THE EFFECT OF EXERCISE ON A NEW VIRTUAL REALITY BASED BALANCE TOOL FOR USE AS AN OBJECTIVE PITCH SIDE ASSESSMENT OF CONCUSSION

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ABSTRACT

Concussion has been a cause for concern in the sporting world for many years with it being highly debated in the medical and scientific community as well as the sporting world. Balance is a crucial factor in identifying when an athlete has sustained a concussion. Accordingly, balance tests are the foundation of the current multi-faceted concussion tests. However the current balance test within the widely used Sport Concussion Assessment Tool relies on subjective measures of COP to determine the balance score of an individual, whilst the objective options for balance testing, such as a force plate, are too expensive for wide scale use and too restricted to a laboratory set-up so provide no option for pitch side concussion testing. Consequently our new test was devised to address these issues by being inexpensive and portable through use of a Wii balance board (WBB) to objectively assess balance pitch side using centre of pressure measurements. The WBB balance test takes place within virtual reality (VR) where participants are required to maintain their balance whilst completing an immersive cognitive task. Random perturbations occur in the VR to create a conflict between their sensory inputs requiring participants to react, adapt and respond quickly and correctly in order to maintain their balance which would not be possible if a concussion had been sustained due to the known cognitive deficits of the injury. The primary aim of this research thesis is to ascertain the feasibility of using this balance system pitch side. The secondary aim is looking at whether there is an effect of exercise on participants' ability to maintain their balance during the VR balance test.

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CONTENTS

CHAPTER 1 1

1.1. Prominence of Concussion 1

1.1.1. Sports-Related Concussions 3

1.2. Definition of Concussion 6

1.1.2. Pathophysiology of Concussion 8

1.1.3. Second Impact Syndrome 9

1.1.4. Difference between Adult & Children 12

1.1.5. Possible long term effects of multiple concussion and repeated head injuries ... 13

1.3. Assessment Issues 14

1.4. Balance Importance 19

1.5. Effects of Exercise on Current Balance Tests used in Concussion Assessment 22

1.6. Incorporating Innovative Virtual Reality Technology 23

1.7. Aims and Hypotheses 26

CHAPTER 2 27

2.1. Method 27

2.2. Participants 27

2.3. Virtual Reality Balance Board System 28

2.4. Procedure 33

2.5. Baseline Assessment 35

2.6. Post-Exercise Assessment 36

2.7. Data Acquisition and Analysis 38

2.8. Statistical Analysis 38

2.9. Raw Data 39

CHAPTER 3 40

3.1. Participant Demographic and Dropout Rate 40

3.2. Participants' Experiences with the Virtual Reality System 40

3.3. Effect of Exercise on the VR Balance Test for Concussion 42

3.4. Does the perturbation effect diminish with repeated exposure to it? 46

CHAPTER 4 49

4.1. Discussion 49

4.2. Why Did Participants Perform Better Following Exercise? 52

4.3. Habituation to Perturbation Trials 54

4.4. Implications for Concussion Assessment 55

4.5. Conclusion 56

REFERENCES 57

APPENDICES 65

LIST OF TABLES

Table 1: Links between the mechanisms involved in the pathophysiology of concussion, to common symptoms experienced by individuals who have sustained a concussion adapted from Giza and Hovda (2014). 9

Table 2: List of symptoms from the SCAT5 that athletes are asked to rate on a scale of 0 (none), 1-2 (mild), 3-4 (moderate) to 5-6 (severe) 16

Table 3: List of BESS Errors. If multiple errors occur simultaneously only one error is recorded and the maximum number of errors for any single trial condition is ten therefore the total score for the BESS being out of sixty and thirty for the mBESS. 20

LIST OF FIGURES

Figure 1: Example of BESS stances from Bell et al. (2011). 19
Figure 2: Screenshot of the virtual environment for the balance test. 30
Figure 3: Virtual calibration balance test preceding each trial. 31
Figure 4: Participants' Stance on the Wii Balance Board....33
Figure 5: Flowchart of the Study Design....35
Figure 6: Borg's Rating of Perceived Exertion Scale....37
Figure 7: COP stabilogram showing a normal and extreme response to the VR perturbation 39
Figure 8: Participants' responses to the VR immersion questionnaire....40
Figure 9: Stabilogram of an individual's COP path during a baseline and a post-exercise control trial....42
Figure 10: Graph illustrating significant difference between baseline and post-exercise COP measurements....43
Figure 11: Graph displaying significant difference between baseline and exercise VR balance assessment as revealed by the control trials....44
Figure 12: The effect of perturbation trials on COP length during baseline and post-exercise conditions....45
Figure 13: Graph to illustrate no significant difference between participants' 1st, 2nd or 3rd control trials in either condition....47
Figure 14: Graph illustrating no significant learning effect by participants with repetitive perturbation trials....48

ABBREVIATIONS

ABI – Acquired Brain Injury

BESS – Balance Error Scoring System

CDC – Centre for Disease Control and Prevention

CISG – Concussion in Sport Group

COP – Centre of Pressure

CTE – Chronic Traumatic Encephalopathy

HIA – Head Injury Assessment

HMD – Head Mounted Display

ImPACT – Immediate Post-Concussion Assessment and Cognitive Test

LOC – Loss of Consciousness

mBESS – modified Balance Error Scoring System

MRI – Magnetic Resonance Imaging

mTBI – Mild Traumatic Brain Injury

PCS – Post-Concussion Syndrome

RFU – Rugby Football Union

RPE – Rate of Perceived Exertion

RTP – Return to Play

SCAT – Sport Concussion Assessment Tool

SIS – Second Impact Syndrome

SRC – Sport-Related Concussion

TBI – Traumatic Brain Injury

VE – Virtual Environment

VR – Virtual Reality

WBB - Wii Balance Board

CHAPTER 1

Prominence of Concussion

With one hundred and seventy million adults participating in physical activities and sports in America alone (Daneshvar et al., 2011), it is important that the risks of participating in these activities are fully identified in order to properly educate individuals on injuries they might sustain through participation to give them awareness. Physical activities and sports play an essential part in improving and maintaining the health and well-being of individuals by providing many physical and psychological benefits such as reducing the risk of obesity, diabetes and heart disease to name but a few. Therefore it is important that every effort is made through research and education to keep people participating in sport and physical activity in order to reap these benefits but additionally to reduce and prevent them sustaining any detrimental effects through serious injuries that could affect them in the long run. One injury that stands out and is still heavily debated amongst both the sporting and medical community is concussion. Concussion continually sparks controversy in the media with countless reports coming in from the sporting world each month regarding many different aspects of the injury such as how individuals are treated for it on the pitch and how their recovery is managed. To this day concussion is still a bit of a conundrum in the sporting world with various misconceptions still surrounding it.

According to Langlois et al. (2006) it is estimated that 1.6 million to 3.8 million concussions occur each year in sports in the USA. Amongst the general population in the USA in 2010 as found in Voss et al. (2015) the Centre for Disease Control and Prevention attributed 2.5 million hospital admissions and Emergency Department visits to Traumatic Brain Injury and of these, 75 percent were mild TBIs (Sarmiento et al., 2010). This also concurs with research by Ruff (2011) that says mTBI accounts for 80% of all reported TBI. It is also prominent amongst adolescents: in high school, concussion has been found to account for 8.9% of all athletic injuries and 5.8% of all college athletic injuries (Gessel et al., 2007). Statistics for Europe are harder to come by but in the U.K the latest statistics by the brain injury association Headway (2017) for 2016-17 reveal that every ninety seconds somebody is admitted into hospital with an acquired brain injury (ABI). ABI encompasses any injury sustained since birth excluding neurodegenerative conditions thus TBI is the most common form of ABI (Headway, 2015). Each year in the U.K there is a total of 155,919 head injury admissions which equates to somebody being admitted to hospital with a head injury every three minutes (Headway, 2017).

The estimation of prevalence of concussion by Langlois et al. (2006) and other similar estimations are within such a large range due to the variances in the definition of the injury, the diagnosis criteria and the location of data collection (Engle and Kerns, 2011). Additionally a large proportion of concussions go unreported (Delaney et al., 2002) which is why it is speculated that more concussions are sustained and hence why the higher estimation of 3.8 million is given as well as the lower 1.6 million. This is because there just is not a definitive way of recording how many concussions are sustained as individuals tend to not report to their injury to doctor’s practices or emergency rooms where the statistics are recorded as there is still a view that a concussion is not a serious injury and it is not necessary to be treated for it. Surveys have found that almost a third of athletes have sustained an undiagnosed concussion (Voss et al., 2015). Covassin et al. (2007) identified that many coaches and trainers working with athletes do not utilise the proper concussion protocols for its assessment and management and although it is unclear as to why this is the case it could be another factor as to why there are such variable statistics and incidences of concussions over the years. For if the concussions are not being managed in the initial stages or even picked up as a potential concussion then it is less likely that the athletes will have the forethought to visit a medical practitioner on their own without receiving advice from their coaching staff saying to do so. It has been found that physician observed games have a higher rate of concussion (Voss et al., 2015) but it is highly doubtful that the actual rate is higher just the presence of a trained physician means the concussions are spotted and reported. Another explanation for concussions not being reported is that individuals do not have a complete understanding of the injury with regards to its signs and symptoms thus are unable to identify whether they have sustained the injury. This lack of understanding is possibly due to the many misconceptions surrounding concussion such as loss of consciousness and post-injury amnesia. In the sporting environment players are less likely to report when they have a concussion or when they suspect they might as it means they have to be removed from play, which is the last thing a player wants. Lastly an interesting statistics that can to like is that according to Headway for the UK population it has been found that males are 1.5 times more likely to admitted for a head injury but that female admissions are up by twenty three percent since 2005-6 (Headway, 2017). These gender related statistics are noteworthy as the statistics could be due to the part sport and physical activity plays in the number of head injuries that are sustained. It is well known that there are more males participating in sport and physical activity than women with a gap in the UK of 317,000 between them with men being more active However in the last few years sports participation numbers for women has risen considerably due to Sport England's 'This Girl Can' campaign showing an increase of 250,000 women participating between 2014 and 2016 (England, 2016) therefore this increase in participation could be a factor as to why head injuries hospital admissions for women have increased.

Sports-Related Concussions

Over the past two decades, concussion has been at the forefront of debate in the sporting world and scientific community alike. The spotlight is heavily on the sporting world with many high profile cases of concussion in the news and sporting world that have piqued the public's interest and highlighted the issues surrounding concussion. It is a worldwide matter; over in the USA a large concussion-related lawsuit was brought and a settlement approved by approximately five thousand former football players suing the NFL (BBC News, 2014). The players accused the NFL of hiding the dangers of head trauma and the known risks of concussion in order to keep players competing and maintain the league's and sport's image. In the United Kingdom cases in RFU have hit headlines over how suspected concussions sustained during a game are treated and managed in regards to returning to play. There has been large amount of media attention on rugby players who sustain hits to the head during international matches were not removed from play despite showing some signs of concussion (BBC Sport, 2015). Media attention continues to surround rugby players who are reported to sustain multiple concussions in short period of time and in matches where they are not removed from play for assessment after hits to the head (BBC Sport, 2016). These types of events and reports spark further debate over the concussion protocols in place during matches and how they can be improved to better improve the safety of players. Furthermore there has been mounting research into the potential long term detrimental effects of concussion on cognitive health and recently multiple players in the rugby premiership league have been forced to retire early at the age of 30-32 years old based on medical advice related to concussion (BBC Sport, 2017).

Even the lesser publicised sport of field hockey has gained the attention of the media because even though hockey is a non-contact sport, it is one of the fastest team sports with the rules constantly evolving making the game much quicker. Therefore the risk of accidental collisions much higher between players but also between the equipment: composite carbon-fibre and Kevlar enforced sticks and balls (Gardner, 2015). With the media reporting various Great Britain athletes side-lined for major tournaments due to sustaining a concussion from an accidental collision with an opponent's shoulder and one athlete labelling it 'easily the worst injury they have ever had' (BBC Sport, 2018). Which is coming from the experience of an athlete who has no doubt experienced the pain of being struck by wayward hockey ball within the close quarters of the shooting circle that can easily travel up to 80km/h (Gardner, 2015). According to Lincoln et al. (2011) there was a 4.2 fold increase in the number of sports-related concussions from 1997-1998 to 2007-2008 representing in an annual increase of 15.5 percent. Although it is unclear as to what exactly has caused this increase; is it possible that due to the media attention and better awareness and education of concussion to the sporting population people are reporting concussions more and seeking medical attention more than before as they are able to recognise the signs and symptoms of a potential concussion or is it because the actual incidence rate has increased? And if so, is this linked to players receiving more strength and conditioning work as sports science techniques are always improving and creating players that are stronger and faster than those before them.

This vast number of concussions and the trend of concussion rates increasing from year to year indicates just how important concussion research is as it affects such a large population for it not only affects the sporting community but also the general population as the risk of concussion still exists in everyday life although its prominence and risk is just higher in sports which is why SRC is the main focus. There is a risk of concussion in nearly all sports regardless of whether it is a contact or non-contact sport but of course some sports have a higher risk and frequency of concussion than others. Firstly, before taking into account the type of sport the risk of concussion is three to fourteen times higher in competitive matches and games than in training or practice across a variety of sports and genders. In field hockey the injury rate is twice as high in games than in practice and head injuries were the only type of injuries to increase over the time from 1988-89 to 2002-03 becoming the most common injury in the game in number and rate (Dick et al., 2007). Clay et al (2013) detailed that 68.5 percent of concussions occur during competition. Gender also has an impact on rate of incidence of concussion with various studies showing that in sex comparable sports the rate of concussion is higher in the female sporting population (Clay et al., 2013). There was just one exception for this trend of concussion incidence which was lacrosse where the frequency of concussions was higher in males than females.

These differences could be explained by Daneshvar's (2011) research which highlighted the patterns in reporting of concussion by athletes and it was found that females were better at reporting their concussions. Therefore it is not necessarily the incidence rate that is at play here but actually the rate of reported concussions which could be a huge difference. In regards to the reversed lacrosse incident rate the actual reason behind it has not been explored but it could be attributed to the substantial difference between the two games in regards to the rules of the male and female games in which contact is allowed in the former but not the latter.

Definition of Concussion

An initial definition of concussion by Wilfred Trotter (Rogers, 1938) stated that concussion was an instantaneously occurring transient state which displays multiple symptoms but does not show any structural cerebral injury and is always followed by amnesia from the moment of injury. Although this definition is largely unchanged and similar to the current widely accepted definition by McCrory et al. (2017), the last two decades have shown a major change in the definition of concussion in regards to loss of consciousness and/or amnesia. Up until the late 1990s loss of consciousness was deemed to be a key determinant of whether an individual had sustained a concussion, (Carson et al., 2014, McCrory et al., 2005) this has since been found to be incorrect. While an individual may lose consciousness after sustaining a concussion it does not happen on every occasion as a concussion can be sustained without loss of consciousness or post-traumatic amnesia. Therefore these two symptoms can be an indication that an individual has sustained a concussion but not conclusively determining factors that they were once thought to be.

The definition of concussion has been developed over the recent years due to numerous conferences with the leading researchers and experts on concussion coming together to discuss the latest advancements. The international conference on concussion in sport first came together in 2001, the main aim of the conference was to provide recommendations on concussion assessment and management of the injury to improve the health and safety of players (Aubry et al., 2002). The international concussion conferences occur every four years since their commencement in 2001 where it was discussed and agreed that the guidelines must be updated to keep them relevant and appropriate as new research and information is published furthering the understanding of the injury. The group of experts that lead these conferences are referred to as the concussion in sport group (CISG) and have met five times to date to ensure the definition of concussion is based on current literature and that the protocol for the assessment of concussion is not outdated. They discuss and implement changes to medical procedure for treatment of concussion within sports club and also referral of concussions to medical practitioners as the CISG has devised a tool called the Concussion Recognition Tool (CRT) to aid non-medical personnel such as coaches to identify possible signs and symptoms of a concussion and can advise the athlete on how to get treatment. They also developed the Sport Concussion Assessment Tool (SCAT) for use by medical professionals only for initial assessment of a concussion but also can be used to follow an athlete recovery and ensure they are back to full health before returning to play (RTP) after sustaining a concussion.

The latest definition of concussion by the CISG at the 5th International conference on concussion in sport is defined as a “traumatic brain injury caused by biomechanical forces which may be either a direct blow to the head or an impact elsewhere with the force being transmitted to the head with it typically resulting in rapid onset of short term neurological function which resolves itself naturally (McCrory et al., 2017). Concussion has a complex pathophysiology process that affects the brain, following a concussive injury a neurometabolic cascade of events is initiated disrupting multiple functions of the body.

Pathophysiology of Concussion

The term concussion comes from the Latin verb *concutere* which translates to 'shake violently' (Bey and Ostick, 2009) which provides us with the basic understanding that a concussion occurs when the brain is shaken violently within the skull. This 'mechanical shake', referring to the acceleration and deceleration forces of the brain due to the impact, immediately initiates the complex cascade of neurochemical and neurometabolic events behind a concussive injury (Signoretti et al., 2011). The biomechanical injury results in ionic flux and glutamate release due to defects to the membrane created by the traumatic injury. This ionic flux is linked to the common symptoms individuals experience after a concussion such as headaches/migraines and sensitivity to sound and lights (Giza and Hovda, 2014)(table 1). Subsequently causing a plethora of neurotransmitters to be released, particularly excitatory amino acids, which doesn't help stabilise the ionic flux (Barkhoudarian et al., 2011).

In order to try and restore the ionic and cellular homeostasis the Adenosine Triphosphate (ATP)-requiring membrane potassium/sodium pump works harder. This causes hyperglycolysis resulting in the intracellular energy reserves being depleted thus creating an energy crisis (Giza and Hovda, 2014). Although the reason behind it is unclear, cerebral blood flow seems to be reduced which also further clarifies the energy crisis as it means cells receive less glucose. Animal research has shown that this metabolic state can last between 7-10 days and although it was initially undetermined if this state meant the brain was relatively protected from secondary injury (Giza and Hovda, 2001). Further research cleared this up and showed that the brain is in fact in a more vulnerable state as it is unable to respond adequately to further energy demands (Giza and Hovda, 2014).

The biomechanical forces also cause stretching of axons causing disruption to microtubules and possible axonal disconnection but at the very least axonal dysfunction which is attributed to the slow cognition and reaction time players may exhibit after a concussion. Impaired neurotransmission is also noted to be a behind the same symptoms (Table 1) as it is difficult to differentiate the contribution of the two events in the neurometabolic cascade to these concussive symptoms (Giza and Hovda, 2014).

Physiological Perturbations After Concussion and Proposed Clinical Correlates	
Post-TBI Pathophysiology	Acute Symptom
Ionic Flux	Migraine headache, photophobia, phonophobia
Energy Crisis	Vulnerability to second injury
Axonal Injury	Impaired cognition, slowed processing and/or reaction time
Impaired Neurotransmission	Impaired cognition, slowed processing and/or reaction time
Altered cytoskeletal proteins, cell death	Chronic atrophy, persistent impairments

Table 1: Links between the mechanisms involved in the pathophysiology of concussion, to common symptoms experienced by individuals who have sustained a concussion adapted from Giza and Hovda (2014).

Although these biochemical modifications are reversible and will resolve themselves spontaneously this concussion induced pathophysiological condition puts the brain in a vulnerable state during which if a second impact is sustained the brain is more susceptible to a more severe and irreversible cellular injury (Signoretti et al., 2011, Barkhoudarian et al., 2011, Bey and Ostick, 2009).

Second Impact Syndrome

Research into brain injuries and subsequent changes to sporting rules and pitch-side medical aid by national governing bodies in the last two decades has dramatically decreased the more serious brain injuries such as subdural haematomas however the same cannot be said for concussions (Cantu, 1998). Whether this is down to increased awareness and being able to identify the phenomenon as to why a spike in incidences has occurred or whether the actual rate of incidences has increased is speculation but it is assumed the reason is due to better awareness and education of medical professionals reporting the injuries. The incidences of concussion increasing is problematic as there have been rare occurrences of death following a concussion. Although the two are not distinctively linked to each other as the relationship and pathophysiology is complicated but research has shown that two concussions sustained in a short period of time heighten the risk of death. For if two mTBIs occur within a too short space of time they can elicit the same effects of a single severe injury (Signoretti et al., 2011).

This phenomenon is called second impact syndrome, media attention was drawn to this in 2011 when the first incidence of a death attributed to second impact syndrome occurred in the UK (Bull, 2013) after a child playing rugby union died following multiple hits / two missed concussions in a rugby match due to officials and coaches not following or knowing the latest concussion protocols and SCAT of the time. Although the media is only just catching wind of second impact syndrome, it was first described in the scientific research community in 1973 by Schneider and then Saunders and Harbaugh devised the term for it as 'second impact syndrome' in 1984 when describing the events surrounding a nineteen year old American football player who sustained a brief loss of consciousness after head injury but returned to play and then on the fourth day collapsed and subsequently died (Wetjen et al., 2010).

SIS occurs when an athlete sustains an initial head injury but before they are asymptomatic from the first injury they have returned to play and suffered another injury to the head (Cantu, 1998, Cantu and Gean, 2010). The concussed brain is in a vulnerable state and if more disturbance is sustained, such as a second impact, before metabolic homeostasis has occurred then the risk of a more debilitating injury is heightened (Leddy et al., 2012). The symptoms from the initial concussion include, but are not limited to, headaches, dizziness, nausea, fatigue, impaired balance, lethargy, irritability, personality changes and/or disrupted cognitive processes such as memory and thought (Cantu, 1998, Cantu and Gean, 2010, Bey and Ostick, 2009, McLendon et al., 2016, Bowen, 2003). The second impact does not have to be a big one, it can be a minor one to the head or even a minor impact to the chest which indirectly injures the brain from the acceleration forces going to the head. Within seconds to minutes the athlete goes from being in control and standing, to collapsing on the ground to a semi-comatose state which is determining element as to why SIS is different to that of a concussion of a subdural haematoma and why it is a syndrome on its own (Cantu and Gean, 2010).

The pathophysiology of SIS is what brings the syndrome under scrutiny and its existence questioned as the etiology and pathology is not completely clear (Mori et al., 2006, McCrory, 2001 cited by). McCrory (2001) questioned the reliability and therefore occurrence of second impact syndrome as in some of the case studies on SIS the reporting of the incidents relied on anecdotal reports by other athletes that witnessed it therefore the recall was not necessarily accurate. Additionally in many of those cases it was deemed that the athletes did not sustain a second impact hence why McCrory (2001) is questioning how it can be SIS and not just the known but rare and delayed complication of a single brain impact called diffuse cerebral swelling he previously discussed (McCrory and Berkovic, 1998). It is accepted that SIS is caused by loss of autoregulation of the cerebral blood vessels and arteries. After the initial head injury the brain's auto regulatory mechanisms compensate for the physiological stress and protect from swelling by limiting cerebral blood flow but after sustaining the second impact the brain loses its ability to regulate the intracranial pressure. (Bey and Ostick, 2009, McCrory et al., 2012). This leads to swelling in the brain, increased intracranial pressure and subsequently in severe cases causes a brain herniation and cerebral oedema (Cantu and Gean, 2010).

Further research is needed to fully understand the mechanisms behind this syndrome and to ascertain the level of risk it poses to the sporting community. Despite the controversy and misunderstanding surrounding SIS, its constant appearance in medical literature, anecdotal reports and news reports makes it an important aspect of concussion management. For although there are no current statistics available on second impact syndrome making the incidence rate and occurrence of it unknown (Wetjen et al., 2010) it still underpins RTP guidelines following concussion as this rare syndrome can be a fatally serious consequence of concussion and multiple head injuries. Even though it is predominantly based around concussion sustained in children and adolescents (Leddy et al., 2012) there have been case studies on young adults and college athletes aged between twenty and twenty-four, (Cantu, 1998, Mori et al., 2006) who have suffered and even unfortunately died from second impact syndrome, so SIS is not limited to the population of children and adolescents. For that reason its existence is a strong factor along with countless other reasons as to why RTP guidelines are in place and it is so important that they are adhered to protect the athlete from further harm or long-lasting debilitating injuries.

Difference between Adult & Children

It is important to note that concussion should be treated and managed different for children and adults. Whilst it was previously thought back in the 1940s that if you were going to have a brain injury you should do it early, known as the ‘Kennard principle’, it was supposed that sustaining a concussion during childhood/adolescent would have better outcomes due to the increased plasticity you have when young (Reed et al., 2016). However research from 1949 onwards began to contradict this principle when Hebb found children with frontal lobe injuries had more severe and debilitating injuries than adults with the similar injuries (Engle and Kerns, 2011). Children have weaker neck muscles than adults and due to not being fully grown their large heads are slightly out of proportion with the rest of their body which means that they are more susceptible to the impulsive forces that lead to mTBIs (Engle and Kerns, 2011). Additionally their brains are still developing so symptoms and the effects of a concussion might be more pronounced than adults and they may present symptoms in different ways (Halstead et al., 2010).

Possible long term effects of multiple concussion and repeated head injuries

Recently in the last decade there has been lots of discussion over the potential long term debilitating effects that concussion and multiple concussions can have on the brain and the one such degenerative brain disease that is linked to repeated brain injuries and concussions that is worrying the sporting community with its prevalence and media attention is Chronic Traumatic Encephalopathy (CTE). The first description of the persistent neuropsychiatric symptoms that boxers were displaying from repeated head injuries was labelled as 'punch drunk' by Martland (1928). Prior to Martland's paper, there was no mention of the condition in medical literature despite it being plainly obvious and well known to all involved in the sport of boxing with spectators nicknaming the state boxers got into various names such as 'slug nutty', 'cutting paper dolls' 'goofy' or 'cuckoo' (Martland, 1928). Martland noted that one of the initial symptoms boxers exhibited was a 'slight unsteadiness in gait or uncertainty of equilibrium' and could be seen as early as during the fight but also explained the chronic nature of some of them such as a gait similar of that in Parkinson syndrome, tremors, vertigo and even mental deterioration (Martland, 1928).

Martland's publication was a pivotal moment in the medical community as prior to his paper post concussive symptoms were not recognised with many distinguished physicians dismissing boxers seeking treatment, as they considered there was no link between boxing and repeated head trauma and their persistent symptoms (Changa et al., 2018). In 1937 Millspaugh expanded on Martland's initial exploration of the syndrome and renamed it 'dementia pugilistica' which took away the negative connotations of 'punch drunk' syndrome and this introduction of a Latin term helped improve its standing and credibility amongst the medical community (Shurley and Todd, 2012). Critchley suggested the term CTE in 1947 and then in 1957 added to it calling it chronic progressive traumatic encephalopathy as he identified that is a progressive condition that cannot be reversed and will always steadily get worse even after the athlete has retired and no longer sustains repeated head injuries (Castellani and Perry, 2017, Critchley, 1957 cited by). Critchley's case studies revealed that CTE did not present itself until a number of years after the start of boxing ranging from six years to forty years and the average being sixteen years after retirement from the sport (Critchley, 1957). An important factor into the development of the condition is the sum total of contests not just the occasions they were knocked out therefore indicating it is the quantity of impacts not just the hard impacts (Shurley and Todd, 2012, cited by Critchley, 1957).

Despite the knowledge of CTE being around for many years, the research predominantly focussed on looking at former boxers and so it seems that nobody linked this well-known degenerative consequence of repeated head injuries in boxing to the similarities presented in other sports such as American Football until the twenty-first century (Shurley and Todd, 2012). As studies on the effects of cumulative and multiple head injuries on long-term cognitive function and related degenerative cognitive diseases is starting to mount within the scientific literature it is important that the way concussion is assessed in sport is re-approached (Guskiewicz et al., 2001). This means rethinking what new technology and assessments can be incorporated into concussion protocols to improve the reliability of assessments so that the initial injury can be properly diagnosed and managed in the early stages.

Assessment Issues

Assessment of concussion is difficult due to it being shown to be a functional injury rather than a structural one which is why no apparent abnormality can be seen on current standard neuroimaging such as MRI or CT scans following a concussion. (McCrory et al., 2017). These conventional brain imaging techniques just lack the sensitivity to detect the subtle changes that occur with a mTBI (Slobounov et al., 2012) therefore providing no assistance when it comes to concussion assessment. Although advanced imaging technologies e.g. functional MRI (fMRI) or positron emission tomography (PET) may reveal the subtle abnormalities not visible to the naked eye or standard imaging (Haller, 2017) the research is still relatively new and when looking specifically at fMRI the findings have been quite confusing and conflicting (Slobounov et al., 2010). Furthermore these advanced brain imaging technologies are not available for widespread clinical use nor are they able to be used pitch-side for the immediate assessment of concussion (Lovell et al., 2006).

Magnetic Resonance Spectrography (MRS) is an emerging technology that shows promise in influencing the clinical management of concussion and potential in the future to be a gold standard for concussion assessment. It differs from the other neuroimaging techniques as it detects signals from individual solutes to provide in vivo neurochemical information (Belanger et al., 2007). This enables it to assess the biochemistry of the brain non-invasively and provide biomarkers of neurological disorders even when nothing is observed by standard imaging methods (Gardner et al., 2014). Studies have revealed that MRS can still identify metabolic disturbances in sports-related concussion after clinical symptoms have resolved showing a delay between patients being asymptomatic and metabolic recovery (Difiori and Giza, 2010 citing, Vagnozzi et al., 2008). More research is needed to make the clinical relevance of this finding clear however it suggest that MRS can be significant in the management and return to play/work of athletes who have sustained a sport-related concussion (Difiori and Giza, 2010). MRS is still a relatively new technique so its ability to be a gold standard for concussion assessment is yet to be decided through more in depth research. Additionally, although MRS might become an important clinical tool for monitoring and managing the recovery of concussion, it is still no different to other advanced imaging technologies in terms of being able to assess pitch side or be widely available.

Currently there is no single, reliable biomarker for concussion and due to neurological imaging showing no consistent abnormalities for diagnosis this responsibility resides with the pitch-side physicians and trained medical staff to identify the possible signs and symptoms of concussion (Clay et al., 2013). This further highlights why concussion assessment is difficult as not every sport has pitch-side medical staff and even those sports that do, it is not available all the way down to grass roots. Additionally if there are suspected concussions during play, the assessment normally has to take place under strict time constraints and with an athlete eager to get back in to the game (Putukian et al., 2013).

Headaches	Dizziness	Sensitivity to noise	Difficulty concentrating
Pressure in head	Blurred vision	Feeling slowed down	Difficulty remembering
Neck Pain	Balance problems	Feeling like 'in a fog'	Fatigue of low energy
Nausea or vomiting	Sensitivity to light	Don’t feel right	Confusion
Nervous or Anxious	Sadness	Drowsiness	More Emotional
Irritability	Trouble falling asleep		

Table 2: List of symptoms from the SCAT5 that athletes are asked to rate on a scale of 0 (none), 1-2 (mild), 3-4 (moderate) to 5-6 (severe).

One stage of concussion assessment is observation of injury but this is tricky as a concussion can be a result of an impact to any part of the body provided the impulsive forces from the impact are transmitted to the head causing the abrupt acceleration and deceleration of the brain that start the cascade of events leading to a concussive injury (McCrory et al., 2017). Diagnosis of a concussion is also a clinical judgement made by a medical professional and as state previously not all sports take place with medical personnel present, therein identification of suspected concussions are often missed and no assessment carried out.

Identifying the signs and symptoms is another difficult aspect as there is no single distinctive sign or symptom that identifies a concussion. There are a multitude of symptoms (Table 1) related to concussion and they vary depending on the individual and even these can change between incidents. If an individual has sustained a concussion previously they would not necessarily present with the same signs and symptoms in the case of a second concussion.

Additionally many of the symptoms associated with concussion can be present in everyday life such as a headache, fatigue, drowsiness or irritability and an athlete may have been experience them prior to beginning the game/training thereby confusing reporting of symptoms for potential concussions. Research has found that an athlete presumed to have a slow recovery from concussion several months post-injury was in fact suffering from a pre-existing anxiety disorder mimicking the signs of post-concussion syndrome (PCS) (Lovell et al., 2006). This is helps highlight that symptoms should not be used in isolation to assess concussion but as one facet of a multifaceted approach to concussion assessment.

The current widely used concussion assessment was devised by the CISG called the Sport Concussion Assessment Tool (SCAT) with the latest version being SCAT5 (McCrory et al., 2017). The SCAT5 is a multidimensional approach to concussion assessment incorporating various cognitive tests, balance assessments and symptom evaluation. The initial steps of the SCAT5 on field assessment comprises of Maddock's Memory assessment, the Glasgow Coma Scale and a cervical spine assessment, thereby aiding in the elimination of any serious injury (McCrory et al., 2017). Within the SCAT5 athletes are asked to rate their symptoms from 0 (none) to 6 (severe) with a total of 22 listed (table 2).

This self-reporting of symptoms opens up concussion assessment to manipulation by players as they can deliberately under report their symptoms in order to try and avoid detection of a suspected concussion so that they can RTP. This can also occur after an athlete has received a concussion diagnosis and are going through the graded RTP stages they may report they are asymptotic in order to speed up their recovery (Guzman and Aktan, 2016). Additionally they may not be aware that the symptoms they are experiencing are linked to concussion (Broglio and Puetz, 2008).

In order for the SCAT5 to be most effective, pre-season testing is required to provide individual baselines as this helps quantify cognitive deficits when assessing for a suspected concussion during the season (Iverson and Schatz, 2015). It is especially important for individuals with above average or below average cognitive abilities that a reliable baseline is obtained to prevent any discrepancies from normal scores to lead to a misdiagnosis when assessing post-injury (Iverson and Schatz, 2015). When taking baseline measures it is important that it impressed on athletes to do their best as it has been known that some athletes deliberately perform badly during their baseline concussion test in order to have a negative diagnosis of concussion when assessed post-injury this is commonly known as 'sandbagging'.

Concussion assessments are focussed around balance tests and tests of cognitive function and ability because of the many symptoms associated with concussion, the two initial symptoms that present themselves are balance and cognitive deficits (Slobounov et al., 2011). Guskiewicz et al. (2000) reported that thirty percent of individuals who have sustained a SRC report balance dysfunction and seventy-five point six percent reported dizziness, thus accentuating why assessment is centralised around measuring athletes' ability to balance.

Balance Importance

Balance and posture control involves the complex integration and coordination of three major sensory systems working together: the primary being vision with the other two being the vestibular and somatosensory systems (Winter, 1995). Athletes suffering with a concussion display deficits in neurocognitive function such as information processing and these areas of the brain that are affected by the injury are responsible for maintaining balance (Guskiewicz et al., 2001). Balance deficits are most pronounced in the initial 24 hours post-injury but usually last up to day five post injury (McCrea 2003) hence why concussion assessment relies heavily on measures of balance for initial diagnosis and monitoring of recovery.

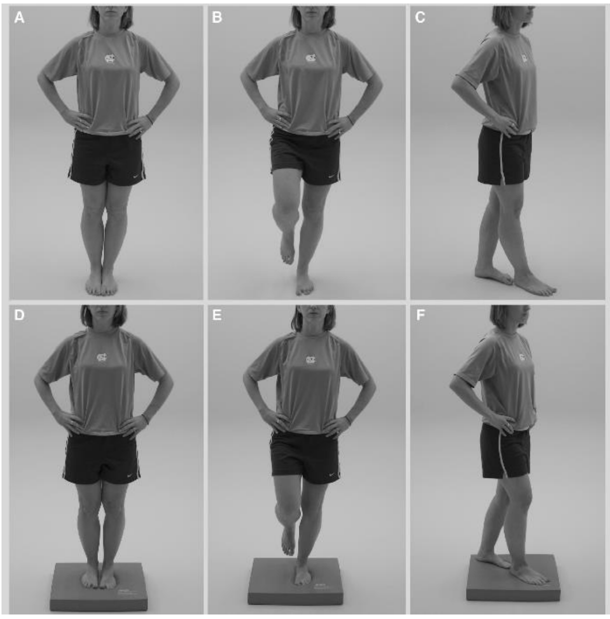

Figure 1: Example of BESS stances from Bell et al. (2011).
a-c (from left to right) double leg stance, single leg stance and tandem leg stance on the firm surface. These first three stances on the firm surface are the ones used in the mBESS. **d-f** are the same leg stances as **a-c** respectively but on the foam surface.

The current most commonly used evaluation of balance by clinicians and researchers is the Balance Error Scoring System (BESS) as it is a cost effective portable method of assessing static postural stability. It is useful as it takes approximately 10 minutes to administer and there is a modified version (mBESS) that takes even less time which means it can be included in pitch-side concussion assessments that sometimes restricted to be undertaken within 10 minutes for example in RFU a Head Injury Assessment (HIA) needs to be completed within 10 minutes of the player leaving the playing field otherwise the temporary replacement has to become permanent and that player is not allowed to return to the field.

The BESS entails three different stances to be performed on two different surfaces: firm (ground) and foam. For all of the stances the eyes are closed, with hands on the iliac crests, and the given foot position of the stance with shoes removed. The first stance is a double leg stance with feet together (Fig). The second stance is a single leg stance with the standing leg being the athlete's non-dominant leg and their dominant leg raised and held at 20° of hip flexion and 45° of knee flexion (Fig). The final stance is a tandem stance with the non-dominant behind the dominant foot with them touching heel to toe (Fig). Participants are asked to hold each stance on the two different surfaces for 20seconds with the six trials assessed on a set of errors (table 3). The physician carrying out the test is to determine whether the participant has made errors and total up errors giving a score out of sixty.

Hands off the hips	Abduction or flexion of the hip beyond 30°
Opening the eyes	Lifting forefoot or heel off the testing surface
Step, stumble or fall	Remaining out of the testing position for >5secs

Table 3: List of BESS Errors. If multiple errors occur simultaneously only one error is recorded and the maximum number of errors for any single trial condition is ten therefore the total score for the BESS being out of sixty and thirty for the mBESS.

The mBESS included in SCAT5 consists of the three stances performed only on the firm surface thus scored out of thirty instead. The judgement of errors in both the BESS and mBESS is why this balance assessment has come under scrutiny as it relies on subjective measures of errors and can lend itself to interrater discrepancies which can affect the test-retest reliability. The first study on the reliability of the BESS was performed by Riemann et al in 1999 and found the inter-tester reliability was 'good' but this was not based on the total BESS score, which is the most used score within the BESS, only four of the individual stances (Bell et al., 2011). Finnoff et al. (2009) performed a more in depth analysis and found that the total BESS score only had a moderate intra-rater and inter-rater reliability with intra-class correlations coefficients (ICCs) of 0.74 and 0.57 respectively. The reliability for individual stances varied widely with intra-rater ICCs of 0.50-0.88 and inter-rater ICCs of 0.44-0.83. Consequently showing that whilst certain stances of the BESS may be sufficiently reliable for postural stability, the BESS in its entirety is not reliable (Finnoff et al., 2009). A study on the modified BESS by (cited by Bell et al., 2011), Hunt et al. (2009) found a similar result of moderate intra-rater reliability ICC of 0.60 which is not sufficient reliability. These findings of insufficient reliability helps highlight why this study is essential to the improvement of concussions testing through balance tests as inclusion of emerging technologies into these tests will enable to overcome the limitations of the current test and enable us to eliminate the subjectivity of assessors.

As postural stability has been found to be the main indicator of concussion, (Teel and Slobounov, 2015) it is important that subjective aspects of the current balance tests are removed and an objective measure is put in its place which can reliably assess postural stability and thus aid in the detection of possible concussions. Use of computerized systems and sensors can give objective measures of balance and provide the much needed more sensitive and specific balance tests (Mancini and Horak, 2010). Centre of Pressure (COP) is the main index of postural stability and the gold standard of measuring it is a laboratory grade force plate (FP). However in order to use a balance test in concussion protocols it needs to be portable and inexpensive so it can available to a large range of sports clubs. Many studies have looked at alternatives to a FP and found that a Wii balance board (WBB) provides a reliable alternative for COP measurements. The use of four transducers to detect force distribution in WBB and resultant movements in COP are very similar to that of a laboratory-grade force plate. Clark et al. (2010) compared the FP and WBB and found that both devices presented a good to excellent test-retest reliability on COP path length for both within-device and between-device reliability. Therefore suggesting that the WBB is a valid tool for assessing static standing balance. Huurnink et al. (2013) also compared a FP and WBB but did it simultaneously by placing the WBB on the FP. Their findings concurred with the results from Clark et al. (2010) that there was a good correspondence of balance measures between the two devices and that the WBB is sufficiently accurate in quantifying the trajectory of COP (Huurnink et al., 2013). Pavan et al. (2015) also directly compared the WBB and FP simultaneously and confirmed that the WBB could be used as a tool for standing balance assessments by using typical measurements such as COP sway path. Consequently validating the use of the WBB to develop an objective balance assessment for use in concussion assessment that can be paired with a VR system. This corresponds with the aim of this study to certify an objective balance test involving VR can be performed pitch side so that it can be implemented as a sports related concussion assessment.

Effects of Exercise on Current Balance Tests used in Concussion Assessment

When using a measure of balance to evaluate postural control and subsequently assess whether a SRC has been sustained it is important to establish that it can only be the injury that is causing the deficits in balance not another confounding variable. Due to the nature of SRC they occur whilst the individual is participating in a sport or physical activity. Accordingly they are not at rest when they sustain the suspected concussion so it is important to understand the implications of that physical exertion on their ability to balance and thus the ramifications on any possible concussion assessments.

Numerous studies have been conducted on the current gold standard balance assessment used in sports related concussion assessments called the BESS and how exercise affects its ability to aid in concussion assessment. Research by Fox et al, using a total BESS score as its measurement, found that postural control was negatively affected by both aerobic and anaerobic exercise with the effect lasting up to 13 minutes before returning to baseline levels

(2008). This indicates that when using the BESS to determine a suspected concussion it is not useful for immediate pitch-side assessment of an athlete as a minimum of 13 minutes needs to elapse before the results of the BESS can be a result of a suspected concussion rather exercise induced fatigue affecting the balance results. Susco et al. (2004) also discovered similar findings when administering the BESS after participants completed a station based exertion devised by Wilkins et al. (2004) comprising of jogging, sprinting, push-ups, sit-ups and step-ups. They found that there was a decrease in BESS performance after the exercise program and did not return to normal until 20 minutes after exercise (Susco et al., 2004). Consequently the objective of this study is to investigate the effects of exercise induced fatigue on our novel Virtual Reality (VR) WBB balance test. As its use as sports related concussion assessment is dependent on it having no effects of exercise on its reliability and validity to function as an effective balance test pitch side.

Incorporating Innovative Virtual Reality Technology

Although balance is the main indicator of concussion and is the most apparent for initial assessment it has been found that deficits in cognitive function can be apparent from weeks to months (Shaw, 2002). This makes inclusion of cognitive tests within the initial assessment necessary but more crucially, essential for RTP and serial testing to monitor improvement and progression of the injury. This is where the inclusion of the ever evolving and advancing VR technology becomes advantageous as the assessment can become a dual task paradigm through combining the balance test with a cognitive assessment in the virtual environment (VE). One of the major downfalls of the current balance tests for concussions is the subjective measurement of balance but this could be overcome by the inclusion of VR as it has the ability to detect more subtle changes in individuals' balance control (Nolin et al., 2012). Furthermore it has the capability to assess cognitive process such as depth perception in a 'real life' scenario (Slobounov et al., 2011) whilst still being in a controlled computer generated environment to prevent any further injurie. When combined with a WBB for COP measurements there could be no issue with unreliable subjective measurements of balance. Another benefit of using VR as part of the balance test for concussion is that it is able to notice balance deficits thirty days after a concussion which is not only crucial in initial assessment of a concussion but also for following assessments to monitor athletes recovery and graded return to play (GTP) to ensure they are fully recovered and show no signs of cognitive deficits before returning back to play (Slobounov et al., 2006, Teel and Slobounov, 2015).

VR technology has improved vastly from its inception in the 20th century when it was recognised that through the use of computer generated visual scenes projected on to a screen could cause the perception of ego motion in individuals (Warren, 1976). This discovery lead to numerous studies investigating the impact of an alteration of the visual scene on postural stability with various methods being used from tilting rooms or swinging rooms (Lee and Lishman, 1975) to projected computer displays on a large screen (Keshner et al., 2004, Keshner and Kenyon, 2004, Mergner et al., 2005) to the most currently used head mounted devices (HMD) (Akizuki et al., 2005) . A perturbation of the visual field in the VE causes a conflict between the vestibular, somatosensory and visual systems that are responsible for postural control. When one of these sensory inputs is removed or altered then postural stability is reduced as the systems are reporting different information concerning what they sense to be moving or stationary (Mergner and Rosemeier, 1998, Broglio and Puetz, 2008, Keshner and Kenyon, 2004). When the visual scene is manipulated it is going to have a more profound effect than if other systems' information was altered as vision has been found to be the 'most efficient source of proprioceptive information for balance control' (Lee and Lishman, 1975). Additionally if the individual is in an unfamiliar position they would not normally be in, such as feet together quiet standing, the proprioceptive information is unreliable for postural stability (Lee and Lishman, 1975). Therefore the other systems that control balance and postural stability, i.e. the visual system, has to play an even more important role in controlling an individual's balance (Horak et al., 1997). Consequently causing a bigger visual-vestibularsomatosensory conflict which urges the individual to adapt to the visual field given to them in the VR and in this adaptation process individuals may show postural instability (Akizuki et al., 2005).

'A perturbation is a sudden change in conditions that displaces the body posture away from the equilibrium' (Horak et al., 1997). The foundation of our VR balance test is the use of a perturbation in the visual field to create a conflict between the sensory systems that control balance in order to assess a participant's cognitive ability whilst being assessed on quiet standing. Some trials there will be no perturbation in order to assess purely balance but in the others the VE will be perturbed by tilting in the roll axis which through our own previous unpublished research was found to be the most destabilising axis. This coincides with Gresty and Bronstein's (1992) research that visual inadequacy occurs in the roll plane rather than in pitch or yaw due to the eye's limited reflex ability to roll. This tilting in the roll axis will form part of the cognitive assessment as the individual will need to decipher which stimuli to respond to in order to maintain their balance whilst standing on the WBB through which the COP measurements can obtain an objective quantifiable measurement of balance can be determined. It is hypothesised that whilst healthy participants will be able to withstand the confusion of the conflict and adequately adapt to it in time to maintain their balance, individuals who have sustained a concussion will not be able to react and adapt as well or in a timely fashion therefore will experience balance dysfunction due to the reduction in cognitive ability associated with concussion. Various research by Slobounov et al. (Slobounov et al., 2012, Teel and Slobounov, 2015, Teel et al., 2016, Slobounov et al., 2013, Slobounov et al., 2006, Slobounov et al., 2011) has already started to show the advantageous use of this concept in the concussed population by identifying that although balance deficits appear for 10 days post injury and resolve.

Abnormal results are still recorded up to 30 days post-injury (Slobounov et al., 2006) thus highlighting the distinct benefits this technology has over the current old-fashioned balance tests used in concussion assessment. It is these residual abnormalities that will be vitally important in regards to making RTP decisions about athletes (McCrory et al., 2013) and crucially aiding in the prevention and minimisation of risk for further head injuries upon placing an athlete back in the field as they will be a more complete understanding that they are fully recovered.

Aims and Hypotheses

The primary aim of this study was to establish whether the current equipment, procedures and combination of the VR-WBB balance test could be performed outside of a laboratory and in a pitch-side setting in order to supports its assertions that it can be an objective and reliable measure of balance for use as a concussion assessment.

The secondary aim of this study was to investigate the effect of exercise, performed during sport specific matches and training sessions, on the VR-WBB balance test in order to understand and eliminate any possible factors that could alter an individual's ability to balance so that this test would be suitable in future to be used for the assessment and management of sports-related concussion.

Drawing on previous research and literature, hypotheses were made that the VR-WBB balance test can certainly be used in the pitch side setting without it affecting the production of objective COP measurements. The other hypotheses was that there would be an effect of exercise on the VR-WBB balance board.

CHAPTER 2

Method

This virtual reality based balance assessment has been tried and tested previously with voluntary healthy participants in a laboratory based setting in order to ascertain that the balance task is feasible and achievable whilst altering the scenes within the VR. This previous experiment also provided us with speeds and angles of tilt that the participants reacted best too, which was an important part of preparing the system.

In order for this virtual reality based balance assessment to be suitable for future assessment of concussion of an individual in a sporting environment it needs to be portable and usable pitch side and be able to withstand confounding factors such as exercise that could affect an individual's ability to balance on this assessment and obscure the results of a concussion test.

Participants

A sample of convenience was used which consisted of 14 female hockey players from the University of Birmingham Hockey Club. The head coach of both the women and male teams was contacted to establish a link with the coach and get the club on board with the study which meant that the testing was able to be done before and after their normal training session. All participants voluntarily took part in the study and prior to agreeing to take part in the testing sessions the participants were all given an information sheet explaining what the study entailed and what was required of them. It also detailed that they were entitled to withdraw from the study at any point during or after the testing protocols without needing any explanation and it would not affect how they are treated during the study.

Within the participant information pack was an inclusion/exclusion criteria in the form of a suitability checklist. Participant were unable to participate if they met any of the following criteria: if they had sustained a concussion or head-related injury in the past 12 months, if they had a history of epilepsy, if they had any existing balance deficits or they were pregnant or had given birth in the past 12 months. They were asked to carry out their normal daily routine prior to session as long as they were not participating in any high intensity aerobic exercise within a few hours prior to the session.

On arrival to the session participants were given an information sheet to refresh themselves with what the study entails and to give them an opportunity to ask any questions they may have about it before they begin. They completed a suitability checklist form to confirm they were eligible to participate and then they signed a consent form to participate. Additionally they completed a participant demographic form asking them for their age, weight, height and level of sports participation; club, regional, national or international.

This study was given a favourable ethical approval by the University of Birmingham STEM ethics committee and given the ethics code: ERN_17-0777

Virtual Reality Balance Board System

Our unique virtual environment (VE) was designed and created using the game engine Unity (Unity Technologies) and run using a high-spec ASUS (ASUSTek Computer INc.) Republic of Gamers gaming laptop. The participants were immersed in the VE using an Oculus (Oculus VR) Rift Development Kit 2 headset. A standard commercial Wii balance board (Nintendo, Kyoto, Japan) was used to obtain the centre of pressure measurements from the participants and was used in its original state with no modifications made to it. The VE created was a simple room in a house setting including everyday details such as sofas and dining tables in order to create a realistic environment for the participants to be immersed in. Upon immersion into the VE was orientated so that participants would directly face the board on the wall where the words for the Stroop task would be shown (Figure 2) however the participants were able to look around themselves a full 360° in all directions. Due to the nature of using VR this VE can easily be changed for future use to a more relevant sporting environment such as a football, rugby or hockey pitch to make it more realistic for the player. Additionally the VE can be changed to possibly vary the cognitive task on the wall from a Stroop task to another suitable immersion task or cognitive assessment task in order to give the VR test dual assessment qualities.

The Virtual reality based balance test was performed using the WBB which was connected to the laptop using its in built Bluetooth. The Bluetooth pairing was set-up prior to each testing session and the link between the laptop and WBB was confirmed by running the a mock up trial and calibration test to show that movement on the WBB was being picked up and recorded by the Unity program. The Oculus Rift VR headset was connected to the laptop via a simple HDMI and USB connection for the headset and the accompanying position-tracking infrared camera that sits on top on the laptop screen. Once plugged in the connection was confirmed that is was working prior to starting a testing session by running the Oculus configuration software which confirms that the graphics card, memory, operating system, processor and USB are all connected and meet the recommended specifications for Rift. The Oculus software also allows you to launch a demo scene to ensure that the VE moves and reacts as you move the HMD thus confirming it is working correctly before starting the Unity program ready for the participant's testing session.

The virtual reality based balance test consisted of one block of eight trials with each trial lasting twenty seconds. The duration was based on previous research that found that the optimum test retest reliability for measures of COP is for trials lasting between 20-30seconds (Doyle et al., 2007 citing, Le Clair and Riach, 1996). The first two trials were programmed to always be control trials so that an absolute baseline balance measurement could be obtained for all participants before any possible influence the perturbation trials may have on this measurement. It also prevents any participants having an apparent advantage or disadvantage due to complete randomisation of all trials. As previous research with this VR balance tool and complete trial randomisation highlighted that some participants started off with multiple perturbation trials in a row which created extreme responses and skewed the data. Therefore the first two trials were fixed to be control trials and then following six trials were randomised to be either a control or perturbation trial however these parameters were not known to the participants.

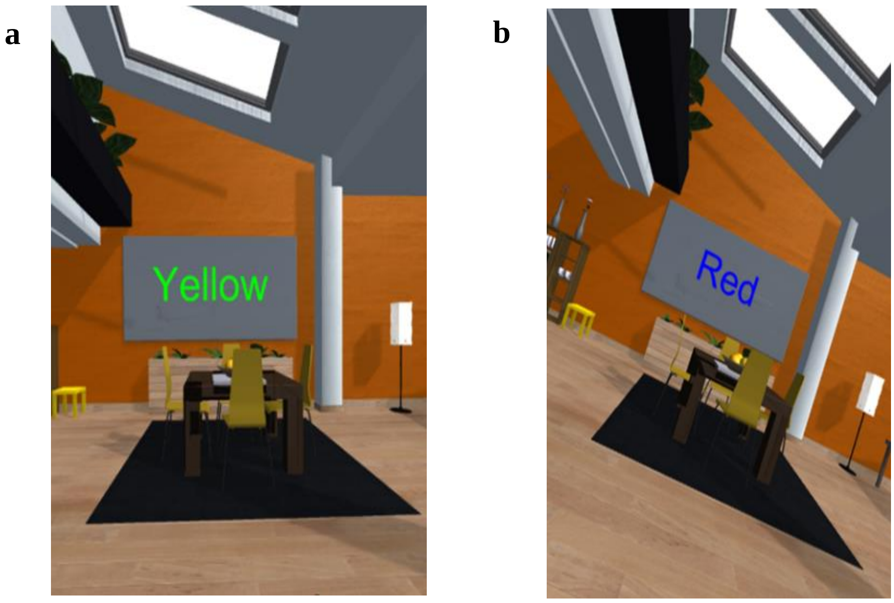

Figure 2: Screenshot of the virtual environment for the balance test.
What the participants saw during the balance test through the Oculus Rift VR headset with the Stroop task presented immediately in front of them.
a: An example of the VE during a control trial. **b:** An example of the VE during a perturbation trial showing the tilting of the VE room in the roll axis.

A control trial involved no tilting or manipulation of the VE (Figure 2a) whilst the participant maintained their balance stance on the Wii balance board therefore assessing just the individual's balance ability. The perturbation trials involved the VE tilting in the roll axis (Figure 2b) either left or right with the tilt occurring in a randomised fashion. The perturbation was randomised so that it occurred between 5-10 seconds to safeguard from participants anticipating of predicting when the perturbation would occur and reacting or preparing for it before it presented itself. The perturbation trial looks at the participants' ability to balance when a conflict between the sensory systems has been created through tilting the VE whilst their real life stays the same. Hence the visual system perceives the body to be off balance whilst the somatosensory system is feeding back from proprioception that the body is balanced. This conflict will be the crucial aspect of the VR balance test when progressing on to assessing concussed athletes as although some concussed athletes may be able to complete a standard control balance test their decreased cognitive ability might prevent them from being able to resolve the conflict in the perturbation trial.

Previous research on the axis and speed of perturbation in the VE found that there was no significant effect on COP sway path length when the speed of the VE tilting was changed. COP response was saturated between 5.6^{o}/sec and 11.3^{o}/sec so the optimal option for tilting speed of 7.5^{o}/sec was chosen for this study. It was also found that tilting in the roll axis had a greater

Figure 3: Virtual calibration balance test preceding each trial.
A screenshot of the calibration balance test to be completed prior to the beginning of the trial. Red dot signifies the participant's centre of pressure which they need to get it in the middle of the green circle as close to cross hairs as possible and to hold it for 3 second. The trial begins immediately after completion of this calibration task.

effect on COP sway path length than in the pitch axis so for this study only perturbations in the roll axis, with a total tilt angle of 22.5°, were used in order to limit the variables so that the focus could be on the effect of exercise.

Prior to each trial they had to complete a simple calibration balance test (Figure 3). The red dot shows their COP in real time and they have to make sure they kept it on the crosshairs or maintain the same COP position within the green circle until the virtual WBB disappeared which indicated the calibration was complete and the trial could commence. The calibration is there in order to help orientate the participant, it gives them real time feedback on their balance going into the trials and to ensure their COP is centralised on the board before assessment. This calibration helps verify that any following COP deviances or sway can be due to the perturbations that occurred not because the participant was off balance before the trial began. It has further importance due to the randomisation of the control and perturbation trials as it helps reset the participant to the original starting position before changing between the two trial types.

After the calibration board disappears a 3-2-1 countdown appears to indicate to them when the first trial starts so that no input is needed from the experimenter or the real world thus aiding in keeping the participant fully immersed and focussed in the VE. The trial starts as soon as the Stroop test words show up on the board in front on them (Figure 2). An mixture of a congruent and incongruent words were used for the Stroop task so the colour names (red, yellow, blue or green) and could be displayed in any one of the four font colours including its own colour e.g. Red, Red, Red or Red. The participant says the colour of the word out loud so that the experimenter can check for mistakes against the visible laptop screen. For each trial there are ten words for the Stroop test occurring at an interval of two seconds ensuring that there is not too much time for deliberating over it and the process is almost instantaneously

Procedure

All testing took place in the University of Birmingham Sports Pavilion alongside the hockey AstroTurf pitches. Prior to arrival of the participants the Wii Balance Board (WBB) and Oculus Rift Headset were connected, set-up and confirmed that all were working accordingly ready for the start of the participants' testing session.

Before commencing their first VR balance session participants were given a full introductory brief on what they needed to do during the trials. The introductory brief included giving the participant verbal summarisation of what they had previously read on the study information sheet (Appendix C) detailing what the study entailed and obtaining additional verbal confirmation that the participation was happy to continue and understood any of the risks outlined in the documents they had just read and written consent they had just given.

Figure 4: Participants' Stance on the Wii Balance Board
Example of the stance the participants were instructed to stand in for the duration of the trials. Feet must be together in the middle of the Wii Balance Board and their hands on their hips. Astro-turf shoes were kept on during both the baseline and post-exercise tests.

Participants were given a demonstration of the stance that they needed to stand in for the test; feet together and hands placed on the iliac crest (Figure 4). They were given an opportunity to try out the stance for themselves both with the headset off and on. It was also explained to them again verbally that as it is a balance task there is a risk of falling but that both experimenters were trained in physiotherapy manual handling techniques. Although unlikely loss of balance would occur, during the trials the trained experimenters were on either side of the participant to prevent them losing their balance or to minimise the risk of injury if they did fully lose their balance.

They were given detailed instructions on how to carry out the Stroop test; which required them to say out the loud the colour of the word not the word itself. A short familiarisation period was carried out prior to the commencement of the first trial.

Before standing on the WBB they were instructed to maintain their balance to the best of their ability for the duration of all the trials until they see the end of test notice in the VE and remove their headset. They were not informed of the fact that the VE would rotate in some trials therefore preventing them from anticipating this and affecting their results. Participants kept their shoes on to stand on the WBB as some pilot testing of the system on how different footwear may affect the WBB revealed that no difference in COP measurements was found between studs, bare feet and Astro Turf shoes. An additional benefit of participants keeping their shoes on is it fits into the premise that this system will be used in concussion assessment pitch side and time will not want to be wasted in taking shoes off rather than conducting assessments. The Oculus Rift headset was fitted comfortably and securely to the participants head with adjustments being made to both the horizontal and vertical straps where necessary. The program was started for the participant, visible through the Oculus Rift head set and additionally visible to the investigators on linked computer screen to monitor the participant's progress through the trials and to confirm the participant was completing the Stroop correctly.

Baseline Assessment

The first session the participants attended they arrived in a relative rested state so they just carried out their normal daily routine and refrained from doing any strenuous aerobic exercise

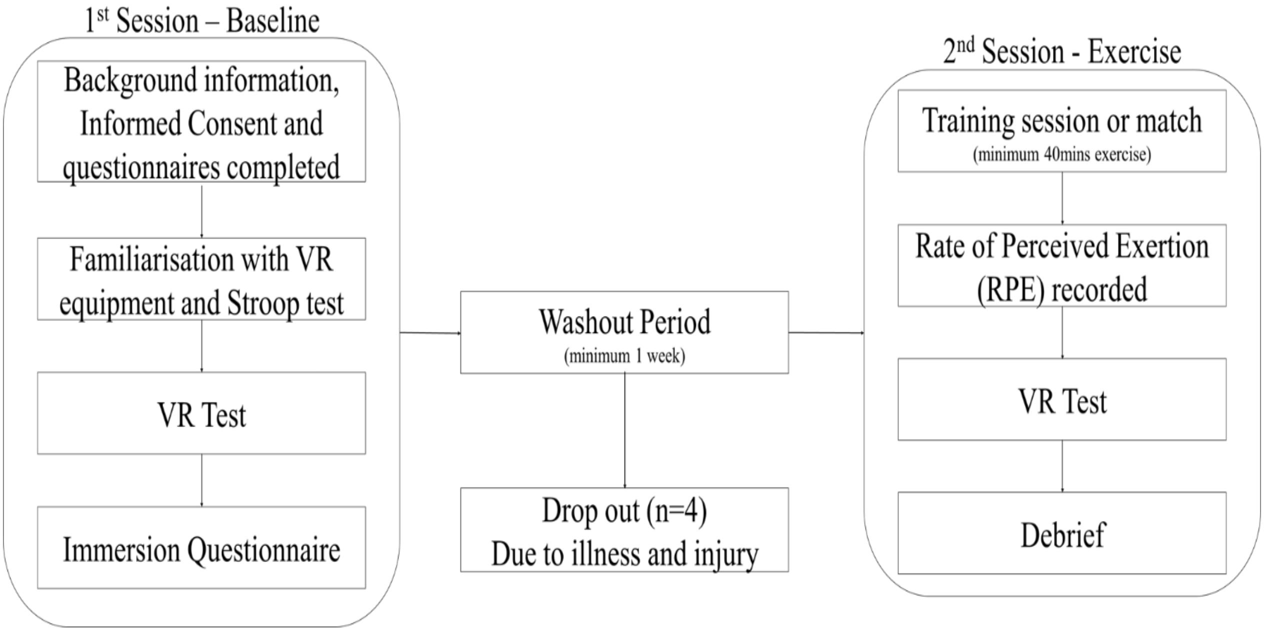

Figure 5: Flowchart of the Study Design
Outlines the events involved in participation and what order they occurred in during each session. Identifies when participants dropped out of the study and reasons why.

in the hours prior to the baseline assessment session. This baseline assessment normally took place on the participants' rest day or before they trained that evening in order to ensure they were in a fully rested state and not fatigued when carrying out the baseline measurement. After completing their baseline assessment, participants were asked to fill in an immersion questionnaire to ascertain how they felt about the VR system. The questionnaire was adapted from Gil-Gomez et al. (2013) and consisted of 13 questions (Appendix E). The questions included ones such as how they sensed to be in the virtual environment and whether it was realistic. The questionnaire also asked particular discomforts participants may have felt during the immersion in the VR such as dizziness, nausea or eye discomfort. These questions relating to how they felt about the VE were rated on a Likert Scale of 1 – 'not at all' to 5 – 'very much'. The questions relating to the difficulty of the tasks the VR system entailed were rated on a scale of 1 – 'very easy' to 5 – 'very hard'. The final two questions were open ended allowing the participants to voice their opinions on the VR system in their own words and not restricted to a scaled response.

Post-Exercise Assessment

After completing their baseline measurement, participants had a washout period of at least one week in order to limit any learning effect from the Stroop test and perturbation trials. During training sessions and matches participants came off the pitch after completing at least 40minutes of exercise and came straight into the pavilion to complete the VR balance assessment.

Previous studies investigating the effect of fatigue on balance tests or a complete concussion assessment used an exercise protocol of 20 minutes. However these protocols involved a 7-station indoor court based exertion protocol designed by Wilkins (2004) which was a mixture of squatting, jogging and sprinting to replicate what would be sustained during athletic activity. A longer period of 40 minutes was used in our study as the participants would be taking parting in their actual hockey training session and the high intensity aerobic activity would not be so condensed but rather a mixture of moderate and high intensity aerobic exercise spread over a greater distance and time. Therefor the longer time period would ensure that all the participants would achieve the appropriate level of exertion before running off the pitch to complete the VR balance test for their post-exercise score.

As soon as they came off the pitch and entered the pavilion changing room they were shown Borg's scale of Rate of Perceived Exertion (RPE) and asked to say what number they felt applied to how they were feeling at that time in regards to the training session they has just stepped off of (Figure 6).

#	Level of Exertion
6	No Exertion at all
7	
7.5	Extremely Light (7.5)
8	
9	Very Light
10	
11	Light
12	
13	Somewhat Hard
14	
15	Hard (Heavy)
16	
17	Very Hard
18	
19	Extremely Hard
20	Maximal Exertion

Figure 6: Borg's Rating of Perceived Exertion Scale
Borg's RPE Scale was used prior to the participants' 2nd session between coming off the pitch and stepping onto the WBB. It was used identify how exerted the 40 minutes of exercise during their training session made them feel before commencing the VR balance test for their post-exercise score.

As they were stepped on to the WBB and put the VR headset on, the participants were given a quick reminder of the main points of the assessment; feet together, hands on hips, maintain balance and for the Stroop task to say colour of the word not the actual word. They then proceeded to undertake the VR balance test in the same set up as their first session; one block of eight trials, with the first two trials set as control trials and the other six completely randomised between control or perturbation trials. Once the VR balance test finished they were debriefed on the purpose of the study and how to get in contact should they want to know the results or any further queries arise despite completing their participation in the study.

Data Acquisition and Analysis

The computer coding software MATLAB (Mathworks Inc., 2016) was used to generate our bespoke code which extracted the data from the .csv file containing the information from the four sensors integrated in the footplates of the WBB. One .csv file contained the information from just one individual trial and just looking at the .csv the only discernible information that you could learn from it was the type of trial it was and if it was a perturbation trial whether it had tilted to the left or right as shown by either a ±22.5 tilt angle. Therefore an additional custom made script in MATLAB was used to extract the data from the .csv files and plot it in to the corresponding COP coordinates through calculating the differences between the different load values of the four integrated sensors of the WBB. The MATLAB script extracted and presented the data as values for COP length before the perturbation, length after the perturbation, and also length before and after specifically just for the x axis and y axis.

A Graphical User Interface (GUI) was then generated by this code and gave a COP path trajectory for each trial the participants completed. As perturbations occurred randomly during the trial the extracted individual's COP path length came from the period 5s before the perturbation and 5s from the onset of the perturbation. These points were aligned on the graphs so that the perturbation was shown at 0 in order to directly compare multiple trials. These time points also enabled us to directly compare the participants' baseline balance ability from the quiet standing portion against their ability to balance in response to the VR perturbation.

Statistical Analysis

Statistical analysis was carried out using IBM SPSS (IBM Corp., 2016). A dependent paired samples t-test was used to analysis the statistical difference between the baseline and post exercise assessments. To analyse the habituation between trials a one way repeated measure ANOVA was conducted with the alpha level of significance set at $p<.05$. Mauchly's Test of Sphericity was used and if the assumption of sphericity was violated then it was corrected using the Greenhouse-Geisser estimate of sphericity. All data measured and reported within the results are presented as mean ± standard deviation.

Raw Data

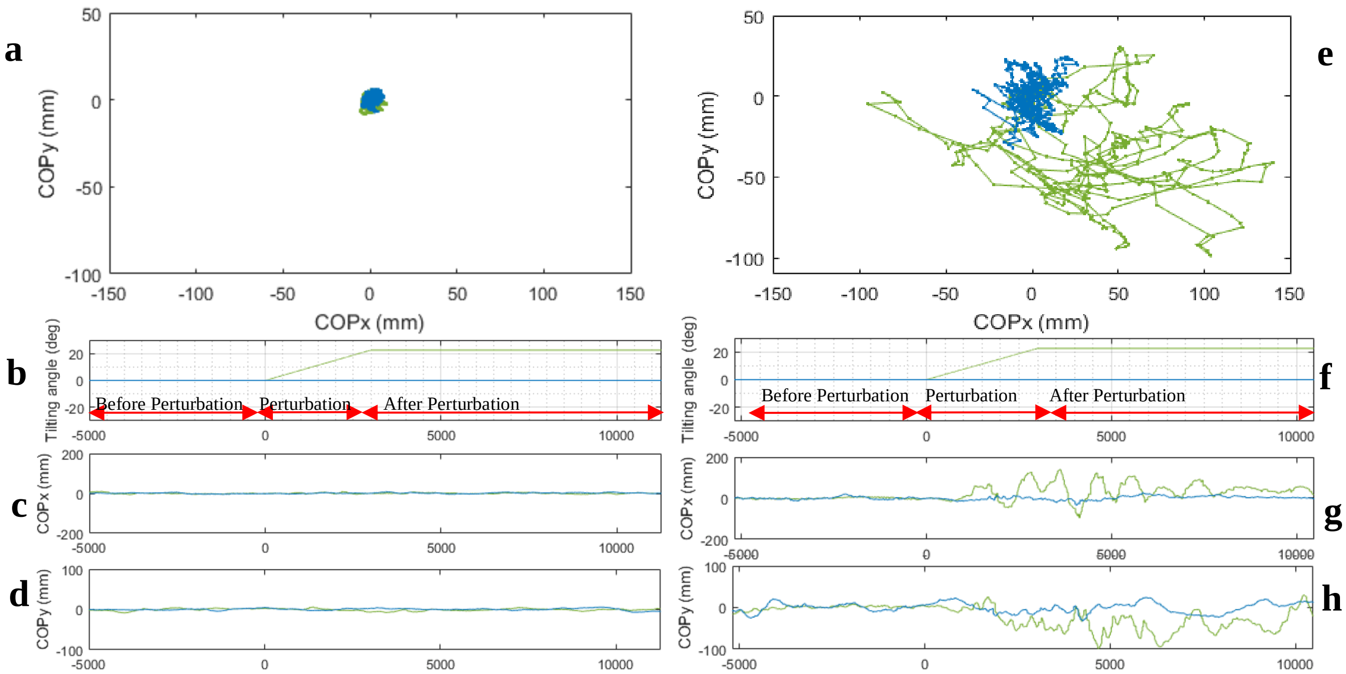

Figure 7: COP stabilogram showing a normal and extreme response to the VR perturbation Raw data from the baseline assessment of two different participants to illustrate the variance in balance response between different participants and also between a control trial (blue) and a perturbation trial (green). The left hand side figures **a-d** are from a participant that had no major balance response to the test. The left hand figures are presented on the same scale axis that best suits the right hand side graphs in order to directly compare them. The right hand side figures **e-h** are an example of a participant with a massive balance response. Figures **a** and **e** are a stabilogram of the participants' COP trajectories in the x and y axes showing a greater deviation in COP sway during the perturbation trial (green) compared to the control trial (blue). Figures **b** and **f** shows the tilt angle during the trial therefore identifying the type of trial. It gives the reference point for the figures below it as identified by the additional arrows it shows the 3 phases during the trial. Figures **c** and **g** show the COP movement in the x axis with figures **d** and **h** showing the COP movement in the y axis in order to visualise which direction elicited a greater COP response during the trials.

The custom MATLAB script was purely designed for producing the above figure and stabilogram for ease of visually comparing various participants and different types of trials to understand what the data was showing prior to running any further statistical analysis to assess the significance of the findings.

CHAPTER 3

Participant Demographic and Dropout Rate

Of the 14 participants recruited for this study, 10 participants completed both the baseline VR balance assessment and the second session for the post exercise VR balance assessment so all their data was included in analysis (10 Female, Age 18.6±1.1y, Height 166±5.9cm, Weight 67.4±5.1kg,). 4 participants dropped out of the study after their baseline assessment session due to illnesses and injuries picked up during the hockey season. These illnesses and injuries meant they were no longer able to train and exercise and thus would not be able to complete the 40 minutes of exercise required before completing their second session for the post-exercise assessment. Subsequently the baseline data from these 4 participants were excluded from analysis as it would have skewed the results and affected the statistical analysis by not having a full data set for the paired t-tests and repeated measures ANOVAs.

Participants' Experiences with the Virtual Reality System

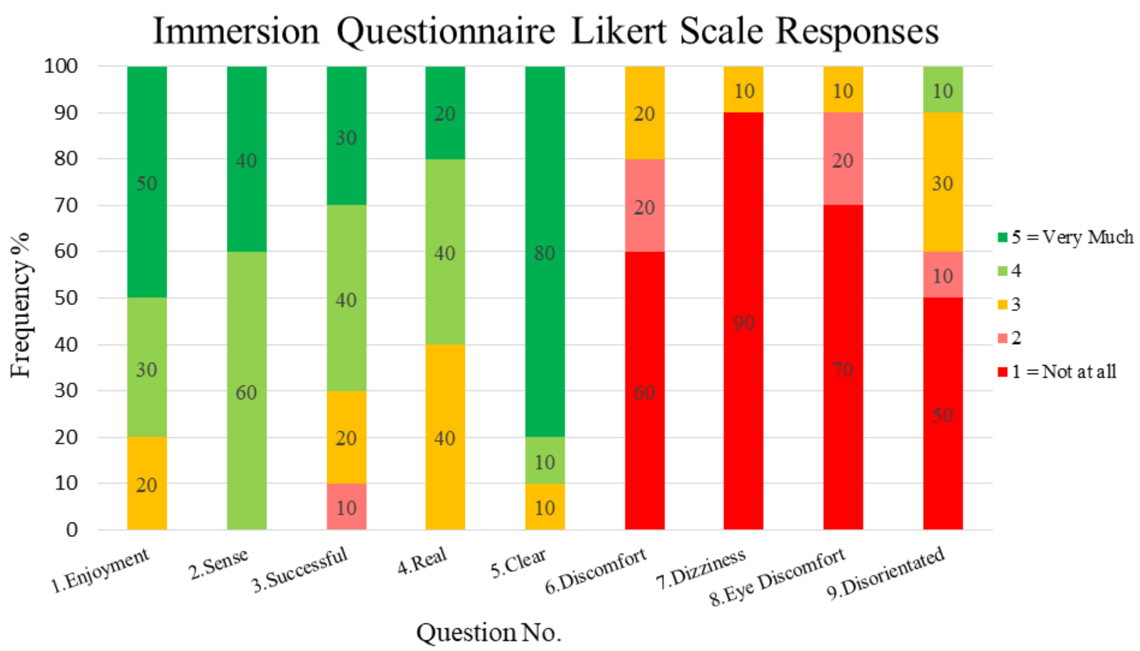

Figure 8: Participants' responses to the VR immersion questionnaire
Frequency percentage of the Likert Scale responses to questions 1-9 in the Immersion Questionnaire showing how the participants felt and responded to the VR. Questions 10-13 were not included in the figure as a different Likert Scale was used for Q10-11 and the latter needed worded responses (Appendix E)

Feedback from the immersion questionnaire (Appendix E) showed that 80% really enjoyed the system indicated by a 4 or 5 on the Likert Scale (Figure 8). Importantly all participants 'sensed to be in the environment' and that the virtual environment was 'real' with 90% of participants reporting that the system was very 'clear' as indicated by a 4 or 5 on the Likert Scale. The Stroop task acted as immersive tool rather than a cognitive assessment for this study to limit the variables and focus on post-exercise effect however there were noticeable mistakes on the Stroop task with the majority of participants easily completely all Stroop words. This concurred with the answers they gave to how difficult they felt the Stroop task was with only 20% responding that they felt it was hard. Thereby confirming that the participants were fully immersed in the environment and focused on the task at hand. All participants responded no to whether they felt uncomfortable during the task which demonstrates that whilst there are risks to using VR such as nausea and dizziness when it is carried out in the controlled manner of this test and only used for short periods of time, there are no ill effects and risks are only mentioned as a safety precaution.

Prior to the second VR balance assessment, which was carried out after 40 minutes of exercise, participants were asked to give a Rating of Perceived Exertion on the exercise they had just carried out during their training session. The maximum RPE given was 15 and the minimum RPE given was 10 with a modal average of 12/13 signifying that they felt the exercise was 'Somewhat Hard'.

Effect of Exercise on the VR Balance Test for Concussion

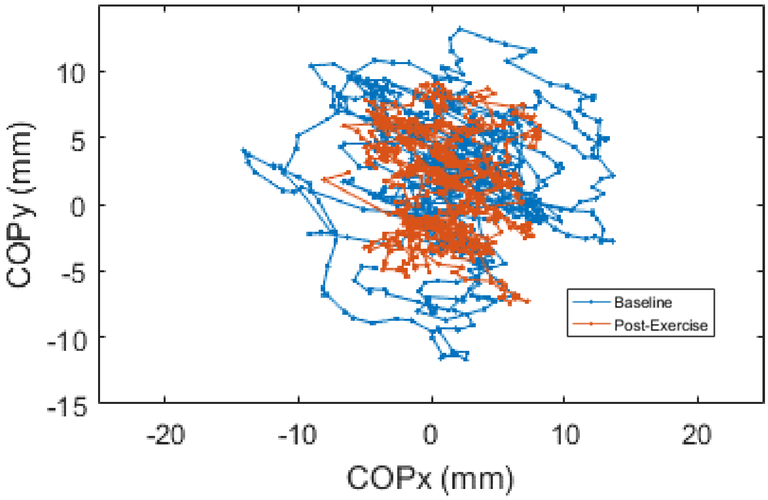

Figure 9: Stabilogram of an individual's COP path during a baseline and a post-exercise control trial.
An individual's control trial from their baseline assessment (blue line) against a control trial from their post-exercise assessment (orange line). The COP sway from the post exercise assessment is much less expansive and is more consistently grouped around the centre compared to the first assessment which is much more inconsistent and erratic.

Looking at the raw data from an individual's baseline control trial and post-exercise control trial (Figure 9) there is a distinct visual difference between them. The COP movement for the control trial from their baseline assessment is much more spread out in both the anterior-posterior direction and the medial-lateral direction compared to the COP sway in the post-exercise assessment. The post-exercise COP movement is actually much more consistent with less extreme movements away from the main COP placement within the centre of the board.

A paired sample t-test looking at the COP length before perturbation in the baseline and the post-exercise assessment for all trials confirmed the difference between the participants' baseline and post-exercise assessments (Figure 10) and revealed that their COP path length was significantly greater in the baseline assessment (M=173, SD±78) than the post-exercise assessment (M=159, SD±49), t (79) =2.80, p<.05. Analysis of COP length after between the two assessments (Figure 10) also revealed an equivalent significant different with the baseline assessment (M=256, SD±306) being significantly greater than the post-exercise assessment (M=188, SD±96), t (79) =2.25, p<.05.

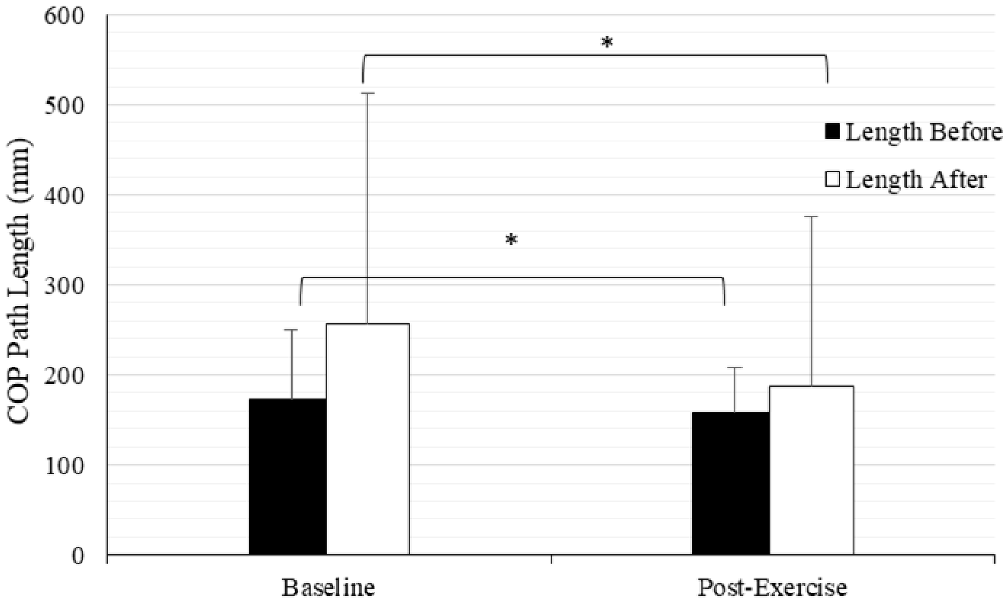

Figure 10: Graph illustrating significant difference between baseline and post-exercise COP measurements.
Figure shows that there is a significant difference for both the length before and length after COP path length measurements (M±SD) between the baseline and post-exercise assessments. As the post-exercise COP scores are better than the baseline it suggests that exercise isn't responsible for the differences in the two conditions.
*indicates significance at the $p<.05$

Due to the nature of the virtual reality based balance system, participants' ability to maintain their balance is not the only process involved therefore further analysis was carried out between the two conditions looking specifically at trial types to understand where this difference occurs and why participants performed better balance measurements in the post-exercise assessment. For if there was truly an effect of exercise on the VR balance system the post-exercise scores would be significantly worse rather than better. A paired t-test looking at the length before perturbation between the baseline control trials (M=174, SD±85) and post-exercise control trials (M=165, SD±54) revealed no significant difference $t(34) = .951$, $p = .348$. Additionally as they are control trials it is important to look at the length after perturbation as no perturbation occurs during the control trials the COP measurements should be similar to the length before in all conditions. Therefore a paired t-test was carried out for length after perturbation for baseline control trials (M=175, SD±99) and post-exercise control trials (M=162, SD±58) which found no significant difference between them t (34) =1.08, p=.290. Even further t-tests were carried out to confirm that length before and length after were the same within the same condition too so for the baseline there was no significant difference between control trials' length before and length after t (35) = -.128, p=.899 nor was there a significant different for the post-exercise condition between control trials' length before and length after t (38) =.596, p=.555. Thus confirming that the participants' balance ability on the VR balance system was not affected by the exercise as all the t-tests unanimously revealed there was no significant difference between the baseline and post-exercise control trials.

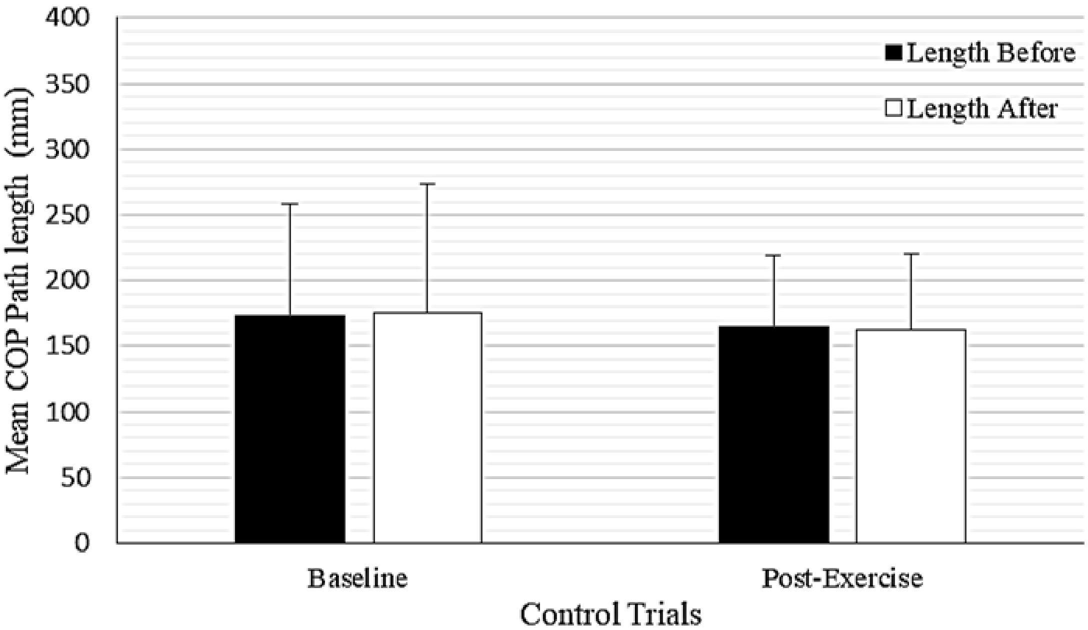

Figure 11: Graph displaying significant difference between baseline and exercise VR balance assessment as revealed by the control trials.
Figure shows there is no significant difference to the COP path length (M±SD) for the control trials between the baseline assessment and post-exercise assessment. Shows both the length before perturbation and length after perturbation COP measurements for both exercise conditions with there being no significant difference between any of the four COP measurements shown here. Consequently showing there is no effect of exercise on balance when using this VR based balance system and that the cause of improvement between the baseline and post-exercise assessment is down to another variable not exercise.

Having shown through the control trials there is no significant effect of exercise on the VR balance system it is now crucial to understand the part the perturbation trials play in the VR balance assessment. As they are purposely trying to disrupt the integration of different systems that control balance and measure how well an individual can adapt to this.

A paired t-test was carried out on the COP path length before perturbation between the baseline (M=175, SD±77) and post-exercise (M=156, SD±47) perturbation trials which revealed a significant difference between them with the post-exercise trials having a significantly lower COP path length than the baseline trials t (39) =3.05, $p<.05$. A paired t-test was also carried out for length after where a significant difference was also found between the perturbation trials COP length after between the baseline (M=340, SD±408) and post-exercise (M=216, SD±118) assessments t (39) =2.46, $p<.05$. This significantly lower COP path length in the post-exercise condition in both length before and length after (Figure 12) suggests habituation may have occurred with the perturbation trials.

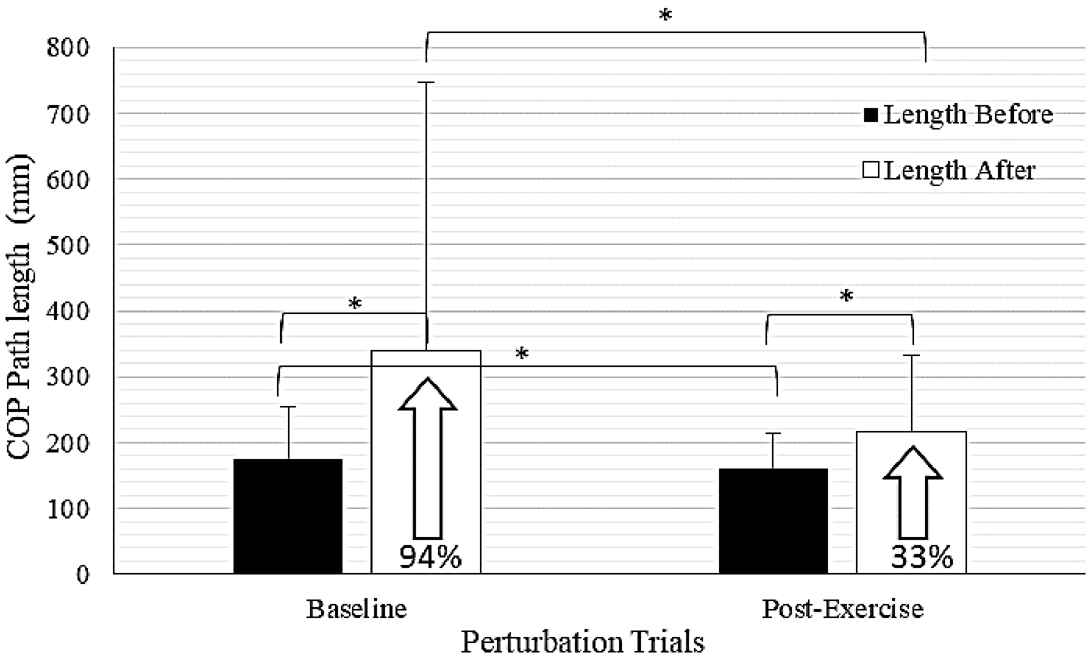

Figure 12: The effect of perturbation trials on COP length during baseline and post-exercise conditions
The effect of perturbation on COP path length before (the 5s before perturbation occurs) and length after (5s from onset of perturbation) perturbation directly comparing baseline and post-exercise trials. The annotations indicate the percentage change value between the length before and length after perturbation within the same condition.
*indicates significance at the $p<.05$

For that reason analysis on the effect of the perturbation on COP length was carried out by looking at the length before compared to the length after within the same assessment. Naturally a significant difference was found between the baseline length before (M=173, SD±74) and the length after (M=324, SD±392) t (43) = -3.04, p<.05. A significant difference was also found between the post-exercise length before perturbation (M=156, SD±46) and length after (M=214, SD±117) t (40) = -4.61, p<.001. However, although both elicit a significant difference the percent change is far greater in the baseline assessment perturbation trials with an increase in COP length of 94% between the length before to after compared to just 33% in the post-exercise trials(Figure 12). Therefore showing that the effect of the perturbation is much lower once the participants are aware that is going to happen and they have done the trial type multiple times previously. These results indicate that the earlier significant difference shown in Figure 11 with the post-exercise assessment being significantly lower COP path length can be attributed to the perturbation trials and the diminished effect the movement of the VE has on the participants as in their first session, the baseline they are blinded to the involvement of the perturbation trials whereas they are no longer blinded in their second session, the post-exercise session despite having a washout period the participants cannot be blinded again.

Does the perturbation effect diminish with repeated exposure to it?

It is obvious that the first perturbation in the VE evokes a major balance sway response but as shown in the second session, the post-exercise condition, this first perturbation trial does not evoke the same magnitude of COP sway response. This can perhaps be explained by the participants being blinded to the VE manipulation prior to starting the first session but then knew when came back for the second session but it is still important to analysis the individual trials to see if and where any other habituation may occur or be present.

Due to randomisation of the eight trials, participants performed a different ration of trial types so when looking at the learning effect of repetition of trials only the first three trials were used as all participants completed three for both trial types and test conditions. Firstly a repeated measures (RM) ANOVA was carried out comparing the COP length after perturbation between the first three control trials in both sessions; baseline and post-exercise. It revealed that there was no significant main effect between trial number and COP path length so no significant effect between either the first (M=167, SD±78), second (M=166, SD±56) or the third (M=178, SD±106) control trials in the baseline test $F(2,27) = .322$, $p = .727$ $\eta_p^2 = .023$. Additionally a RM ANOVA found no significant difference in the COP length after in post-exercise test between the first (M=189, SD±70), second (M=155, SD±60) or the third (M=146, SD±38) control trials $F(2, 27) = 1.52$, $p = .236$, $\eta_p^2 = .101$

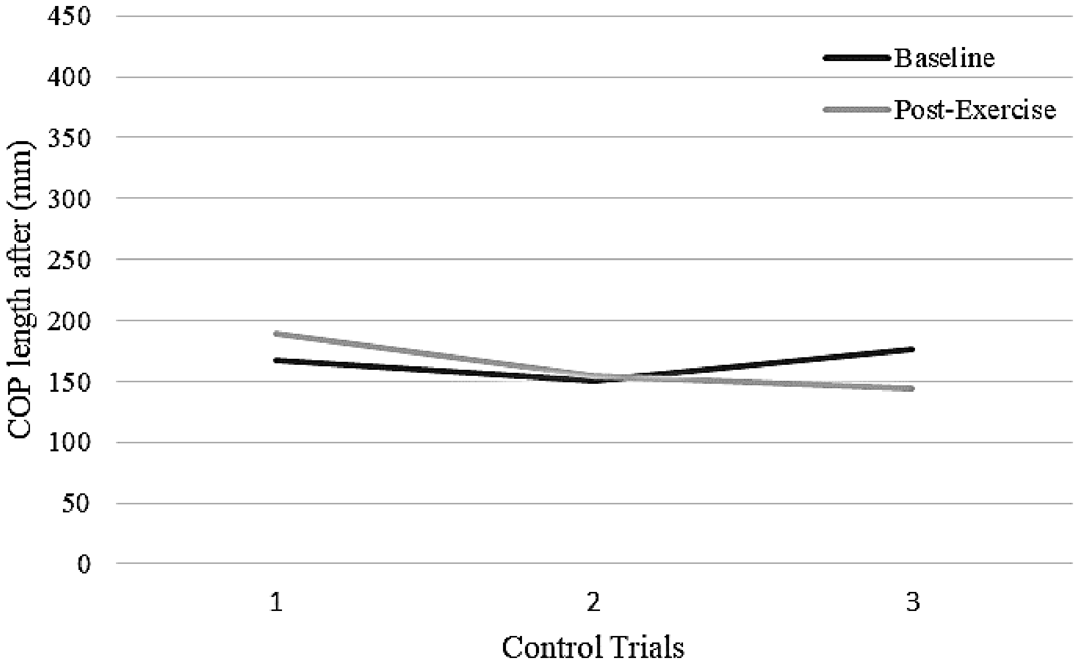

Figure 13: Graph to illustrate no significant difference between participants' 1st, 2nd or 3rd control trials in either condition.
Shows the mean length after for participants' 1st, 2nd and 3rd control trial in the baseline and post-exercise assessment with statistical analysis revealing there was no significant difference between any of the control trials indicating no habituation to the control trials.

More importantly statistical analysis was carried out on the effect of trial number on COP length after for the perturbation trials in order to comprehend if there is any habituation to the rotation of the virtual environment the more trials of it the participants completed. A RM ANOVA was run for the baseline perturbation trials and found no significant effect between th1st (t (M=403, SD±374), 2nd (M=341, SD±481) or 3rd (M=276, SD±192) perturbation trials' COP length after $F(2, 27) = .294$, $p = .748$, $\eta_p^2 = .021$. Another RM ANOVA was carried out for the post-exercise perturbation trials and also found no significant effect of the trial number on

COP length after so there was no significant difference between the 1st (M=245, SD±167), 2nd (M=194, SD±75) or 3rd (M=220, SD±123) trials' COP length after perturbation for the participants' post-exercise assessment.

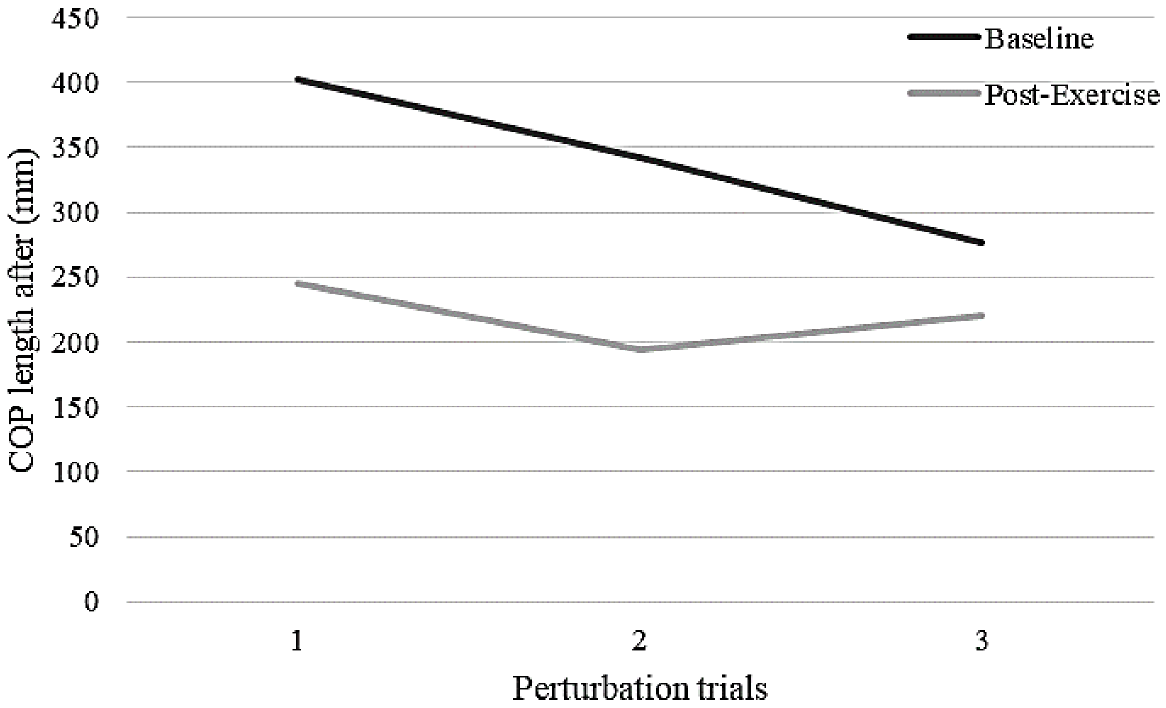

Figure 14: Graph illustrating no significant learning effect by participants with repetitive perturbation trials.
Figure shows the mean COP path lengths after the onset of the perturbation for the first second and third perturbation trial that occurs within the baseline and then within the post-exercise assessment.

Despite there being no significant effect of trial number on COP length in either the baseline or post-exercise assessment there is clearly a downward trend between the trials in the baseline assessment. Additionally in post-exercise assessment although the first trial COP length is less defined than the baseline first trial there is still a downward trend between the first and second trial in the post-exercise trial showing that the athlete is still able to adapt and improve in response to the perturbations. Discussion on this finding will be explored later, as this finding could have a significant impact going forward for using this VR balance test for concussion assessment.

CHAPTER 4

Discussion

This thesis looked to investigate the effect of exercise on a novel virtual reality balance tool for future use as a concussion assessment. Additionally it looks to determine the feasibility of using this model for pitch-side evaluation of sports related concussion during matches and training. The study is using a unique virtual reality Wii balance board system for balance assessment that incorporates quiet standing assessment with a cognitively conflicting scenario to test an individual's ability to react and adapt to a changing visual stimuli. Although various other researchers have since used numerous different virtual reality systems whilst assessing for balance to the best of my knowledge it is the first time a portable system has been developed and used outside the confines of a laboratory setting.

This study confirmed that it is not only practical and achievable to perform the test pitch-side but it allows the system to be tested on athletes who have exercised in actual training sessions of their sport therefore more closely mimicking the scenarios that athletes would experience in a game which makes it more applicable to the future in game concussion testing it will be required for. Secondly it is also my understanding that little to no research has been done on how exercise affects VR and especially not on how it affects a VR based balance test developed for concussion assessment. This study found that there was no effect of fatigue on the COP measurements and that the significant difference between the baseline and post-exercise assessment showing a lower post-exercise COP measurements can be attributed to the participants' awareness of the perturbation trials and thus diminished response in their second session of the post-exercise assessment.

Feasibility to use pitch side

Whilst this study found that the VR balance test in its current form is suitable and can feasibly be performed pitch side as shown by completing all of the research at the pitch side with no problems with the functionality of the system. A minor hindrance was discovered relating to the battery life of the laptop because although it was a high specification laptop specially directed towards gaming and therefore with the suitable capabilities of running the high demanding software for the virtual reality system it meant that battery life was sacrificed to accommodate for the high performance of VR system. Although it did not impact the research as plug sockets were accessible it does limit the system's complete portability as it does not want to be limited to be only assessing two or three participants in a row. A potentially minor inconvenience for future research within the concussed population is that the VR headset still attaches to the laptop via a long wayward wire that could become an obstruction or trip hazard which would need to accounted for to prevent further injury to individuals with concussion. During the development of the system and pre-testing an issue arose with the WBB where we discovered that the system cannot be set-up to accommodate different WBBs. Despite having two WBBs at our disposable, we were unable to simply just connect a WBB to the laptop and run the software. The software had to be specifically set up to the specifications of one WBB and not just WBBs as a whole, meaning it is not easily interchangeable across different WBBs. This finding concurs with what Bartlett et al. (2014) discovered and seems to confirm that the WBB is best for relative measures of COP using the same device rather than an absolute measure of COP across multiple WBB devices. The issue with the WBB does not affect the results of this study as the system was set-up to suit the specifications of one WBB and that was used throughout and as Bartlett et al. (2014) also researched; heavy wear and usage of WBB does not significantly degrade performance. Nonetheless it has ramifications on the potential to replicate this system across multiple platforms for future wide scale use across the sporting world.

Subsequently this study has made great strides in making an objective COP measured balance test portable and is one of the first studies to take the virtual reality platform out of the laboratory and test it in the field. However there are still potential and simple avenues to explore in order to improve it and to make it an unequivocally beneficial tool for concussion assessment. Since its inception and development of this VR balance system the technology involved has improved drastically and has evolved which could mean that even more portable options could be available for future use.

Research has started to emerge which could eliminate the use of the WBB balance for the objective measurements and suggests potential new VR devices that are less bulky and wireless. One such study by Salisbury et al. (2018) investigated the validity of balance measurements using smartglasses and concluded that the measurements were consistent with ones obtained from waist-mounted accelerometer. These new findings could provide a solution to the current downfalls with the WBB as even a waist mounted accelerometer could be beneficial to team up with a VR HMD and would be an improvement to our current system provided the sensitivity and validity of the balance measurements is at same level or better than the reliable COP measurements the WBB delivers. However if it was possible to get a reliable measurement of balance within smartglasses with VR capabilities then it would solve both inconveniences of our current system in regards to portability. A perspective from Zanier et al. (2018) provides a useful resource to identify the current available VR systems and outlines their affordability, body tracking capabilities and user interaction with VR. This resource identifies many mobile based VR devices such as the Samsung Gear and Google Cardboard that could make our VR system more portable and affordable so that its future concussion application would be accessible to all of the sporting community. However whilst we want to improve the portability of the system by minimising the size and number of devices to obtain and objective measurement of balance it cannot be at the expense of the quality of the VR. The current quality of VR the Oculus Rift provides for our current system cannot be taken for granted and it is important that any future reduction and change to the VR device for advantages to portability meets the same level of quality. For the reason that if the VR quality is reduced it has the potential problem of inducing motion sickness and nausea rather than evoking the intended postural sway response for balance assessment. As this would not be suitable when using it in the concussed population where dizziness and nausea is a common symptom and could cause a regression of their injury thereby going completely against the intention of this research to develop a tool that improves the concussion assessment and management, and reduces the risk of further serious injuries through inadequate testing protocols.

Why Did Participants Perform Better Following Exercise?

The COP of measurements for the post-exercise assessment were found to be significantly lower than the baseline measurements therefore showing that there was no detrimental effect of exercise that is commonly associated with balance and postural control. When accounting for the type of trial, there was no significant difference found in the control trials between the baseline and post-exercise condition indicating that there is in fact no effect of exercise on balance whilst immersed in VR. Thus the significant different must occur in the perturbation trials where there is an added reliance on the participants cognitive ability and how that manages and controls balance when deliberate manipulation of visual inputs have occurred to disrupt the control of balance.

One preliminary simple explanation for the difference could be put down to an exercise enhancing effect that is well known and documented amongst the scientific and sporting community alike and is also acknowledged as one of the most beneficial aspects of participating in the physical activity (Mandolesi et al., 2018, Fernandes et al., 2017). Physical activity affects the brain plasticity which influences the brain's cognition in a positive manner which could be reflected in the improvement in the perturbation trials in the post-exercise assessment (Mandolesi et al., 2018). Another benefit of the exercise could be down to a warm-up factor. Meaning that similar to how a warm-up is very beneficial to athletes prior to a match to ready themselves for the demands of physical activity, the 40 minutes of exercise acts as a warm-up and performing enhancing element for the VR balance test. When they step on the WBB their muscles are warm, readily available and fully active going in to the balance test making them more ready for the simple balance test compared to when they performed in a rested state for baseline when their muscles were cold and inactive. Additional information that could further add to this explanation is that the testing was carried out during the winter months when hockey training occurs so as postural control is impaired in cold conditions (Mäkinen et al., 2005).

Further explanation could be that the baseline assessment it not an adequate assessment of their participants' baseline. It may not be their absolute baseline as it was only taken from one instance so a more reliable baseline assessment taken using an average of a few assessments taking over a substantial period of time could provide a more suitable measure for comparison to the post-exercise condition. Additionally athletes are known to perform sub optimally in their baseline assessment known as 'sandbagging' (Higgins et al., 2017, Alsalaheen et al., 2017) in order to create a lower score so that they can pass the assessment when a concussion is suspected. However every effort was made to prevent this from happening by ensuring that the baseline assessments were administered individually and that before every participant's assessment the emphasis was placed on ensuring they maintain their balance to the best of their ability as previous research has shown that these small procedures help reduce the likelihood of 'sandbagging' (Alsalaheen et al., 2016).

Habituation to Perturbation Trials

No significant difference in either the baseline or post-exercise assessment between the trials was found to identify a learning effect however looking at Figure 14 there is clearly a downward trend in the baseline assessment perturbation trials demonstrating that the first perturbation had the greatest effect which became less defined each time the perturbation trial was repeated. The post-exercise condition shows that the perturbations caused less of an impact on COP path length on their first one than it did during baseline but that upon exposure to the second perturbation trial the effect was again diminished which suggests there is a possible habituation to the effect of the perturbation.

Therefore the apparent difference between the effect of the first perturbation in the baseline assessment and diminished effect in post-exercise assessment could be explained by the fact that all participants completed the baseline assessment first and then after a washout week of at least a week carried out their post-exercise assessment. Accordingly during their baseline assessment they were unaware of the perturbation trials so were not mentally or physically prepared for them thus evoking a major COP sway response whereas when they returned for their post-exercise assessment they had the prior knowledge and knew what to expect, even if they did not know when to expect it therefore explaining why there was a still an effect. Although there was no significant learning effect in this study, if this system was to be used as a concussion assessment either on its own or as part of a battery of tests then it would be possible that athletes would complete it numerous times throughout their career for baseline testing each season, for any subsequent suspected concussions and also for follow and RTP for any sustained concussions. As a result a significant learning effect may appear due to a larger participant sample and increased number of trials therefore this VR balance test needs to be resilient against a learning effect and possible habituation.

‘One method of reducing the magnitude of practice effect is to use alternative forms’ (Collie 2001), which is why the use of virtual reality is advantageous because it can easily be changed and reconstructed to simulate a different life like scenario. The construction of the test can easily be changed either so that the participants are placed in a different VE therefore inhibiting their recognition that the balance task is the same or so that the tilting of the room occurs in a different axis or speed so they have to readapt to a different perturbation. The potentials for limiting any potential habituation is endless due to the integration of virtual reality to the balance test.

Furthermore, although the Stroop test acted more as an immersive tool in this study than a cognitive assessment, it too can be altered to prevent habituation. The Stroop task can be changed to be a congruent Stroop task, for instance the participants have to say the word itself and ignore the colour of the word. The number of colours and words can be increased from the current four or it can even be removed completely to make way for other neuropsychological tests that are better suited to assessing cognitive deficits following concussion. Tests that are included in the SCAT5 such as the standardised assessment of concussion (SAC) that assess attention and memory functional have been shown to practical and effective (McCrory et al., 2017) so could be possible options to adapt and incorporate in to the VR in place of the Stroop task. A delayed recall task as seen in the SCAT5 could easily be incorporated into the beginning and end of the VR balance test to which could be an extra test to aid evaluation of cognitive function.

Implications for Concussion Assessment

This study found no significant reason why this VR balance test cannot be carried out straight out after exercise consequently thus providing no clear reason why it shouldn’t be implemented as a pitch-side balance test for concussion assessment.

Further research would need to be carried out in the concussed population before use as a diagnostic tool as this type of fully immersive virtual reality paradigm using a HMD has not been clinically tested let alone this particular type of virtual reality based balance test. Based on research by Slobounov et al. (2006) the hypothesis for identifying concussed individuals using this VR-WBB balance test would be that concussed patients would not be able to react as quick or as effectively as they did during their baseline tests due to the concussion related cognitive deficits and postural instability. In some extreme cases it is hypothesised that some individuals suffering from concussion may not even be able to complete the balance test without having to step off the WBB and take off the VR to regain their sense of balance making diagnosis very observable before consulting the data. The current safety measures of using trained experimenters in physiotherapy manual handling would need to be evaluated to ensure they are sufficient when using it on patients would need to evaluated and assessed. Although harnesses have previously been used to support participants to prevent the risk of complete loss of balance and falling and further injuring themselves (Slobounov et al., 2011) these types of measures detract away from endeavours that have been made to increase the portability of the test so therefore would not want take a step backwards with this ground-breaking research.

Conclusion

This study conclusively shows that this VR balance test for use in concussion assessment is not affected by exercise induced fatigue and can be performed efficiently and effectively pitch side. This is a ground-breaking step forward for virtual reality balance tests and the results of the study could have profound effects of the assessment of sports related concussions. It has the potential to prevent concussions going unrecognised, misdiagnosed or incorrectly managed and for that reason the results of this study will have a huge impact on many lives.

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APPENDICES

Appendix A

Suitability to Participate Checklist

I, ……………………………………………………………………., confirm that:

Please initial here:

- I have received and read the document entitled 'Participant Information'. ☐
- I do not suffer from any form of epilepsy. ☐
- I have not suffered from a concussion or head-related injury in the past 3 months. ☐
- I do not have any existing balance deficits or health problems relating to the inner ear ☐
- I am aware of the possible side-effects during, or shortly after, participation in this study and know that I can ask questions at any time. ☐
- I authorise the assistance of trained organisers in the event of a trip or fall during this study, and accept that manual-handling techniques may be issued. ☐
- I am not currently pregnant, or have not given birth in the last 12 months. ☐
- I give consent my balance tests to be video recorded. This will only be used for analysis by the investigators, and will not be publically accessible. ☐

Signed: ………………………………………

Date: ………………………………………

Appendix B

UNIVERSITY OF BIRMINGHAM

INFORMED CONSENT FORM

Participant Identification for this Study:

Title of project: Impact of fatigue on pitch-side virtual reality based balance assessment for concussion

Ethics code:

Name of researcher:

Please initial here:

1. I confirm that I have read and understood the Participant Information Sheet detailing the above study. I have had the study and what it entails explained to me, and I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason. If I withdraw my data will be removed from the study and will be destroyed. ☐
3. I understand that 24 hours after participation, I will no longer be able to withdraw my data from the study. ☐
4. I agree for my performance of the mBESS test to be videoed by one of researchers. This will only be used for the data analysis stage of the study, and will only be accessed and viewed by members of the research team. ☐
5. I agree to take part in the above study. ☐

______________________	____________	____________________
Name of Participant	**Date**	**Signature**
______________________	____________	____________________
Name of Researcher	**Date**	**Signature**

Appendix C

Participant Information Sheet

We are doing a study to investigate the effects of a Virtual Reality (VR) environment on participants' balance during the completion of a simple cognitive task. There is currently no accepted or reliable method to test patients for concussion following a head injury or collision in a pitch-side environment. Therefore, we aim to apply our results to aid in the development of future pitch side concussion assessment tools.

If you agree to participate in this study, you will be required to complete a short balance test in a pitch-side environment. The first visit will take no longer than 15 minutes, and the second visit will take place following exercise, and will take no longer than 1 hour. On arrival you will be introduced to the equipment and procedures that you will experience. In the interests of safety, we will also require you to complete a short checklist to ensure your suitability to participate in this study and a short background questionnaire, details of which are enclosed.

Firstly, we will measure your height and weight. You will be asked to undertake a current and widely used pitch-side balance assessment tool whereby you will be asked to perform three different stances. This test will be video recorded for later analysis for research purposes only and only members of the research team will have access to this. For the VR task will be required to stand on a balance platform whilst wearing a set of goggles to view a virtual scene on the built-in display.

There is a very minimal risk of experiencing a seizure as a result of using the VR equipment. To reduce this possibility, you will only use the VR system for short periods of time, and will be encouraged to give alert of any post-VR effects such as discomfort, loss of awareness, altered vision, or dizziness throughout the testing. If you experience any post-VR effects, you will also be advised not to drive, operate machinery, or engage in other visually physical demanding activities that have potentially serious consequences, or other activities that require unimpaired balance and hand-eye coordination, until fully recovered from symptoms. All investigators will be trained in manual handling and will stand next to you at all times whilst you complete the VR balance assessment, to ensure you do not lose your balance.

Your participation in this study is entirely voluntary, and as such, you are entitled to withdraw from participation at any point before or during the study, and until 24 hours after the last data session is completed. After this time, it will not possible to remove your data from the study. You will not be required to provide reasons for your withdrawal, and withdrawing from the study will not lead to any change in your treatment or care. If you withdraw after the last assessment your data will be kept anonymous in the data analysis of the study. Any information obtained from the visit may be held in secure conditions for up to 10 years following the visit, and any data used in future studies or publications will be entirely confidential. Any participants wishing to be kept informed of the results of this study may contact an organiser on the details below.

Further information is available on request, so please do not hesitate to contact us using any of the below email addresses if you have any questions or concerns.

Appendix D

<u>Participant Demographic Questionnaire</u>

Name …………………………………………………..Age ....

Height ....
Please specify units

Weight ....
Please specify units

Main Sport/Activity ....
Position………………

Level of Participation: *circle as appropriate*

Recreational Club County Regional National International

Other Level *(please specify)* ....

Appendix E

Immersion Questionnaire, Adapted from Gil-Gomez et al. (2013)

Immersion Questionnaire

Participant Number:

Question	Response				
	Not at all				Very Much
Q1 How much did you enjoy your experience with the system?	1	2	3	4	5
Q2 How much did you sense to be in the environment?	1	2	3	4	5
Q3 How successful were you in the system?	1	2	3	4	5
Q4 How real is the virtual environment of the system?	1	2	3	4	5
Q5 Is the information in the system clear?	1	2	3	4	5
Q6 Did you feel discomfort during your experience with the system?	1	2	3	4	5
Q7 Did you experience any dizziness or nausea due to the system?	1	2	3	4	5
Q8 Did you experience eye discomfort due to the system?	1	2	3	4	5
Q9 Did you feel disorientated during your experience with the system?	1	2	3	4	5
	Very Easy				Very Hard
Q10 Did you find the Stroop task difficult?	1	2	3	4	5
Q11 Did you find it hard to maintain your balance throughout the test?	1	2	3	4	5
Q12 If you felt uncomfortable during the task, please indicate the reasons	(No) or (Yes + reasons)				
Q13 Any additional comments					