' tracking would not have such limitations and would enable a much longer shopping aisle. A larger virtual supermarket would mean that longer user studies could be conducted. A future study in this area should also consider longitudinal research to identify the degree of training retention learnt from the posture learning.

Given the surge in exergaming (Kelly, 2021; Heater, 2021) and the lack of emphasis on task quality, users are putting themselves at risk of injury by participating in virtual activities without any feedback on the quality of their physical movement.

An interesting follow up to CartRight would be to combine the qualitative findings and apply them to a more rigorous exergame that is typically focused on motivating enhanced output. One such example would be a mixed reality martial arts or boxing game where a virtual boxing bag would be seamlessly overlapped with a physical counterpart. The user would wear a motion capture suit and would be tasked with striking the boxing bag based on poses assigned to them by the exergame. After each strike the user would be graded based on the quality of their performance relative to mocap data. In addition to qualitative feedback real-time data would be displayed relating to estimated energy expenditure. This concept would provide a balance between performance quality and energy expenditure.

7.7 ANALYSING THE RELATIONSHIP BETWEEN DECEPTION & PHYSICAL OUTPUT

Switching It Up experimented with the use of manipulated data with a view to motivating enhanced physical output. The avatars speed was controlled by the user's heart rate. During the deception condition, the displayed BPM was reduced by 20%. Prior exertion-based studies have motivated enhanced output through data manipulation, although the findings from Switching It Up did not provide any evidence to support this (Stone et al., 2012; Lochtefeld et al., 2016).

I believe that the difference in outcomes may be attributed to two factors: duration of the task and the level of dissociation in the interface design. Prior work has demonstrated the relationship between immersion and dissociation (Glen et al., 2017), suggesting that participants engaged in exergames with higher levels of immersion will perform for longer periods. According to Morgan et al. (2008) users in a dissociative state are less aware of their own physiology than those in an associate state. Stone et al. (2012) had demonstrated that providing participants with data from their previous performances generated enhanced output, even though no audio or visual stimuli was used in the experiment. Participants with less distractions would have become aware of their own physiology quicker and this may explain how the displayed manipulated data had more of an impact on their output.

Löchtefeld et al. (2016) had demonstrated that user output could be increased by 15.2% when the mapping between bike cadence and avatar speed was altered. However, the bespoke game was designed using low visual fidelity which may have impacted on the length of time the participants remained in a dissociative state. The length of each game in this study was two minutes which was twice the duration of the conditions used in Switching It Up. Tenenbaum & Hutchinson’s (2007) exertion model maintains there is a cutoff point when the task intensity gets so high that users become unable to take their mind off the physical task and they begin exercising in an associative state. In this scenario the combination of low visual fidelity and longer cycling times may have caused users to enter an associative state. If such a change in state did occur, it would explain why output increased when users focused more on their displayed user data.

Whether users who participated in Switching It Up entered into an associative state in such a short time frame is unlikely. Had the participants cycled for longer periods and entered associative states, a greater sense of physiological awareness may have resulted in a different outcome for this condition.

Though there was no main effect of deception on user output, it did have a combined interaction effect with resistance and immersion. When there were no adjustments made to resistance, and displayed player heart rate was manipulated, the participants in the non-immersive condition felt that the exercycle task felt more rushed than it had done when viewed through the HMD. A suggested explanation for this is that the lack of immersion caused less dissociation and more association, influencing participants to pay closer attention to the remaining time on the heads-up display. This justified why deception had an impact on perceived temporal demand in the non-immersive condition but failed to have any impact in the immersive condition.

Having discussed the design rationale, outcomes and contributions of these three studies the following section will summarise their findings and identify the limitations of this Thesis.

7.8 LIMITATIONS

The use of resistance in Switching It Up had no main effect on perceived or real exertion levels and yet it had done so in Chase or Be Chased. This may have been due to the statistical power which may have increased the possibility of incorrectly accepting the null hypothesis. Switching It Up had twelve participants with each condition lasting exactly sixty seconds; during conditions involving resistance only 30 seconds of each sixty second game involved an increase in resistance. Chase or Be Chased had thirty participants with an average play time of 153 seconds per condition. The time length of participant activity in exergame studies and the limiting impact it may have on user data has previously been raised by other researchers (Mueller et al., 2016). The length of these conditions could be increased in a follow up study and could consider reaching out to the online cycling community to partake in a longitudinal study.

Considering that visual fidelity was used to increase dissociation in all of these studies its impact could have been measured. Doing so would have provided a way to compare the impact of various HMD and game engine combinations on immersion, dissociation and exertion. It would have also enabled comparisons between Chase or Be Chased and Switching It Up relating to the resistance style (i.e. dynamic or manual) and user exertion.

Switching It Up investigated whether user exertion could be enhanced through the manipulation of the user's displayed heart rate. At the time in 2016, there was no prior work that had manipulated heart rate in an exergame and therefore no optimum level of heart rate exaggeration existed. A pilot study was conducted with one participant to establish a proposed level of BPM reduction. In hindsight more than one participant should have been used to determine the optimum falsification rate during this pilot study.

Another design limitation to take into account in Switching It Up was the manner in which manual resistance was controlled. I was confident that resistance was being adjusted without drawing the user's attention; participants may or may not have been aware of the resistance changes. There is no way of knowing this as it was not recorded in any questionnaire. In hindsight, participants should have been asked if they had sensed resistance manipulation and to what extent.

CartRight compared pre and post postural data which had been recorded when participants were engaged in an immersive task involving dynamic resistance. Participants performed the task five times. During the second, third and fourth tasks augmented postural feedback was displayed on the VR heads-up display, however none was displayed in the first and fifth tasks. No control condition was implemented to prevent learning effects from distorting data, this should have been considered. A future study in this area should also consider longitudinal research to identify the degree of training retention learnt from the posture learning.

7.9 IMPLICATIONS

Developers can learn from these findings and apply them to their own exergame designs with a view to motivating increased physical output and improving players physical technique and form.

FEELING VIRTUAL WORLDS

The implications for game designers based on the findings from Feeling Virtual Worlds is that there is an opportunity to expand the use of virtual and augmented reality to include a more embodied interactive experience that is not limited to the exclusive use of visual and aural modalities, but instead also incorporates tactile feedback. The study cites related research that explored responsive tactile hardware to add enhanced realism into tangible interfaces and interactive simulations. However, research in the area of seamlessly overlapping a virtual and physical interface was not as prevalent. Although there were some overlaps in the area of entertainment, none involved large mobile interfaces. The study's findings fill this gap by demonstrating the use of high torque servos to generate real-time variable and automated resistance.

The servo-controlled brake friction was robust enough to withstand full body force yet small enough to fit on a mobile device. The lower cost and size of these servos compared to commercial pneumatic or hydraulic hardware makes them more accessible and versatile for smaller companies and independent developers. Game designers can use this technology to create affordable dynamic resistance that can be scaled to suit stationary and mobile virtual environments, making gaming more interactive and immersive and enhancing the overall gaming experience.

CARTRIGHT

The results of the study found that by providing haptic feedback that is synchronised with movements, individuals can be motivated to maintain good posture and reduce the risk of injury. The study suggests that by using haptic feedback to provide real-time information about posture, individuals can improve their performance and maintain good posture throughout the task. The results also suggest that providing adaptive haptic feedback, which changes in response to an individual's movements, can further improve motivation to maintain good posture. By providing personalised feedback, individuals can be more engaged and motivated to maintain good posture during the task. Ultimately, the study suggests that by incorporating adaptive haptic feedback into exertion-based tasks, individuals can be motivated to maintain good posture, reduce the risk of injury, and improve overall performance.

Real-time postural feedback is essential during immersive gameplay because it can help players maintain proper posture and prevent musculoskeletal injuries. When players are fully immersed in a video game, they may lose awareness of their body posture and positioning, leading to prolonged static postures, poor body alignment, and repetitive movements that can cause strain or injury. In video games involving adaptive resistance, real-time postural feedback is even more critical. These games may challenge players to push their bodies beyond their usual limits, and without proper feedback, they may unknowingly use improper techniques or overexert themselves, leading to injuries.

Game designers can use this information to design games that incorporate adaptive haptic feedback and promote physical health and well-being. Real-time data on the quality of a user's physical output can provide players with immediate information about their posture and movement patterns, enabling them to make corrections. Another benefit of qualitative physical output in exergame design is that it can provide valuable data to players and healthcare professionals. By monitoring a player's physical output during gameplay, the game can provide feedback on their progress and skill acquisition and help identify areas for improvement. This can be particularly useful in rehabilitation settings, where exergames can be used as a tool for physical therapy.

Finally the use of digital twins in the manufacturing industry offers significant benefits for optimising processes and improving overall system performance. However, to fully realise these benefits, designers must prioritise human centred ergonomics and ensure that workers are comfortable and safe while interacting with XR development processes. This can be facilitated by promoting interface design that monitors user posture and provides real-time feedback on the quality of an employee's activity.

SWITCHING IT UP

This study demonstrated that the medium of VR could be used to motivate participants to exert themselves more than in a non-VR environment. Exergames viewed through a HMD can increase dissociation and enhance physical output during exercise in several ways. When wearing a HMD, users are often transported to a virtual environment that is visually and spatially distinct from their physical surroundings, leading to a sense of dissociation. Exergame designers can leverage off these findings and use them to create virtual worlds that allow their users to focus more on the interactive experience and less on the discomfort or fatigue associated with the exercise. High-end visual content viewed through a HMD can enhance physical output by creating a sense of immersion in the virtual environment. This feeling of being immersed in the game world can lead to a greater sense of engagement and motivation, as users feel more invested in the virtual experience. This, in turn, can lead to increased physical output as users become more engaged with the virtual environment and the physical challenges presented within it.

The study demonstrated that manipulated heart data could be used to alter perceived temporal demand in a non-immersive condition without adaptive resistance. One example where this could be applied to is a spinning class. By manipulating the user's perceived heartrate data, a designer can potentially create the illusion of a more challenging or faster-paced spinning class, even if the actual pace or intensity remains the same. For example, if heart rate data is manipulated to show that the class or the user is working at a higher intensity than they actually are, the participants may perceive the class to be more challenging and feel a greater sense of time pressure. This can lead to an increase in motivation and engagement during the class, as well as a greater sense of accomplishment at the end of the session. Conversely, if heart rate data is manipulated to show that the class is working at a lower intensity than they actually are, the participants might perceive the class to be less challenging and feel a reduced sense of time pressure. This could be beneficial in situations where the participants are new to spinning or have lower fitness levels, as it can help to increase enjoyment during the class.

Finally the study demonstrated the potential that adaptive interventions can have on enhancing physical output during exergaming. One of the key benefits of adaptive resistance in exergaming is that it can help to increase the intensity of the workout, leading to greater physical output and improved health outcomes. By adjusting the resistance level to match the player's fitness level, adaptive resistance can help to ensure that players are always working at a challenging level, pushing their bodies to improve and grow stronger over time. Another benefit of adaptive resistance in exergaming is that it can help to prevent injury by ensuring that players are not overexerting themselves. By adjusting the resistance level to match the player's current fitness level, adaptive resistance can help to prevent players from pushing themselves too hard and potentially causing injury.

CHASE OR BE CHASED

Game developers can explore alternative hardware and software combinations that can enhance the physical output of players in the absence of open-source universal communication platforms and plugins for physical interfaces. This can be done through the use of game 'modding' and script hacking. Modifications such as these provide an opportunity to create bespoke video games. Pairing these modified video games with commercial hardware such as the Wahoo Kickr can lead to the development of new exergames with robust reliable dynamic physical resistance, providing an alternative to traditional workout routines.

Customising existing hardware and software combination allows exergame developers more time to focus on prioritising the interaction quality and immersive fidelity of the exergame experience. Chase or Be Chased demonstrated that chase-based mechanics can be used to increase player motivation and output by incorporating elements of competition and challenge into the game. Chase based game mechanics can be used to address some of the barriers to exercise, such as boredom or lack of motivation, by providing a fun and entertaining way to stay active.

The high number of participants who chose to replay the game rather than accepting payment in the form of an energy drink highlights the appeal of the experience. The combination of enhanced visual fidelity and lactate limiting strategy likely contributed to this choice. By limiting the accumulation of lactate, the body is able to maintain a more sustainable level of physical activity, which can help to prevent the onset of fatigue and reduce the risk of injury or muscle damage. In addition to reducing fatigue and muscle damage, lactate limiting strategies can also help to improve overall exercise performance. The use of lactate limiting strategies in exergame design can also help to increase the overall enjoyment and engagement of the game. Studies have shown that enjoying the activity and focusing more on the game and less on the exertion generates greater output than a less enjoyable game. Game designers could benefit from incorporating lactate limiting strategies and enhancing visual fidelity to maximise user engagement, exertion, and enjoyment.

7.10 CONCLUSION

Chase or Be Chased demonstrated that unconventional methods such as script hacking and game modding can be applied to commercial hardware and software to create a bespoke exergame. Doing so saves time without having to compromise on the interaction or immersive fidelity. From a game design perspective, the use of chase based game mechanics were successfully deployed as a motivational feature. Future research in this area could consider combining the Chase game mechanics from both games into a single exergame with a view to maximising user exertion and enjoyment during a longitudinal exergame activity.

Switching It Up demonstrated how high end visual content viewed through a VR HMD could be used to increase dissociation and enhance physical output. The use of manipulated heart data could be used to alter perceived temporal demand in a non-immersive condition without adaptive resistance.

The fact that deception did impact on perceived temporal demand in the non-immersive condition suggested further exploration using manipulated physiological data as a motivational game mechanic in a real world scenario. One example would be manipulating accelerometer or GPS data during outdoor activity.

Results from CartRight demonstrated the linkages between increased resistance and poor posture during an immersive exertion based task. They also demonstrated how real-time feedback can be used to improve user posture under significant dynamic musculoskeletal loading both during and after the presence of the augmented feedback. The interface design used in CartRight demonstrated that servo-controlled brake friction could be used to replicate dynamic resistance capable of withstanding full body force. This was something that had not yet been applied on a mobile mixed reality interface. It also demonstrated how the HTC Vive's inertial measurement unit (IMU) data and the Brekel application could be combined as an affordable and reliable method to effectively monitor, record and analyse postural data.

Dynamic resistance features prominently in the relatively new exergaming sector which is resistance based home training. Peloton (2018) and Zwift (2019) are two home training platforms which integrate dynamic resistance in their virtual workouts by means of electromagnetic smart trainers. Gamification of the cycling experience within these VE's is used as a motivational method to encourage enhanced exertion from participants. Time trials are provided whereby a players' previous best score is displayed on screen providing the cyclist with a feed forward mechanism to try to either maintain or beat their existing record. Virtual rewards in the form of virtual jerseys or access to hidden levels may also be earned with the accumulation of points relative to distance and calorific expenditure. In addition to supporting solo workouts, Zwifts' strong social network presence encourages remote competition amongst virtual clubs and also helps to further the platforms usage both on and off the bike trainer.

I believe that the replication of real world resistance, compelling graphics and real-time biometric feedback within these exergames are what have led to their increased popularity, subscription base and revenue. These are the exact areas which I had felt were lacking in the exergaming sector and which my work has addressed. Switching It Up, which was developed and tested in 2016 (Chapter 5) predated market demands and I argue that this justifies the relevance and practical application of my work in relation to bringing about positive change to people's health and wellbeing. I also believe that the focus on qualitative output (as seen in Chapter Six) is very applicable to this virtual fitness market.

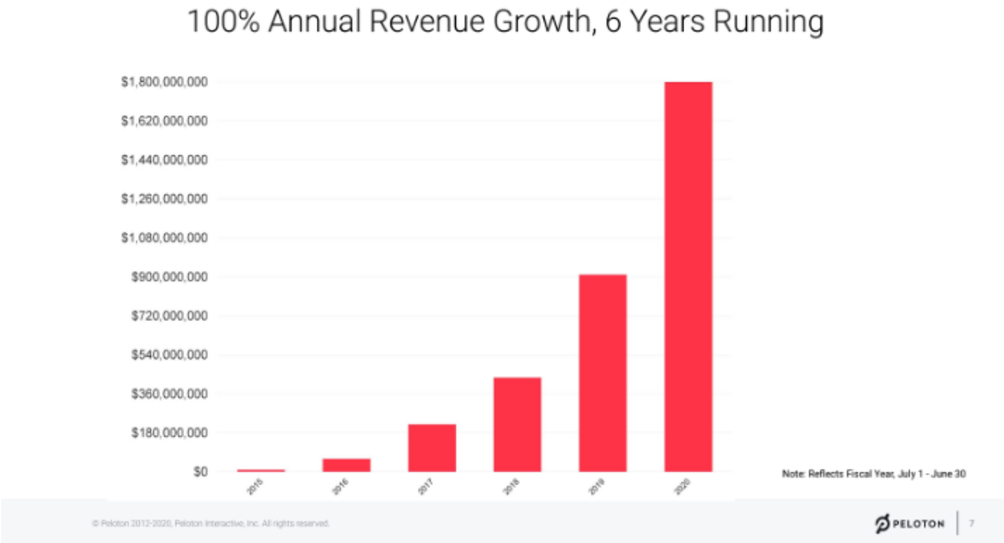

Figure 7.1. A graph charting Peloton revenue growth 2015 - 2020.

Home based immersive physical activity is a rapidly expanding commercial sector. The first financial quarter of 2021, saw Zwifts membership base reach 3 million subscribers (Reed, 2021) and the fourth financial quarter of 2021 saw Pelotons’ membership base grow to 5.9 million (Peloton Investor Resources, 2021) (Figure 7.1). A tendency by commercial VR exergames to focus entirely on motivating and marketing enhanced physical output (VRIHE, 2018) has meant that the qualitative aspects of the physical activity have been ignored. As a result consumers who partake in virtual exercise do so without knowing how efficiently or safely their body is being put to use. Corporations have a responsibility to advise their customers on how well they are conducting the physical activity so that they exercise correctly and also so that they can quantify the quality of their performance and skill acquisition.

Moving beyond the present, data relating to future trends in the workplace highlights an imminent need for qualitative postural feedback in mixed reality environments (Digital Twin Market Size, 2022). As mentioned in Chapter Six, research has predicted that the use of XR technologies within industry will see significant growth in the coming decade (Dalton, J., & Gillham, 2019). As workplaces begin to adopt these technologies, XR developers need to ensure user safety and human posture are promoted in future interface design.

The way that my research has concluded with a focus on qualitative output can contribute towards the current virtual fitness sector and act as a reference to assist XR future developers in designing for an emerging era.

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APPENDICES

‘Chase Or Be Chased’ Risk Assessment

Room / Lab Number	N/a	Building	N/A

Equipment:

- Wahoo Kickr Bike Trainer
- Bicycle (back wheel removed mounted on the Wahoo Bike Trainer).
- PC
- Lucozade Sports Drink

Activity:

- Participants will be asked to cycle a distance of 1.5km three times on the stationary bike.The speed they cycle at will control the speed of a virtual on-screen avatar.
- The speed at which participants cycle at will be entirely up to them and no pressure or verbal encouragement will be given by the researcher at any stage.
- There will be a 5 minute resting break between each of the 1.5km conditions. During this break a seat will be provided for participants to rest on and if they wish they may rehydrate with their own water bottle which they will have been asked to bring.
- After the third 1.5km condition participants will be given the option of receiving a bottle of lucozade sport or to repeat one of the 1.5km conditions. If they chose the latter they must rest for 5 minutes before doing so. Participants who opt to receive the lucozade sport drink will be able to choose it from an outdoor windowsill that it will have been left on and it will have been wiped down with antiviral spray in advance.

Please fill in the workers involved with this activity and their category letter (see Key below)

Categories of workers Key	Academic Supervisor (AS)	Post Doc (PD)	Post Grad (PG)	Technician (T)	Under Grad (UG)	Other (O)

	Name	Worker Category	Name		Worker Category
(a)	Joey Campbell	PhD Candidate			
(b)	Dr. Paul Marshall	AS			
(C)	Dr. Oussama Metatla	AS			

Hazards (See attached guidance notes and examples)

- Falling, getting on or off bike
- Exhaustion in subjects – heat, fluid loss, oxygen deficit.
- Use of electrical hardware outdoors.

Precautions (See attached guidance notes and examples)

- A minimum fitness criterion is set whereby users must either run 5km, swim 800m or cycle 15km once a week. There is no target age group but of the 34 potential recruits the current ages range between 22 and 50.
- Resting and water breaks are given between conditions.
- Cycling distance is limited to 1.5k per condition.
- User tests are conducted beneath a gazebo to protect users from the elements.

- All subjects are briefed that they may terminate the procedure at any point
- Participants will be asked to complete a health questionnaire to ensure that there are no underlying health issues (mainly in relation to asthma or cardiovascular issues).
- The outdoor patio surface has been swept of gravel.
- All obstacles (plant pots and garden furniture) have been removed.
- Stepping areas have been painted to highlight tripping hazards.
- Electrical cabling has been kept to a minimum and covered with foam matting.
- Bike handlebars and body as well as the participant chair will be sprayed and cleaned with antiviral spray and wipes between each user test.
- Bike stability and connection to the bike trainer will be checked after each user test.
- The power going into the wahoo kickr is 12volts, the kickr is located beneath a gazebo, the mains to 12v power adapter will be wrapped in thick polythene to protect it from dampness. Testing will not be conducted if there is heavy rain.

Emergency procedures	• If a subject complains of feeling unwell, the test will be stopped and they will be allowed to rest and recover **FIRST AID INFORMATION** John Hough is a technician from University College Cork. He is first aid trained and is the department's on site medic contact. John is a neighbour and friend and has volunteered to be on call during all user tests in the (unlikely) event of any health-related issue. Cork University Hospital is 6km from the user test site and I have a car to bring anyone directly to the hospital should such a situation arise. John Hough Bio.
Name of student: **Signature:** **Signature:** **Signature:**	

Faculty of Engineering Research Ethics Committee

University of BRISTOL

APPLICATION FOR RESEARCH ETHICS APPROVAL

1. Title of the research:

Immersive exertion: Examining energy expenditure in an immersive cycling exergame.

2. Name of Applicant, with their job title:

Joey Campbell (PHD Candidate).

3. Name of Supervisor (if applicant is a postgraduate or undergraduate student), with their job title:

Professor Mike Fraser, Professor of Human-Computer Interaction.

4. Other investigator(s) involved, with their job title:

Not applicable.

5. Source of funding and grant code:

This PHD is being funded by my current employer 'Cork Institute of Technology'.

6. Does this source of funding place any restrictions on public dissemination (publication, etc.) of the results of the research? If yes, please say what these are.

No.

7. Background and aims of the research:

This is the second of three video games I am designing as part of my research, which is looking at the gamification of physical exercise and the impact this can have on exertion levels. The game in question is controlled by the users heart rate; as the user cycles a stationary 'Watt Bike' the users BPM governs the speed of a virtual cyclist on screen. The aim of this experiment is to look at the influence 1. Immersion, 2. Altered Physiological Data & 3. Resistance Control can have on exertion levels (measured in wattage) and Rates of Perceived Exertion (measured using a Borg scale). While there have been several heart rate based exergames created to date [1] and several exergames designed using Virtual Reality [2], to the best of my knowledge there is no prior research examining a combination of heart rate control, VR and altered physiological data.

1. *Stach, Tadeusz, et al. "Heart rate control of exercise video games." Proceedings of Graphics interface 2009. Canadian Information Processing Society, 2009.*
2. *[Bolton, John, et al. "PaperDude: a virtual reality cycling exergame." CHI'14 Extended Abstracts on Human Factors in Computing Systems. ACM, 2014.]*

8. Who will be recruited to participate in the research?

I hope to recruit students from the BA. in Multimedia which I deliver in Cork Institute of Technology. Students would not need to have prior knowledge of video games but should be relatively fit and exercise 2-3 times per week for 20-25 minutes.

9. How many participants will be recruited?

12 students aged between 19-29 (6 male and 6 female).

10. How will the participants be recruited?

A post will be placed on the internal department blog.

11. Are there any potential participants who will be excluded. If so, what are the exclusion criteria?

No.

12. Where will the research take place?

Cork Institute of Technology, e-learning department.

13. How will informed consent be obtained from all participants or their parents/guardians prior to individuals entering the research study?

Participants will be given an information sheet to read prior to being tested, after which they will be asked to sign a consent form. Copies of these documents are attached.

14. Will the study involve actively deceiving the participants?

One of the research topics we are looking at is whether altered physiological data can be used to improve physical performance. One of the experiments we plan on doing is altering the users displayed heart rate within the video games 'Heads Up Display' to see if it has any impact on their exertion levels. We plan on letting the user know about this 'data altering' once their user study is complete. While it is impossible for us to say whether people will object to this 'deception' we do think that it will be extremely unlikely.

15. Will participants be made aware they can drop out of the research study at any time without having to give a reason for doing so?

Yes and it is on the user instruction form also.

16. Outline the design of the research study and list the procedures to which the participants will be subjected, the anticipated testing time and any treatments administered.

This is an eight conditioned within subjects design experiment. Each user will cycle for 8 x 1 minute games with a 2 minute resting period between each game. At the end of each game they will complete a Nasa TLX Questionnaire as well as selecting a Rate of Perceived Exertion Level on a Borg Chart. The estimated total testing time for each participant will be between 25-35 minutes. The 8 conditions are as follows:

1. Immersive Headset, True BPM, No gear resistance applied.
2. Immersive Headset, True BPM, Gear Resistance applied.
3. Immersive Headset, False BPM, No gear resistance applied.
4. Immersive Headset, False BPM, Gear Resistance applied.
5. Non-Immersive, True BPM, No gear resistance applied.
6. Non-Immersive, True BPM, Gear Resistance applied.
7. Non-Immersive, False BPM, No gear resistance applied.
8. Non-Immersive, False BPM, Gear Resistance applied.

17. Describe potential risks to participants (physical, psychological, legal, social) arising from these procedures.

The research will not involve risks beyond those normally encountered by the participants in their life outside research.

Is there likely to be any risk to the investigator in the course of this study eg. dealing with potentially aggressive subjects?

No

Is there likely to be any risk eg. legal, adverse publicity, to the UoB?

No

18. How will participants be debriefed?

The user will be told about the falsified heart rate data after the experiment. There will be no further correspondence.

19. Is any reimbursement of expenses or other payment to be made to participants?

Yes – there will be a raffle for a gift voucher once the user tests are complete.

20. Will personal data, beyond those recorded on the consent form, be used in the research?

No

21. Will the participants be audio-recorded or video-recorded?

Yes – this is on the consent form and all users will be informed that the recorded data will only be viewed by the research team (Mike Fraser & Joey Campbell).

22. When will this research be completed? (Give a date)

Within one week of receiving ethics approval.

23. How will the data be made available at the end of the project? (You must declare your level of access)

The research findings will be published in a paper which will be submitted to the 2017 CHI conference. My data can be made openly available through a data repository.

24. Any other relevant information

The users will have a private changing room for putting on gym clothes and also to apply and remove the heart rate monitor themselves.
The medical team on campus have been made aware of the study and an emergency mobile number has been provided for the building medic in the unlikely event that anyone might become ill while cycling.

Signature of Applicant: **Date: 7/06/'16**

[redacted]

Signature of Supervisor (if applicable): **Date:**

Gmail **Joey Campbell** [redacted]

Research Query

7 messages

Joey Campbell [redacted] Tue, Jun 19, 2018 at 3:15 PM
To: kheng-lim.goh@ncl.ac.uk

Hello Dr Kheng-Lim.
My name is Joey Campbell, I am a lecturer and PhD candidate based in Cork Institute of Technology, Ireland. I am concluding my PhD research with a project relating to posture and exertion in Virtual Reality. I am trying to alert users relating to the quality of their trunk posture while pushing a virtual shopping trolley: https://www.youtube.com/watch?v=GpEYAiN32-o

I recently read your article on Spine Ergonomics and I was wondering if you might be able to advise me on something ?

As it stands I have the pitch of the accelerometer giving visual feedback if the upper back alters +/- 12 degrees. (12 degrees is just a test range to make sure the system works but I want to make sure the optimum range I use in the final study has some scientific basis).

1. I believe *optimum range of sagittal plane flexion while pushing a trolley* is what I need to find but I can't find any information on this and I'm not sure if such an optimum range exists ?

2. Does any ergonomic documentation exist relating to *correct trunk posture while pushing a wheeled object ? (I have checked google scholar thoroughly with no luck*).

Any advice would be great.
Regards,
Joey

Kheng-Lim Goh <kheng-lim.goh@newcastle.ac.uk> Mon, Aug 20, 2018 at 9:27 AM
To: Joey Campbell [redacted]

Dear Joey

My apology for the very late reply. I have been away for quite a while and have a lot of catching up to do.

From what you have described, I think there is a dearth of information about the optimum range of the sagittal plane flexion. Wondering if it is also time to address this as part of your study. Do you have the resources to call upon volunteers? The alternative is to source data from a wider study (results reported in the literature and database such as figshare, mendeley) that when pulled together could help you determine the optimum range.

Hope this helps.

Best wishes,

Kheng

[Quoted text hidden]

Gmail

Joey Campbell <joeycampbell60@gmail.com>

PhD Research Query

7 messages

Joey Campbell [redacted] Thu, Jun 14, 2018 at 10:25 PM
To: drew.harrison@ul.ie

Hi Drew.
I am concluding my PhD research with a project relating to posture and exertion in VR. I am trying to alert users relating to the quality of their trunk posture while pushing a virtual shopping trolley (see demo link).

I have met with Trevor Woods in UCC and he mentioned that you might be able to point me in the right direction with two questions I have.

As it stands I have the pitch of the accelerometer giving visual feedback if the upper back alters +/- 12 degrees. (12 degrees is just a test range to make sure the system works but I want to make sure the optimum range I use in the final study has some scientific basis).

1. I believe *optimum range of sagittal plane flexion while pushing a trolley* is what I need to find but I can't find any information on this and I'm not sure if such an optimum range exists ?

2. Does any ergonomic documentation exist relating to *correct trunk posture while pushing a wheeled object ? (I have checked google scholar thoroughly with no luck*).

Any advice would be great.
Thanks
Joey

Drew.Harrison <Drew.Harrison@ul.ie> Fri, Jun 15, 2018 at 11:09 AM
To: Joey Campbell [redacted]

Hi Joey,

Thanks for your email.

I am not aware of any research that identifies an optimum range of sagittal plane flexion while pushing a trolley ... but it isn't something I have considered.

If you can't find anything, this probably indicates that your work is quite unique. My guess would be that the optimum range of trunk flexion relative to horizontal will be related to the amount of horizontal force that is exerted on the object. So if the object is massive or the person wants to exert greater force to accelerate the trolley then they will lean forward to facilitate the increase on horizontal force.

Sorry I can be of any more help.

Best wishes with the rest of your research.

Regards

Participant Information Sheet

Background

This user study is looking at the impact immersive environments have on rates of perceived exertion. It is part of a broader study being carried out by Joey Campbell as part of a PHD in 'exerGaming' which is being supervised by Professor Mike Fraser of Bristol University.

Research procedures

12 participants are required to try out a virtual reality video game I have created. The game is controlled by the users heart rate while cycling a Watt Bike and viewed through a VR headset.

Participants would be required to cycle at their own pace (as fast or as slow as they wish) for 8 x 1 minute games. There would be a 2-minute interval between each 1-minute game. Each user study would last approx. 30-35 minutes.

Each user will wear a heart rate monitor as their BPM will be controlling the speed of a virtual cyclist within the video game. The provided heart rate monitor should be attached by the user prior to beginning the user test and removed by the user once complete in a private changing room beside the lab. The Heart rate monitor will be cleaned with disinfectant wipes prior to each user test for hygiene purposes

The user will be given a demo game in order to become comfortable with:
1. Wearing a VR Head Mounted display
2. Being in a VR environment
3. Steering the bike
4. The height of the exercise bike saddle
5. The heart rate monitor and ensure that it is sending a strong signal to the PC.

While playing the demo game three real-time pieces of data on the in game Heads Up Display will be brought to the user's attention:
- Heart rate
- Virtual Distance Covered
- Timer countdown

The user will also be shown a Rate of Perceived Exertion Borg scale, comparisons will be given to familiarize the user with this scale (1. Sitting/rested, 20. Exhausted).

There are eight different games and the object of each game is to cover as much virtual distance as possible within a sixty second period. During each game the users heart rate and wattage output via the Watt Bike will be recorded for further studying. Users will have a resting period of 2 minutes between each sixty-second game. After each game the user will be asked to rank their Rate of Perceived Exertion on a scale between 6-20 and also to complete a task questionnaire.

Participants would have the right to withdraw from the user test at any stage without having to give a reason.

Bottled drinking water will be provided to participants during the experiment.

For health and safety participants should be relatively fit (exercising twice a week for 20-25mins on a regular basis) and should not have any health conditions or disabilities. A prior knowledge of Virtual Reality or video game experience is not necessary. It will be necessary to have a balance between male & female users so apologies in advance, as we may not be able back to facilitate everyone interested in participating.

It is hoped that the user tests will be conducted on campus during the last week of June roughly between 10am - 8pm. If you are interested in participating please email me and I will work out a time schedule that suits.

As an incentive there will be a 100 euro gift voucher raffled between the 12 users once the user testing is complete.

Data handling
Personal data or video/audio recording will never be made available in the public domain. Participants must give consent to the use of anonymised quotes or data in publications and should be made aware that they *cannot* withdraw their data from the study once they have consented.
University of Birstol will have control of the data.
Data will be made open once compiled.

Other information
<u>Name, position and contact address of Researcher:</u>
Joey Campbell
PHD Candidate
Bristol Interaction & Graphics Lab
Bristol University
[redacted]

Ethical approval code: 37441
If you have any concerns related to your participation in this study, please direct them to the Faculty of Arts Research Ethics Committee, via the Research Ethics Coordinator, Liam McKervey (Liam.McKervey@bristol.ac.uk, 0117 331 7472).