THE DEVELOPMENT OF A NOVEL BALANCE PLATFORM FOR CONCUSSION ASSESSMENT

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ABSTRACT

The visual system has been regarded as the most important system for the maintenance of balance. Notably, in the event of a concussion the visual system can be impeded leading to various, observable balance dysfunctions. Whilst this measure has been exploited within concussion assessments, current balance procedures are expensive, and laboratory-constrained or inexpensive, but subjective. The present study focused on developing an objective, inexpensive tool to assess the visual systems role in balance by utilizing Virtual Reality (VR) to evoke a postural perturbation and a Wii Balance Board (WBB) to track the individual's recovery in response. The first part of this thesis was dedicated to constructing the VR-WBB system to establish whether the device provided an effective means to induce a perturbation and, evoke a balance response that could be adequately quantified by obtaining centre of pressure (COP) data from the WBB. The second part of this thesis focused on refining this prototype, assessing how an individual's balance would be affected by speed-manipulated and axis-manipulated perturbations. Current studies highlighted that manipulating axes and speed of perturbation significantly affected the COP response, which has profound implications when developing the optimal VR-WBB tool. Overall this thesis confirms that the VR-WBB prototype is an effective system to evoke a postural perturbation and obtain quantifiable balance responses to track their recovery in response. With further parameter refinement, this tool could be revolutionary not only for basic balance assessments but also for pitch side assessment of concussion.

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ABBREVIATIONS

TBI – Traumatic Brain Injury

mTBI – Mild Traumatic Brain Injury

LOC – Loss of Consciousness

SCAT – Sport Concussion Assessment Tool

BESS – Balance Error Scoring System

SOT – Sensory Organization Test

SAC – Standardized Assessment of Concussion

SIS – Second Impact Syndrome

CTE – Chronic Traumatic Encephalopathy

RTP – Return to Play

NTs – Neurotransmitters

WBB – Wii Balance Board

HMD – Head Mounted Display

VR – Virtual Reality

COP – Centre of Pressure

VE – Virtual Environment

CHAPTER 1

Introduction

1.1**Background**

Over the last 10 years no other sports injury has been discussed by the media and amongst the sports medicine community to the same extent as has concussion. “Concussion” is a term coined in medicine and sport used to describe a form of mild traumatic brain injury (mTBI). Whilst there is no universally accepted definition, many professionals go by that published by McCrory et al., (2009) stating concussion as a “complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces”. Concussion is the most common and puzzling form of TBI, traditionally characterized as a low-velocity injury and a subset of the more severe, pathological-based TBIs (McCrory et al., 2013; Shaw, 2002). Medical personnel have been aware of this event for more than 70 years, however ambiguity still arises as to what defines a concussion, how to diagnose it, and the best ways to treat it. This problem occurs because no two concussions are alike, and as a result, symptomology can be widespread and vary considerably between individuals (Broglio and Puetz, 2008). Unfortunately, current assessment tools are often reliant on the honest reporting of these symptoms to diagnose a concussion. Thus, their effectiveness is dependent on compliance, which is often compromised as individual’s under-report their symptoms to expedite their return to play (RTP) (Broglio et al., 2007). This problem is becoming increasingly more prevalent, generating the media attention that has long been required. More recently, this has prompted research into assessing objective and physiological based symptoms of concussion, such as balance (Mancini and Horak, 2010). Notably, research has begun to exploit the concept of balance further; eliciting perturbations in an individual’s visual field to evoke a response. Tracking the recovery from an individual’s response to a perturbation (i.e.: sway) may shed some light to whether an individual has sustained a concussion. This thesis will seek to explore the visual component of balance further and in doing so will provide an alternative, objective and cost-efficient prototype for concussion diagnosis.

1.2**Concussion – The Problem**

Concussion is recognised as the most common form of TBI worldwide (Bruns and Hauser, 2003) and is a problem that needs addressing immediately; with prevalence and under-diagnosis rates increasing, healthcare finances surging, and more literature noting the long-term damage of concussions, it is imperative that this sport-induced injury is not ignored (Harmon et al., 2013; Langlois et al., 2006; McCrea et al., 2004; Thurman et al., 1999). In fact, for any progression to be made in improving concussion recognition and diagnosis, this problem needs to be addressed highlighted and responded to imminently.

Whilst moderate and severe TBI have long been recognized and cared for by clinicians from as early as Hippocrates, concussions - a mild TBI - have not had the same recognition (McCrory and Berkovic, 2001). In fact, it has not been until the last decade that the media has recognised and highlighted the importance of such an event. Accordingly, more and more people are beginning to realise the severity of concussions and the repercussions that such an event can cause. This increased focus from the media has come at a pivotal time, as new figures show concussion reaching epidemic proportions, with reported incidences in the US being at 1.6 - 3.8 million annually (Langlois et al., 2006).

In the UK alone it has been approximated that 50% of sport concussions are not reported to professional healthcare staff (McCrea et al., 2004), creating a huge public health concern. Individuals will try anything to continue playing the game they love, but what they do not realize is that by doing so, they can jeopardize their chances of ever playing the game again in future. Continuation of play after a concussion will increase the individual’s risk of sustaining another knock to the head, which could be fatal. Such an event could lead to Second Impact Syndrome; when an individual experiences a second insult to the brain, before homeostasis from the first one is restored, manifesting a diffuse cerebral swelling (Longhi et al., 2005). This was the case for the 14-year old, Benjamin Robinson, who experienced three insults to the head during a game of Rugby. All knocks were left unrecognised until the last insult where Benjamin collapsed to the floor in a state of unconsciousness, to later be pronounced dead. Autopsy investigation confirmed Benjamin suffered from Second Impact Syndrome (BBC NEWS, 2013). The lack of available and objective assessment tools available offers a key explanation as to explain why a concussion can, or is allowed to, manifest into a condition like SIS. Consequently, an injury that was once manageable can turn into ones that leads to severe neurological impairments or, death.

Sustaining repeated concussions over the course of an individual's career that are left unrecognised can lead to a range of neurodegenerative complications in later life like Chronic Traumatic Encephalopathy (CTE). Formally, CTE was recognised only in boxers and known as 'Punch Drunk Syndrome,' a term coined by the pathologist Harrison Martland. Whilst it has been established for over a century that boxing can induce long-term neurodegeneration (Martland, 1928), it has not been until more recent years that more modern sports such as American Football, Hockey, and Rugby have been recognised to follow a similar neurological depreciation (Costanza et al., 2011). This is a huge concern, with reports suggesting that players in the NFL are vulnerable to some degree of dementia, depression or cognitive impairment at a rate 20 times higher than age-matched controls (Amen et al., 2011). One can only speculate these rates would be substantially lower if concussions were diagnosed initially. However, this is not necessarily the clinicians, coaches or players fault. One of the most challenging problems medical personnel face in terms of their responsibility for the wellbeing and healthcare of patients, is the inability to access an objective tool to diagnose concussion (Kissick and

Johnston, 2005).

This problem of under diagnosis is exacerbated further, as participation in contact sports within the collegiate system is increasing (Centers for Disease Control and Prevention, 2011). In accordance with this upsurge, there has been an estimated fourfold increase in concussion rates over the last ten years (Lincoln et al., 2011). Notably, this places huge strains on the public healthcare system (Ashare, 2009) with estimated costs reaching $17 billion in the US (Thurman et al., 1999), and precise costs yet to be established in the UK. Nevertheless, recent surges of media attention have increased the public's awareness and knowledge into the adverse complications of concussions; generating a catalyst for change. In particular, focus has concentrated on the tragic suicides committed by former NFL athletes who have sustained an accumulation of insults to the brain throughout their careers and, as a result, have suffered from the condition CTE, driving a handful of individuals into a premature death (Omalu et al., 2005). The death of a few stars like the centre Mike Wesbter, had repercussions on the masses; as a result numerous lawsuits against the NFL have been filed (Heard, 2013). Players made strong allegations scrutinizing the NFL for fraudulently covering up the long-term repercussions of a concussion. Consequently, a settlement was proposed requesting that the NFL paid $765 million for injury compensation, concussion research and other litigation costs (Heard, 2013). These lawsuits had repercussions for many others sports, in many different countries, triggering a culture change in both management and assessment of concussion.

Actions that occurred within the NFL triggered similar lawsuits to be filed within soccer. Allegations came from a group of 'soccer moms' who targeted FIFA and criticized the organizations failure to protect young players against concussion (Marshall, 28th August, 2014). One key example that caught the eyes of many occurred in the 2014 World Cup Final. In this case the player, Cristoph Krammer, sustained an obvious concussion that was on stage for the whole world to see yet he continued to play for 14 minutes after the insult (Marshall, 28th August, 2014). Notably, FIFA responded to criticisms of being careless and negligent and acknowledged that concussion is one of their prime concerns. However, one can only assume that if an enforced procedure were in place to take every player with a suspected concussion off the pitch and assess them using an objective diagnostic tool, such incidences would be greatly reduced.

Such changes being made within sport in the US has raised the profile of the severity of concussion, forcing review of some of the practices that are currently in place within sports in the UK. Numerous changes have been implemented by the Rugby Football Union (RFU) to improve concussion recognition for players, physicians and coaches. This was evident in the recent 2015 Rugby World Cup whereby a multi-camera Hawk-Eye system that provided 360^0 coverage of the pitch was introduced (Rugby World Cup, 12th September 2015). Implementing such a system meant that the team physician could replay knocks in slow motion. Thus, allowing a more accurate assessment on the severity of concussion, establishing the exact point of collision, mechanistic properties of the injury and rotational analysis. Whilst this is a pivotal advancement and has helped medical personal look at aspects of concussion that were not previously addressed, it still does not resolve the fundamental problem associated with concussion – diagnosis. Thus, future technological advancements should be invested in exploiting a tool to actually diagnose concussion, rather than providing revolutionary ways to assess the type of injury. Nevertheless, it is evident that much is being done to improve the field of concussion recognition and management further.

This recognition has further been evident through changes made within the game itself. Rule refinements have been made within Rugby by altering the “temporary substitution period” – the time permitted to assess a concussion pitch side. The Head Injury Assessment (HIA) has been adjusted so that the time permitted to get an individual off the pitch and assess them for concussion is 10 minutes, instead of the insufficient 5 minutes that was allowed previously (World Rugby, 15th May, 2015). Clearly, a 5-minute period is not long enough to evaluate the various symptoms that could be presented with a concussion. Implementing such procedures into contact sports has been conducted in order improve concussion assessment. One cannot dispute this is a fundamental advancement for concussion diagnosis, however this change could be deemed effectively useless if no objective diagnostic tool is created to be conducted within this timeframe.

Undisputedly, concussion is becoming more and more of a problem globally with the number of people participating in contact sports increasing exponentially, literature emphasising the long-term damage of concussion, and greater reliance being placed on our healthcare system. Consequently, labelling a concussion as a ‘mild’ TBI is proving to be a misconception, deterring away from the severity of neurometabolic complications and range of clinical manifestations that are occurring (Giza and Hovda, 2001; Signoretti et al., 2011a).

1.3 Mechanisms and pathophysiology of concussion

1.3.1 Mechanisms

A concussion is typically obtained through a direct or indirect blow to the head, face, neck or body (Aubry et al., 2002). Such a blow initiates a series of acceleration and deceleration actions that produces rotational or translational movements within the brain tissue. These acceleration-deceleration forces within the brain can cause a series of microscopic damage: stretching of microtubules, damage to the myelin sheath, neural shearing (Barkhoudarian et al., 2011a; Peerless and Rewcastle, 1967). Such events can cause the depolarization of the neurons and subsequent failure to transmit information (Peerless and Rewcastle, 1967).

Upon impact there is extensive movement within the skull, the brain will first strike the interior of the skull where the impact was and then recoil to the opposing side, resulting in two contusion sites. This is recognized as the ‘coup contrecoup’ effect whereby injuries reside where the force directly impacted, coup, and on the opposing side, contrecoup (Drew and Drew, 2004). Consequently, concussions can affect multiple areas of the brain dependent on the locality of The contusion sites. By virtue of these actions, complex and extensive neurometabolic and neurochemical events within the brain are initiated (Signoretti et al., 2011a).

1.3.2Pathophysiology of concussion

Researchers are under the belief that biomechanical forces induced onto the brain exert a wave of energy that travel through the brain tissue and subsequently triggers ionic, metabolic and physiologic events to occur, this is known as the ‘neurometabolic cascade’ (Barkhoudarian et al., 2011b).

Giza and Hovda., (2001) used animal experimentation to demonstrate distinct changes in the brain’s chemistry following a concussion, exploring the neurometabolic cascade. This study deduced that upon initial impact there is a ‘spike’ in neural activity, characterized by a rapid release of neurotransmitters (NTs). This upsurge of NTs engages the Na^+/K^+ pump to alter the ionic and metabolic state of the cell. The binding of excitatory NTs like glutamate to the N-methyl-D-aspartate (NMDA) receptor initiates the ionic movements that proceed. Consequently, there is colossal influx of calcium, concomitant with an efflux of potassium, which substantially alters the cells physiological environment (Giza and Hovda, 2001).

In the absence of a concussion, the brain can maintain potassium levels through action of the glial cells, which operate to prevent the mass efflux that occurs (Paulson and Newman, 1987). However, in the event of a concussion, complications like ischemia can inhibit this regulation of the glial cells and arterioles, and thus compensation fails. The rapid increase in potassium causes neuronal depolarization, acting as a catalyst to trigger further release of glutamate, which causes more potassium to be released (Giza and Hovda, 2001). In the effort to restore normal membrane potential the Na^+/K^+ pump works overtime at the expense of additional adenosine triphosphate (ATP) (Barkhoudarian et al., 2011b). Consequently, there is a huge increase in glucose metabolism that cannot be met, thus leading to an energy crisis.

The energy crisis is exacerbated by calcium staying within the cell as it seeps through to invade the mitochondria. This in itself can have widespread consequences; impairing oxidative metabolism, initiating the disassembly of microtubules, disrupting neuronal connectivity and impairing the cells ability to communicate (Giza and Hovda, 2001). Collectively, the discrepancy between energy demand and supply initiates and intensifies the energy crisis. It is this energy crisis, which makes the individual extremely vulnerable to long-term damage if a second insult were to occur (Signoretti et al., 2011b).

Damage from a concussion is exacerbated in the developing brain, rejecting predisposed beliefs that the child's brain is more 'resilient' (Levin, 2003). From development in the utero up until age 18 the brain is still developing and establishing neural connections that can adapt and reorganize in response to differing environmental situations. This is known as neuroplasticity; the brains capability to adapt throughout an individual's lifetime. In the developing brain tissue cannot recover and respond like that of an adult brain; consequently, adolescents can be at greater risk of damage in the event of a concussion. One reason predisposing children to this risk is the reduced resilience of the musculature of the shoulder and neck, compared to that of adults (Kirkwood, Yeates and Wilson, 2006). Moreover, the developing brain has a decreased ability to render mechanical energy, allowing more impact to transmit to the brain (Kirkwood, Yeates and Wilson, 2006). Thus, an mTBI in children results in higher mortality rates than adults.

Prins et al., (1996) investigated this concept empirically in rats by using the fluid percussion technique to mimic a TBI of three different injury severities. The rodents were separated into two different age groups; one consisting of rats at day 17 of the postnatal stage and the other, adult rats. Physiological responses were more pronounced in developing rats displaying increased mean arterial blood pressure and higher mortality rates. The evidence provided by Prins et al., (1996) highlighted the dramatic consequences that children may face when exposed to such an event. This is of particular concern given that more and more adolescents are participating in contact sports every day, with reports of 7.5 million participating in contact sports within US schools between 2011-2012 (National Federation of State High School Association). This reinforces again the need to establish a reliable and objective assessment tool for concussion.

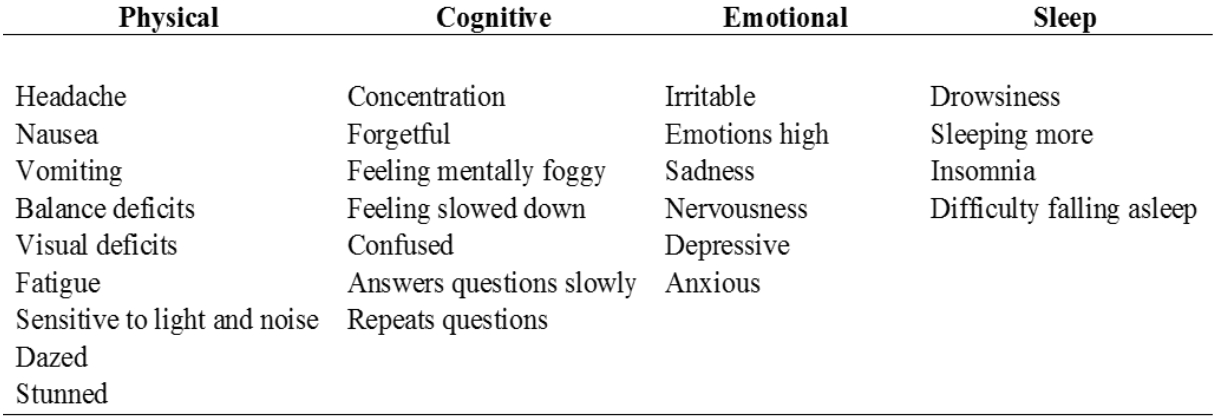
1.4 **Signs and symptoms**

The manifestation of signs and symptoms after a concussion follows a highly individualized and complex course. Assessing a concussion is exceedingly difficult as no two insults result in the same damage to cerebral function (Broglio and Puetz, 2008) and thus, no singular symptom can define a concussion. This complexity is exacerbated as the time course in which signs and symptoms present is completely individualised and unpredictable. There are symptoms which manifest at the time of a concussion that need to be assessed pitch side, but also ones that present in hours or days after which will require in-clinic assessments. Therefore, diagnostic procedures need to accommodate for both initial and extended assessments, appreciating the complex nature of signs and symptom development.

The discrepancy between what defines a ‘sign’ or a ‘symptom’, and what to measure is a further issue for diagnostic procedures. Signs can be observed directly by clinicians, whilst symptoms are reliant on the honest reporting of an individual. Notably, current assessment tools are heavily reliant on symptom reporting whereby the effectiveness of such a procedure is dependent on an individual’s compliance. An observable sign that cannot be tampered with by the individual may be of more value when providing an objective diagnosis. Considering this it is also important to appreciate the time course in which signs and symptoms are presented, as mentioned above. Acute symptoms are categorised as those that manifest in the minutes to hours after the insult, including headaches, vomiting and nausea (Barkhoudarian et al., 2011b). However, later symptoms manifest from days to weeks after such as changes in patterns to sleep, concentration and attention, forgetfulness and general memory dysfunction (Barkhoudarian et al., 2011b). It is imperative to distinguish between the time courses of symptoms in order to implement a successful diagnostic tool that can accommodate for both pitch side and in-clinic assessments.

Formally, loss of consciousness (LOC) was used as the ‘clinical hallmark’ that defined concussion (Giza and Hovda, 2001; Peerless and Rewcastle, 1967), which provided some objectivity in assessments. Whilst LOC can be recognized as a key symptom of concussion, it is not definitive and in fact LOC is not even indicative of the severity of a concussion (Kissick and Johnston, 2005). Instead, concussion presents as various signs and symptoms that can typically be categorized into one of four categories: physical, cognitive, emotional and sleep (Daneshvar et al., 2011; Dziemianowicz et al., 2012; Muir et al., 2014) (*table 1*).

Table 1: Adapted from Halstead et al., (2010) to demonstrate the types of signs and symptoms that one can expect to see in the event of a concussion, categorized under the 4 headings ‘physical’, ‘cognitive’, ‘emotional’ and ‘sleep’.



Physical	Cognitive	Emotional	Sleep
Headache	Concentration	Irritable	Drowsiness
Nausea	Forgetful	Emotions high	Sleeping more
Vomiting	Feeling mentally foggy	Sadness	Insomnia
Balance deficits	Feeling slowed down	Nervousness	Difficulty falling asleep
Visual deficits	Confused	Depressive	
Fatigue	Answers questions slowly	Anxious	
Sensitive to light and noise	Repeats questions		
Dazed			
Stunned			

1.4.1Categorizing signs and symptoms

As demonstrated in table 1 there is a variety of cognitive symptoms that commonly manifest after a concussion. Notably, cognitive assessments are those typically conducted pitch side, forming the cornerstone of concussion management (Aubry et al., 2002). Cognitive symptoms can encompass anything from confusion, forgetfulness, reduced concentration, irritability or sadness. Such symptoms manifest due to changes in neurological function, as a direct result of either impaired glucose metabolism, axonal injury or structural damage (Barkhoudarian et al., 2011b). In some cases, changes in cognition maybe obvious, the individuals are despondent to any instruction given. However, in most circumstances cognitive changes manifest within, and it is up to the individual to be honest and compliant when reporting these symptoms. Dependent on the extent of an individual's desire to play compliancy can be compromised and these symptoms can be overlooked, causing under-diagnosis. This is known as sandbagging where individuals will ignore or conceal the severity of their symptoms in order to continue play (Erdal, 2012).

A further set of signs and symptoms are categorized as 'emotional'. These include feelings of anxiousness, irritability, sadness or nervousness that can greatly inflict on an individual's RTP. In extreme cases concussion can also cause behaviour change, which can persist past the typical window of recovery if not managed sufficiently. As an outcome of such emotions, individuals can become severely depressed. These symptoms more typically prevail in a condition known as Post-Concussion Syndrome (PCS). PCS is a complex disorder categorized when a constellation of concussive symptoms are prolonged past the typical window of recovery (Willer and Leddy, 2006). If symptoms do persist beyond 6 weeks the worry about recovery time can have a significant effect psychologically (Willer and Leddy, 2006). Consequently, individuals become frustrated of not knowing when they will return to physical activity, creating irritability and inducing depressive-like symptoms.

The final set of signs and symptoms is categorised as 'physical', encompassing anything from a headache to visual deficits (*table 1*). This is perhaps the category that provides greatest insight as to whether a concussion is present based on their physiological nature. Notably physical symptoms such as headaches or nausea cannot be detected by a clinician and is completely reliant on the individuals to report. However, physical and physiological-based signs are less vulnerable to this manipulation, such as balance (Mancini and Horak, 2010). Balance abnormalities are commonly observed directly after a concussion, but also persist in hours and days after the event, longer than that of cognitive or emotional (Muir et al., 2014). It has been demonstrated that balance abnormalities observed during visual-kinaesthetic tasks are of the most common symptom presented after a sports induced concussion (Guskiewicz et al., 2003). Thus, detecting balance deficits immediately after the event is extremely useful for pitch side scenarios. What is also highly notable is the persistence of balance deficits; having key implications for implementation in to RTP procedures (Guskiewicz, 2011; Slobounov et al., 2006). Thus, balance provides great scope for a concussion assessment tool for both immediate and graded use.

1.4.2Pitch side assessment of signs and symptoms

As mentioned above, many symptoms are presented in the immediate stages after a concussion and require pitch side assessment. As each concussion manifests differently, one must appreciate that restricting the number of signs and symptoms evaluated can overlook a concussion. However, this is easier said than done, as clinicians cannot possibly accommodate for every symptom of concussion when forming a quick decision pitch side. Considering this focus should perhaps turn to a measure that does not rely on one clinician forming a rather quick and subjective decision and instead, focus on a measure that can be objectively quantified and understood by numerous people, including the player. For example, balance – a physiological measure that can be seen in the acute stages of concussion, and can provide quantifiable measurements based on Centre of Pressure (COP) analysis (Mancini and Horak, 2010).

1.4.3 In-clinic assessment of signs and symptoms

Assessing signs and symptoms extends much further than the initial periods after the insult. As mentioned, long-term symptoms can be anything from sleep disturbances, changes in concentration, forgetfulness or balance deficits (Barkhoudarian et al., 2011a). However, there is no definitive list, symptoms can be presented at different times, each unique to that particular event. Further, continuation of short-term symptoms after the typical window of recovery is also reflective of PCS (Willer and Leddy, 2006). Due to the fact that symptoms can persist or newly appear within the days after the event individuals should be re-assessed within a clinical scenario. Follow up assessments allow individuals to follow their recovery and engage in a RTP protocol to help get them back into sport (McCrory et al., 2013).

After an initial period of cognitive and physical rest, individuals should follow a graded RTP protocol. This is a clearly structured procedure tailored to the individual's need, whereby individuals progress through stages once asymptomatic from the last (McCrory et al., 2013). One must appreciate that recovery is complex, and athletes can get frustrated with new symptoms arising throughout the duration of the procedure. Consequently, RTP procedures are not so clear-cut, with many symptoms developing throughout that can be overlooked. Moreover, the RTP process is based on the subjective interpretations of one clinician, which is made worse by individual's suppressing their symptoms to hasten their RTP. Again, this exemplifies why a more objective and quantifiable measure needs to be ascertained in order to provide a more accurate diagnosis.

Overall, it is clear that signs and symptoms for concussion are much more complex than originally thought, creating subjectivity within assessments. Recognition of the time frame of development, whether it is a subjective symptom or an observable sign, all needs to be considered when developing an assessment tool. An objective balance measure may aid in negating the current guesswork by providing a physiological measure that cannot be concealed or tampered with (Mancini and Horak, 2010).

1.5State of the art assessment

In the event of a suspected sports concussion, the player is attended to immediately and evaluated on-site using standardized management and assessment tools. The clinician present will go onto the field and conduct a generic first aid assessment, dismissing any spinal cord injuries. In the situation whereby a clinician is not on-site the player should be removed from play imminently and taken to hospital. Once first aid issues are addressed the individual is then taken to the side for further assessment and symptom analysis. However, the rigor of such an assessment is highly dependent on the diagnostic tool adopted, the compliancy of the individual, and the environmental situation.

Neurocognitive assessment has been suggested to provide the most in-depth evaluation of an individual's functional state following a head injury, and as such been accredited as the cornerstone of mTBI assessment for many years (Aubry et al., 2002; McCrory et al., 2013). Traditionally examinations were carried out using pen and paper or, verbally to evaluate domains such as memory and processing which, at the time were deemed sufficient to detect cognitive deficits (Broglio and Puetz, 2008; Peterson et al., 2003). Since, advancements have been made and nowadays many opt to use computerized neurocognitive tests such as CogState, ImPACT and HeadMinder, based on their wide commercial availability. These tests operate by comparing the score obtained at the time of a concussion to a previous composite score. However, such tests are flawed by the inability to perform procedures in pitch side scenarios, which leads alternative measures to be explored.

The Standardized Assessment of Concussion (SAC) has previously been used as the predominant tool to assess an individual’s acute neurocognitive status pitch side (Dziemianowicz et al., 2012). The SAC encompasses a range of measures that focus on memory recall, orientation and concentration; all domains that are vulnerable to damage in the event of a concussion (Dziemianowicz et al., 2012; Mccrea, 2001). This test was initially developed to provide clinicians with a more objective and consistent method to assess concussion in the immediate minutes following a suspected injury. This test also benefits from its ease in administration, with only 5-7 minutes required to take the test. Notably, McCrea et al., (2001) used a group of concussed individuals and a group of uninjured controls to assess the effectiveness of the SAC. Both populations had previously had pre-season baseline scores established with the SAC. When a concussion was sustained, the SAC was repeated on the sideline immediately, and again at 48 hours’ post-insult. Results showed that in the immediate minutes after an injury, subject’s scores were significantly lower than baseline scores, and lower than controls. From results it can be deduced that the SAC is a valuable tool to detect acute cognitive abnormalities after a concussion, providing great utility for a concussion assessment tool.

However, the SAC also has drawbacks. The SAC is heavily reliant on obtaining verbal answers, overlooking many other aspects of neurocognition such as visual memory. This is identified as a fundamental problem, with studies establishing that the parts of the brain associated with visual memory, the dorsolateral prefrontal cortex and cerebellum, are those typically affected in the event of a concussion (Talavage et al., 2014). Thus, visual memory is an aspect of cognition, which is imperative to assess. Therefore, the SAC, which focuses on a specific part of cognition, could be deemed inappropriate. Individuals may not display impairments in this particular aspect that’s analysed, yet could be suffering from extreme neurocognitive damage elsewhere. This suggests that SAC should not be utilized as the prime measure of a concussion, but when incorporated into a test battery (McCrory et al., 2013)

In more recent years it has become apparent that such cognitive based assessments may not be as good as once thought. A key problem arises because cognitive deficits are not always displayed immediately, but can be delayed for up to several hours after the impact (Aubry et al., 2002). Therefore, at the time a pitch side assessment is conducted the individual could appear to have normal cognitive functioning and be deemed fit to play. Moreover, results of cognitive tests, on which the SAC is based on, are highly individualized. For example, individual's may have naturally low recall initially and be labelled as concussed if no prior testing had been conducted. Currently, not all teams and clubs adopt baseline testing in pre-season which makes such tests have little value. To make matters worse, individuals that complete such tests are often part of a team that are a superior standard than those playing at recreational, school or lower club level. It is often these elite individuals that 'sandbag' scores, purposefully performing poorly on initial testing and diminishing the potential difference between baseline scores and pitch side scores that are obtained in the event of a concussion.

Recently there has been emphasis on pitch side assessments adopting a more eclectic approach, appreciating the true nature of a concussion (Dziemianowicz et al., 2012; McCrory et al., 2013). For this reason, The Sport Concussion Assessment Tool (SCAT) is now commonly regarded as the gold standard assessment for concussion; accommodating for the vast symptomology presented (Dziemianowicz et al., 2012; McCrory et al., 2013). This tool contains a 22-item symptom checklist, the Glasgow Comma Scale (GCS), Maddox questions, Balance Error Scoring System (BESS) and the SAC. This comprehensive scale was a product of the Zurich Consensus – a conference whereby a group of individuals in the field of concussion meet to review the current situation (McCrory et al., 2009; McCrory et al., 2013). Such a tool appreciates the multifactorial nature of concussion; assessing numerous aspects of cognition, balance and symptom evaluation. For SCAT to be most effective a baseline score should be obtained in the pre-season period when the individual is asymptomatic. Thus, in the event of a suspected concussion, results can be compared to see if, and to what extent the individual has deteriorated (McCrory et al., 2009).

Due to the nature of pitch side assessment where it is of paramount importance to form a quick decision, tests like the SCAT are reliant on someone who is trained and can recognize errors quickly and efficiently. Thus, only a physician who has had extensive practice in these time-constrained conditions can carry out the test. This means the outcome is determined by the subjective decision of one clinician. This problem is made worse by the environment in which the final decision is made which can significantly influence the physician's outcome. A noisy stadium, with pressure to perform from the audience and coaches, can all contribute to making a hastened, insufficient decision (Lovell et al., 2004).

Moreover, some of the tests within the SCAT suffer from reliability issues, with many being vulnerable to the learning effect, such as the BESS (McCrory et al., 2009). Such a problem can make a test completely useless; recalling a right answer due to experience or learning may pass someone who is concussed as healthy, undermining the purpose of assessment. Furthermore, if a value has not been ascertained when the individual is asymptomatic, the score obtained in the event of a concussion has little value, failing to provide an accurate assessment of the individual's deterioration (Dziemianowicz et al., 2012).

Whilst much has progressed within sport medicine to move concussion recognition forward, there is still more to be done. Based on above discussion, it is clear there is still no tool in place to objectively diagnose a concussion. There is scope for a tool to be developed that is not based on the subjective decision of one individual, one that provides a definitive answer, accessible for all and that cannot be up for dispute. One such possibility fitting this criterion and can be exploited further is balance assessment.

1.6**Balance**

Balance, "the process of maintaining the COG within the body's base of support" (Guskiewicz, 2011) is vital for most tasks in everyday life, yet we seldom recognize its importance. As a human we are continuously moving around, interacting with the environment and objects within it. Even when we are engaging in something as simple as quiet standing, the body is swaying. This sway response is set on the premise that the head is always moving relative to the surrounding environment, so the way one views the world is never constant (Lee, 1980). In order for us to remain upright and counteract any sway, requires the complex action and interaction of the sensory systems, musculoskeletal system and nervous systems (*figure 1*) (Prentice and Kaminski 2004).

To maintain postural equilibrium all forces acting on the body must be balanced so that we stay in a desired upright position (Horak and Kuo, 2000), which means resisting external forces such as gravity. In order to retain this state of postural equilibrium information from the vestibular, visual and somatosensory system must be interpreted to determine where the body is relative to space, ensuring correct body alignment (Horak and Kuo, 2000). Such information can then be sent on to the CNS, where it is interpreted and refined to formulate an appropriate motor command. This motor command is further sent to relevant muscles to coordinate a response; introducing the role of the musculoskeletal system (*figure 1*) (Prentice and Kaminski, 2004). This system can then form an appropriate postural response, selecting a series of strategies and synergies to counteract sway and maintain balance.

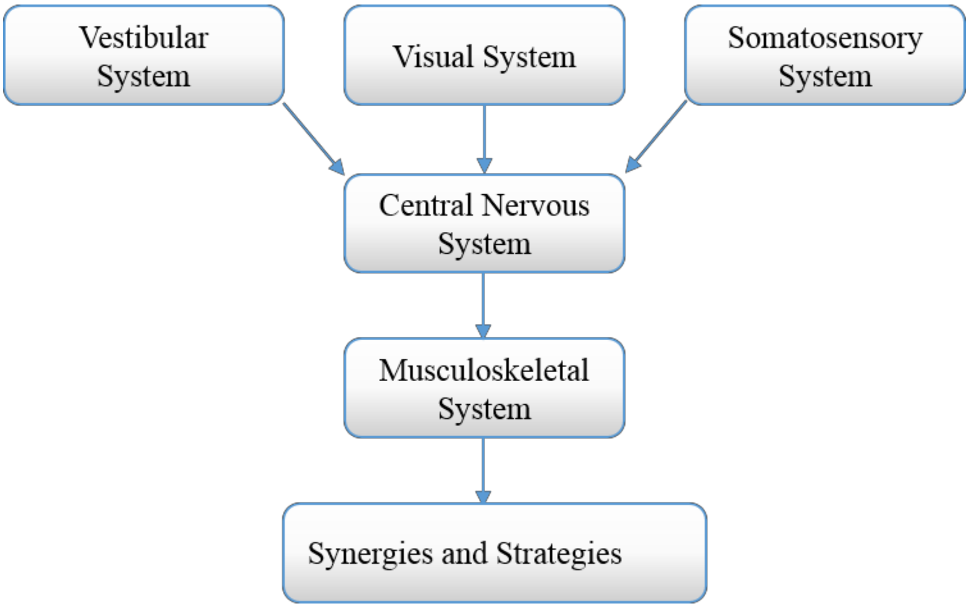


Figure 1: Adapted from Iwasaki and Yamasoba (2015) showing the process involved in the maintenance of balance. This starts from the three sensory modality systems, whereby internalized sensory receptors detect changes that have occurred in the environment. Once receptors are stimulated information is then sent to the CNS where it is processed and refined. The CNS will send the relevant information on via motor neurons to stimulate muscles. The musculoskeletal system is required to coordinate a relevant response through a series of synergies and strategies.

The role of sensory modalities and relative contribution of each can change dependent on the environmental situation and the availability of sensory information (Horak and Kuo, 2000). For example, when individuals stand on an unstable surface the availability of sensory input from the somatosensory system greatly reduces, and thus more reliance is placed on vestibular and visual systems to maintain balance (Mergner and Rosemeier, 1998). Equally, if someone's vision is impaired greater reliance will be on the somatosensory and vestibular systems. In both cases, the quality of information will be compromised compared to a scenario whereby all sensory systems are working optimally. What is notable is how this highly integrative system can accommodate for such impedances and retain balance even when a sensory system is omitted.

The quality of information received from sensory modalities is also dependent on how movements are coordinated; introducing the importance of movement strategies (Horak and Kuo, 2000). Muscular strategies provide sensorimotor solutions to control posture characterized by movement patterns, torque and contact forces (Horak et al., 1997). Horak and Nashner (1986) identified both an ankle and hip strategy implicated in balance maintenance, whereby different muscles are activated in response to differing perturbations. For example, in response to slow surface translations on a fixed surface, individuals will utilize an ankle strategy to counteract AP sway. In doing so, individual's centre of mass (COM) can be maintained through generating torque around the ankle joint to shift COP beyond the COM (Horak and Kuo, 2000). Conversely, a hip strategy is adopted to oppose rapid perturbations when the ability to produce ankle torque is impeded (Horak and Kuo, 2000). Whilst much research highlights the use of hip and ankle strategies (Horak and Kuo, 2000; Winter, 1995), alternative research more recently has highlighted that during quiet standing it is not just necessarily ankle or hip strategies that are required for balance maintenance, but in fact configuration from numerous joints (Krishnamoorthy et al., 2005). Whilst the appropriate selection of strategies is a topic of debate, such research clearly underpins the importance of muscular responses in the maintenance of balance (Horak and Kuo, 2000).

This brief overview of how balance is maintained establishes how complex such a skill is. Whilst historically it was viewed that the information provided from the vestibular system and the biomechanical information provided by the mechano-receptors was the most important for balance maintenance, this claim has more recently been opposed. Notably, it has been established, through a series of experiments utilising a moving room design to perturb the visual field, that we in fact place the greatest reliance on the visual system to maintain balance as it affords the most reliable information for balance (Lee, 1980; Lee and Aronson, 1974; Lee and Lishman 1975). It is therefore of importance, for the purpose of this thesis and the investigation into balance, to explore the role of the visual system further.

1.6.1The importance of vision in balance.

The visual system is perhaps the integral system required for the maintenance of balance. As eluded to previously, the head is always moving relative to our environment. Thus, the stimulus for vision is a continually changing optic array; the stimulus is spatiotemporal (Lee, 1980). The information such a system can provide about our environment, in addition to the orientation and movement of our body in space, demonstrates that it not only contributes via direct visual input but also from an element of proprioceptive input, 'exproprioception' (Lee, 1980). Thus, it can be explained that when normal vision is impaired either by perturbing the visual field, or by blindfolding, that body sway increases (Edwards, 1946). Notably, when the body is swaying there are properties within the optic flow pattern of the eye which will elicit that movement (Gibson, 1958). This concept was exploited in seminal work conducted by Lee and Aronson (1974) who investigated whether, and to what extent, does our postural control system rely on visual proprioceptive input. This study was amongst the first to utilize a moving room scenario to investigate the role of vision in balance control. Implementing this design meant that optic flow would either present with a similar pattern to what normally accompanies backward sway, or the opposite. Throughout the trials the room was swung by the experimenter from one locked position to the next. Results established that 82 % of responses were positive, i.e.: there was a sway, a stagger or a fall in the direction that the room was moving. This pioneering work grounded our understanding of why and how we sway, concluding that we make compensatory adjustments to posture in accordance with visual proprioceptive information that is available to us. From this study alone, it was concluded that visual proprioception is essential for the maintenance of posture. Moreover, this study highlighted, through the conflict created between mechanical and visual proprioception, that we place greatest reliance on the visual system to maintain balance. Knowing the importance of vision for balance control helps shed light into the development behind some balance abnormalities that have been presented in clinical scenarios, such as concussions.

1.7 The effect of concussion on balance

Balance dysfunction has been recognized as one of the most prevalent symptoms of concussion, with a supposed 30% of athletes sustaining balance deficits after such an event (Guskiewicz, 2011). Whilst these deficits will typically resolve within a 3-5 day period, like that of cognitive symptoms (Harmon et al., 2013), studies have proven that some individual's still experience balance deficits up to 30 days post-insult (Slobounov et al., 2006). Understanding exactly why such a symptom occurs is a matter of question, and involves an understanding of the pathophysiological nature of balance.

1.7.1 Pathophysiology of balance deficits in concussion

The pathophysiology of balance dysfunction is complex and somewhat inconclusive. However, there are opposing theories that attempt to elucidate the pathophysiology that causes balance deficits to occur. One such explanation that is repeatedly documented within literature suggests that postural deficits following a concussion occur due to the breakdown of communication between sensory modalities (Guskiewicz, 2011). As a result, there is a disruption between the information received and processed throughout the brain circuitry, initiating a balance response as individual fail to re-weight the sensory information available to them (Guskiewicz, 2011). Whilst the communication between the sensory systems is integral for balance maintenance, literature has confirmed that it is the vestibular system most vulnerable to damage in the event of a concussion (Guskiewicz, 2011). Thus, it is best to gather an understanding of the pathophysiological nature of this system to provide insight as to why balance deficits occur.

The vestibular organ is required to fixate the eyes on a stationary object whilst the head and body move, monitoring angular and linear acceleration in relation to the head (Prentice and Kaminski 2004). Such a mechanism involves two key structures of the vestibular system: the otolith organs; which are sensitive to horizontal and vertical acceleration, and the semi-circular canals; which detect rotational movement. In the event of a concussion hair cells embedded within the canals are damaged (Murray et al., 2014). Consequently, any information on spatial positioning that is received is impeded, causing postural deficits and dizziness that are often reported after a concussion (Mucha, 2012).

Whilst the damage physically caused by a concussion is not known, two mechanisms for vestibular dysfunction have been postulated. Vestibular dysfunction may arise due to direct damage to the peripheral receptors (Guskiewicz, 2011; Murray et al., 2014). This will either result in an inability to detect environment cues or, failure to provide accurate information on acceleration resulting in the reduced ability to orient oneself in relation to space (Mucha, 2012). Alternatively, vestibular dysfunction may occur centrally, where damage has affected the CNS ability to integrate, filter and communicate incoming afferent information (Guskiewicz, 2011). Consequently, this impedance to information will compromise individual's ability to maintain balance.

Whilst different researchers have offered their own alternative ideas of why balance deficits occur, which have not been addressed above, it is undisputable that the main reason behind manifestation of balance deficits following a concussion is the damage done to the sensory modalities. Notably, the use of postural stability testing is progressively becoming more commonplace within sport medicine (Harmon et al., 2013).

1.7.2 Balance assessment in concussion diagnosis.

Balance dysfunction is one of the key symptoms of concussion and hence, is an integral component for concussion assessment (Guskiewicz, 2011; Harmon et al., 2013). Based on the fact that balance has a physiological nature, it is one of the only symptoms that can be objectively measured (Mancini and Horak, 2010) thus making it harder to tamper and conceal, compared to more cognitive-based symptoms that can be overlooked. Consequently, over the past decade the use of balance assessment has become increasingly more adopted in pitch side assessments of sports related concussions (Harmon et al., 2013).

Formally, neurological examination of balance and posture was assessed through Romberg's test (Guskiewicz, 2011). This test exploits the sensory mechanisms that maintain balance: the vestibular, visual and proprioceptive system. By omitting the contribution of one of these systems, evaluation can be made on the effectiveness of the other two. Notably, this test chooses to omit the visual system, asking the individual to stand in an upright position and maintain balance for a minute whilst their eyes are closed. The clinician will then assess whether the individual sways or falls and will subsequently conclude whether a balance deficit is present. This test lacks objectivity as it is based on one person making an interpretation as to whether an individual has swayed enough to indicate a postural deficit. Moreover, this test can be considered effectively useless when analysing a population of elite athletes, who tend to score higher than the generic population on tests of agility and coordination. Consequently, Romberg's test has been deemed as too subjective and insensitive for diagnosis. However, technology has advanced and sports medicine has moved forward, thus more objective tools to assess balance have been exploited (Guskiewicz, 2011).

1.7.2.1The Sensory Organization Test

The NeuroCom Sensory Organization Test (SOT) is an alternative test that can be adopted to assess balance after a concussion. This is a high-tech assessment that uses a force plate system to measure dynamic posturography (Monsell et al., 1997) whilst visual, vestibular and proprioceptive information are selectively being perturbed. This is completed through eliminating information that would usually be delivered and utilized by the eyes, feet and joints to help maintain balance. Sway referencing is utilized throughout the SOT, whereby the platform in which the individual stands on moves in accordance with anterior – posterior (AP) sway. Thus, any useful visual or proprioceptive information is eliminated. By manipulating sensory information through either omitting vision, or somatosensory input a sensory conflict is created which will isolate each system, allowing for an in-depth assessment (Guskiewicz, 2011).

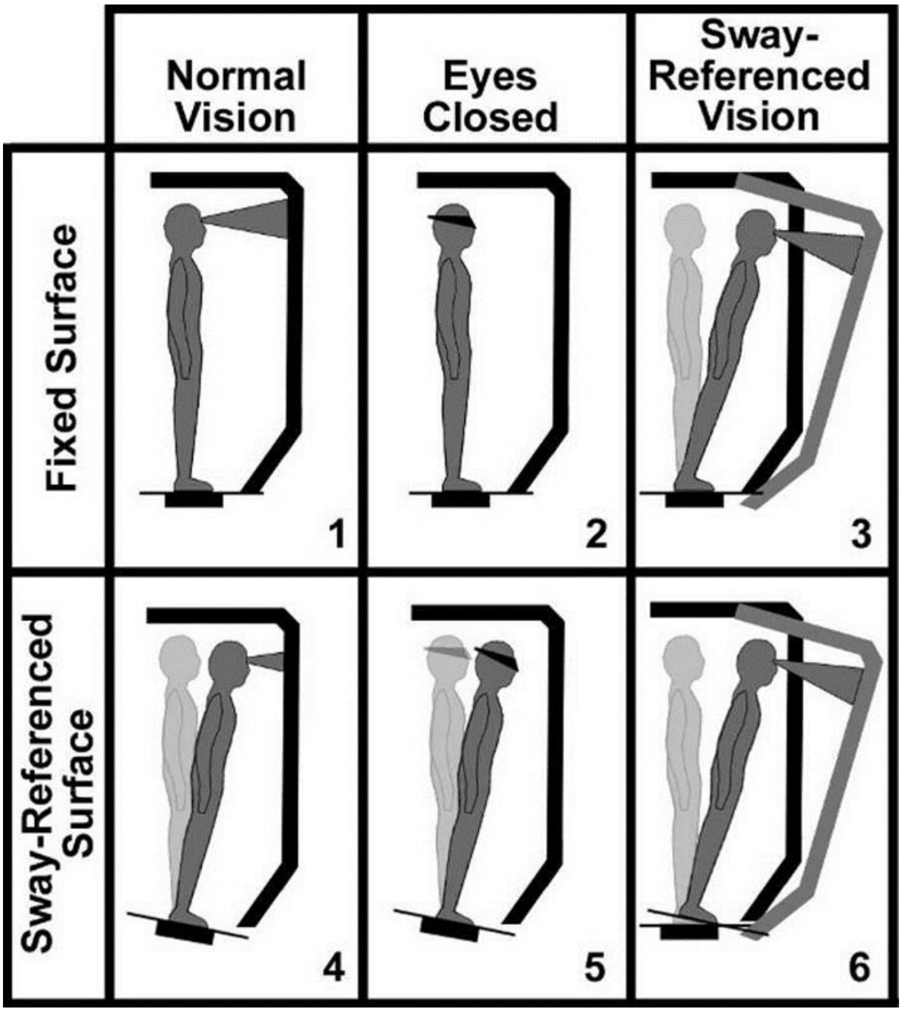


Figure 2: Taken from Resch et al., (2011) providing an illustration of the 6 different conditions of the Sensory Organization Test (SOT) that are required to assess the balance response and analyse the contribution from each of the sensory modalities. This figure demonstrates how in the 'fixed surface, normal vision' condition the individual is left un-perturbed. Whilst in every other condition, the visual system is either perturbed 'eyes closed' or the somatosensory system 'sway-referenced', or both. In the latter case (conditions 5 and 6) heavy reliance is placed on the vestibular system as the predominant source of sensory input to maintain balance.

The SOT is comprised of 3 x 20 s trials that are completed in three different conditions (eyes open, eyes closed, sway referenced) and on two different surface types (fixed or sway referenced) (Guskiewicz, 2011). The first condition acts as a control whereby the eyes are open and the surface is fixed, all systems are functioning as normal. This compares to condition two where the participant's eyes are closed, omitting the use of the visual system. Conditions three to six implement "sway referenced visual surround" whereby the platform tilts with an individual's sway response (*figure 2*). The SOT effectively assesses whether patients can oppose this false information provided by sway referencing. By manipulating each condition to selectively assess a system, an equilibrium score can be calculated from analysis of the individual's limits of stability, with higher scores indicative of better overall balance (Guskiewicz et al., 2001; Teel et al., 2013). To assess the contribution or deficit in each individual sensory modality, ratios are also calculated based on the relative difference on equilibrium scores. This provides an in-depth assessment of an individual's balance, as well as indicating what system may be impeded.

As explored above, the SOT has been repeatedly accredited for its ability to detect balance deficits. Guskiewicz et al., (2001) investigated postural stability in 36 collegiate athletes who had sustained a concussion, and 36 controls where no concussion was present. The SOT revealed, from a mean of individual's composite scores, that balance deficits were still present up to 5 days' post-injury. These deficits were most apparent within the first 24 hours, with recovery occurring gradually until day 5 (Guskiewicz et al., 2001). Such a finding establishes that the SOT is capable of detecting both acute symptoms in addition to the ones that manifest in the following days after.

This test is clearly robust in nature; however, it comes at a cost. The SOT is reliant on the use of laboratory-graded force plates to provide high frequency COP measurements. Whilst this is the gold standard to measure balance, it is extremely expensive system costing anything from \$80,000 to \$180,000 (Broglio and Puetz, 2008) an unviable amount, particularly when needed at lower levels where funding is insufficient. Not only is the SOT cost-prohibitive, it lacks portability making such a tool impractical for pitch side assessments (Pavan et al., 2015).

Notably, there is a need for an alternative low-costing, moveable device, which can provide sufficient measures on COP to assess balance (Huurnink et al., 2013).

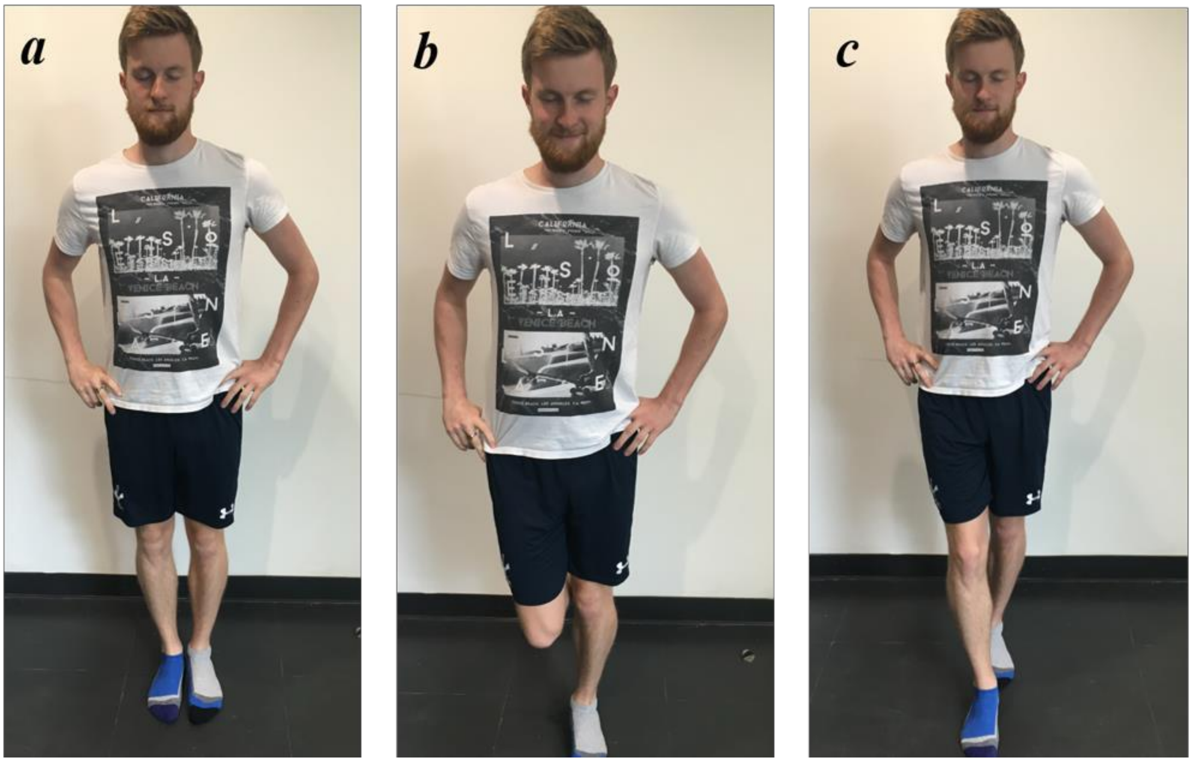


Figure 3: An illustration to show the different stance positions required for the BESS. The hands are placed on the iliac crests of the hips, with eyes closed. Individuals are required to complete a dual stance (a), a single leg stance on the non-dominant foot (b) and a tandem stance with the non-dominant foot behind (c). All stances are maintained for 20 seconds each and deemed incomplete if the individual cannot remain the stance for longer than 5 seconds.

1.7.2.2The Balance Error Scoring System (BESS)

A low cost alternative for balance assessment is the Balance Error Scoring System (BESS) (Guskiewicz, 2011). The BESS is a non-instrumented assessment of balance that requires minimum equipment, can be conducted anywhere, and is of little expense. The BESS assesses balance through asking the individual to maintain three different stances for a 20 s duration, these stances include a dual leg, single leg on the non-dominant side, and a tandem leg stance where the non-dominant foot is placed directly behind the dominant (*figure 3*). The individual is instructed to place hands on the iliac crests of the hip and, to close their eyes once they have found their balance. The contralateral limb should be maintained between 20^0 - 30^0 of hip flexion and 40^0 - 50^0 of knee flexion (Guskiewicz et al., 2001). Individuals are given feedback throughout to maintain this stance, in the event that they did lose balance; instructions are given on how to correct this.

Traditionally the test was conducted on a fixed surface whilst the individual performed the three stances on a fixed surface. Within the same test the individuals had to repeat the same routine and stances on a 10 cm thick foam surface. The more recently modified BESS (mBESS) requires just the use of a firm surface, which shortens the timeframe in which a balance measure can be obtained, more suitable for a pitch side scenario where quick assessments are key. In both the traditional BESS and the mBESS a score is obtained through the clinician totalling the number of errors the athlete makes (*table 2*).

Guskiewicz et al., (2001) investigated the effect of concussion on an individual's postural stability and their neurocognitive function using both the BESS and SOT. Both controls and injured subjects had baseline tests taken at the start of their respective season. As part of the methodological approach adopted, athletes that were injured had follow up tests at days 1, 3 and 5 of post-injury; accordingly, the tests were carried out on controls. Findings showed that those who had sustained a concussion manifested acute balance deficits. Whilst this is a key finding, what is more notable from this study is that the BESS was validated in alignment with the SOT. This implicates that the BESS is perhaps a more practical and cost effective tool to objectively assess an individual's balance preceding a concussion (Riemann and Guskiewicz, 2000). This is corroborated by McCrea et al., (2003), who examined the recovery course of individual's balance after a concussion. Baseline BESS scores were taken in a group of football player's preseason period. Players were then followed throughout their season, and those that had sustained a concussion were compared against the cohort that had not (healthy controls). BESS scores were similar between both populations at baseline, but the concussed group had significantly worse postural deficits after an mTBI was sustained. These values then returned to baseline 3-5 days after the concussion (McCrea et al., 2003). Overall, this study confirms that the BESS is capable at detecting balance deficits in the acute periods after a concussion, and thus emphasises its suitability as an assessment tool pitch side.

However, in more recent years the BESS has been a topic of debate, creating controversy within literature. The BESS has been flawed by poor test-retest reliability, lack of validity, practice effect and influence of external factors such as fatigue and musculoskeletal injury (Finnoff et al., 2009; Fox et al., 2008; Riemann and Guskiewicz, 2000). Given that the test is reliant on the subjective reporting of one clinician, which can be jeopardized by external influences such as the environment in which the final decision is made (Lovell et al., 2004); the accuracy and validity of the BESS can be questioned. Moreover, there is a lack of consistency in what defines an error which can be problematic when making a diagnosis; what one clinician sees as an error the other may not as the criteria is rather non-specific, e.g.: what classifies as moving hands off hips, it could be one hand or it could be two (*table 2*). This could jeopardize the validity between assessments as small balance deficits may be overlooked (Bell et al., 2011). In order to help ensure reliability the same clinician who originally administered the test at baseline should conduct the test again in the event of a concussion, in hope that the same errors are looked for.

Table 2: Adapted from Amick et al., (2015) showing a standard list of errors that a clinician is looking out for when conducting the Balance Error Scoring System (BESS) test.

Classification of Errors in Balance Error Scoring System
Moving hands off hips
Opening of the eyes
Step, stumble or fall
Hip flexion, abduction greater than 30^0
Lifting forefoot or heel off the surface
Remaining out of test position for over 5 seconds

Additionally, it has been questioned as to whether the BESS is an accurate indicator of concussion in the first place. Finoff et al., (2009) evaluated the interrater and intrarater reliability of the BESS. Here, three individuals experienced in administering the BESS were recruited and were asked to review videotapes of 30 individuals performing the BESS, accordingly providing a score on errors for each. Results demonstrated that the BESS has poor interrater and intrarater reliability, confirmed by the lack of consistent error detection between clinicians. This questions the reliability and validity of the BESS as a tool to assess concussion and obtain consistent measures on balance. Reliability of the BESS is further questioned with studies reporting that the BESS is vulnerable to learning effect. Mulligan et al., (2013) conducted a randomized control trial on young adults and established that repeated BESS testing induces a learning effect, which did not even terminate after the 4-week period. Collectively, the above questions the validity of the BESS as a technique and its reliability in obtaining accurate measures of balance and thus, concussion diagnosis.

The BESS has also been scrutinized for its ineffectiveness to accommodate for fatigue when assessing a concussion, which is vital given the context of when such an assessment would be conducted (Dziemianowicz et al., 2012; Fox et al., 2008). Fox et al., (2008) assessed the influence of fatigue on postural control on healthy individuals using both anaerobic and aerobic interventions. Each participant completed 2 counterbalanced sessions within a 7-day period with the BESS being conducted at 3, 8, 13 and 18-minute time intervals after the exercise. Interestingly, results established that exercise had a significant effect on postural control, which lasted up to 13 minutes after exercise was completed. This is a key flaw of the BESS and implies physicians should be aware of the fatigue window, which could significantly distort results. Clearly 13-minutes to wait and assess a concussion would be deemed inappropriate for sports such as Rugby where the head impact assessment time is 10 minutes.

Overall, whilst the BESS and the SOT have been accredited as sufficient tools to assess balance, there are key drawbacks with both techniques. Such profound drawbacks listed above question how useful either tool is for assessing a concussion pitch side. Consequently, this instigates the research into developing an objective pitch side assessment of balance further afield.

1.7.3 Virtual Reality (VR) as a novel balance assessment tool

In more recent years there has been exploration into alternative ways to assess balance, using revolutionary technologies such as Virtual Reality (VR). The concept of VR originates back to the 1900's, when it was established that moving visual scenes could induce ego motion, a term given to characterize the displacement of the observer within the environment (Warren, 1976; Lee and Aronson, 1964). This concept is exploited in many VR-based studies, which use visual perturbations to displace the individual within a VE, evoking a postural response. Perturbing the environment causes a discrepancy between the sensory modalities as the information that will usually be obtained through the visual system is impeded (Broglio and Puetz, 2008). Consequently, applying such a concept to a concussed cohort, where sensory input may be further compromised, has been shown to have a significant destabilising effect (Broglio and Puetz, 2008). This forms the basis of adopting a VR-platform to investigate balance, and therefore assess a key symptom of concussion.

When athletes experience impedance of information through perturbations there is a shift in attentional demand (Broglio and Puetz, 2008). Consequently, an individual's balance response will become exaggerated as the integrative control of balance is disrupted, initiating greater reliance on the proprioceptive and vestibular systems (Horak and Kuo, 2000). By measuring COP, which has been identified as the main clinical index for postural stability, (Teel and Slobounov, 2015a) a quantitative assessment of balance can be obtained.

The advancement of such paradigms provides promise for an exciting future of concussion diagnosis and suggests that the previous BESS and SOT approaches need to make way for this more novel and objective approach. The operation of VR is conducted through computer-generated simulation of a 3D environment where users can interact in real-time. Thus, VR can gage the true functioning of subjects in environments where they can behave naturally, offering heightened ecological validity and sensitivity when analysing behavioural dispositions such as balance. Moreover, VR modules are highly sensitive to movement and have the capability to detect extremely subtle deviances in both balance and cognition, which would be overlooked in present methods (Broglio and Puetz, 2008; Nolin et al., 2012; Teel and Slobounov, 2015a).

Figure 4: Taken from Slobounov et al., (2006) who adopted a 'moving room' as their chosen VR-platform to elicit postural perturbations.

Balance deficits become more apparent in concussed individuals when exposed to conflicting visual scenes (Wright, McDevitt and Appiah-Kubi, 2015). Slobounov et al., (2006) exploited this concept and assessed the applicability of VR as a diagnostic tool, using a concussed population of athletes. Participants took part in a VR moving room experiment on the day of injury and, on the 3rd, 10th and 30th day post-injury. Results established that balance deficits had resolved by 10 days however, abnormal responses were still displayed up to 30 day's post injury. This study proved that there is a significantly destabilising effect of motions within individuals that are concussed. Notably, what this study also highlighted is that such technology was able to detect the residual symptoms of concussion up to 30-days post injury. Clearly, this study emphasises the suitability of VR as a technology to assess balance both acutely and in the long-term.

However, it fails to promote such a tool for pitch side use. Firstly, this study utilized a force plate to obtain COP measures that is not only expensive, but also an immovable piece of equipment unsuitable for a pitch side scenario.

Moreover, the VR-platform adopted, ‘moving room’ *(figure 4)* is neither cost-effective nor feasible for assessing individuals on the pitch side. Whilst costing is an issue perhaps what is more of a concern when considering the moving room VR-platform adopted, is its ability to ensure immersion (Chiarovano et al., 2015), which could question any conclusions drawn from the study. Nevertheless, this study has confirmed the effectiveness of using VR to assess balance deficits within a concussed participant pool. However, it is clear that such a study did not consider the wider application of the findings and the applicability to adopt such a tool into a pitch side scenario. Thus, further evaluation needs to be sought into establishing a tool that is of little expense, easy to access and not laboratory constrained.

Notably, Wright et al., (2015) offered a preliminary study that assessed the reliability, validity and sensitivity of a VR-WBB system. From this study, it was deduced that such a prototype was highly effective in detecting subtle changes in balance in both a concussed and healthy population. Furthermore, it was evident that concussed individuals had significantly impaired balance abilities compared to healthy controls. Whilst this corroborated other’s work such as Slobounov et al., (2006), this study confirmed that a WBB offers a suitable alternative to the expensive, laboratory-constrained force plate, ensuring a balance system that is both inexpensive and portable. Whilst this is promising, one has to note the VR-platform that was adopted - a large screen TV, which is not suitable for pitch side scenarios and further, lacks a sense of immersion (Chiarovano et al., 2015). Nevertheless, it is clear that work is trying to advance VR within balance assessment, with much progression and investigation into the optimal prototype.

Not only can VR provide a potential tool for initial pitch side assessments, it offers a suitable modality for recurrent measures. Given that VR operates through computer technology, assessments are easily accessible and individual participant's data can be stored, saved and re-accessed. As mentioned above, such a system is capable of detecting balance deficits up to 30-days post-concussion, promoting a unique tool, which accommodates for both acute, and long-term symptom evaluation (Slobounov et al., 2006). Thus, implicating assessment of balance using a VR-WBB system into an athlete's RTP module could provide great promise for future uses.

As more modern balance modules such as VR are becoming progressively commonplace in sports medicine, individuals have started to research the effect of additive components; such as dual-task paradigms. Single-task paradigms such as the cognitive or balance assessments previously discussed in studies like Slobounov et al., (2006), are effective in evaluating that particular domain, but they do not appreciate any interaction occurring between systems. Given that any sporting scenario requires the integration of simultaneous information; motor, sensory and cognitive, which single-task paradigms do not accommodate for (Teel et al., 2013) it is imperative to pursue alternative avenues. In the event of a sport-concussion many systems can be impeded, exemplifying that measures need to incorporate assessing the integration of domains. For this precise reason dual-task paradigms can be adopted, incorporating both cognitive and balance assessments.

Researchers have explored the idea of employing an additive cognitive task into pre-established balance assessment tests. Notably VR offers an excellent platform to accommodate for the addition of cognitive measures, with studies confirming the effectiveness of Stroop implementation (Parsons et al., 2011). Teel et al., (2013) experimented this dual-task paradigm, by implementing a variant of the Stroop test into the SOT, concomitantly assessing balance and cognition. In this study individuals were instructed to click a button if the colour of the word conflicts with the colour of the font, assessing their reaction time in response. The addition of the dual-task occupied the individual's attention and subsequently, slower reaction times were displayed in response to the Stroop. Consequently, when an individual's balance and cognition is assessed concurrently, detection of more subtle deficits in cognition and deviances in COP can be detected (Guskiewicz and Broglio, 2011). Adopting such an approach provides heightened sensitivity when assessing a range of deficits that may occur with a concussion and, is something that should be considered when forming the RTP decision. With current cognitive and balance tests being scrutinized, adopting this dual-task paradigm may provide an extremely effective alternative to current assessments. Furthermore, it may help deter individual's attention making them feel more immersed within the environment.

Whilst development of VR-systems to investigate balance continues to progress, more time needs to be invested into refining the parameters of such a system to optimize efficiency. Slobounov et al., (2011) was amongst the first to investigate parameters of a VR-system, establishing that inducing perturbations in the 'x-axis roll' causes a significantly greater disturbance to individuals' balance, when compared to pitch and yaw conditions. Thus, deducing that the axis of a perturbation can manipulate an individual's balance response. Moreover, this investigation construed that perturbations elicit different affects dependent on the angle of tilt, establishing that the 10^0-30^0 range was most appropriate for inducing a significant balance response. Whilst this piece of research is promising, one has to consider the design that was adopted. Slobounov et al., (2006) and Slobounov et al., (2011) used a moving room experimental design to induce visual perturbations and, a force plate system to obtain COP data. Based on previous discussions it is known that this design can be questioned and flawed by its insufficient sense of immersion, cost, and portability (Chiarovano et al., 2015).

Moreover, there are many more parameters that are yet to be investigated such as the effect of speed of perturbation on the COP response. Therefore, there is much progress yet to be made when refining the parameters of a VR-WBB system that would be suitable for pitch side scenarios.

1.8 Aims and hypotheses

Consideration over all that has been mentioned leads to this thesis objective. The aim of this thesis is to develop a cost-efficient, accessible prototype to assess an individual’s balance, which has the potential to be advanced and used in pitch side concussion diagnosis. This will be developed through a series of stages. What first has to be established is whether the methodology adopted is sufficient to assess balance, i.e. whether a VR-system and WBB can operate together effectively to induce postural perturbations and evoke a balance response. After doing so, investigations within this study will look at refining the parameters of a VR-WBB system, in order to optimize efficiency of initiating a perturbation. In summary, the aims of the present study will be:

1) Establish whether a VR-WBB combination would make an effective prototype to assess balance, by inducing a postural perturbation through a VR headset, and recording the subsequent sway response through obtaining COP measures from the WBB.
2) Investigate the influence of manipulating the axes in which a perturbation is received, on an individual’s COP path length and balance response.
3) Investigate the influence of manipulating the speed at which perturbations are elicited, on an individual’s COP path length and balance response.

The following hypotheses are formed on the basis of previous literature and appropriate assumptions that have been drawn:

1) Combining a VR-system with a WBB will provide an effective means to induce postural

perturbations and evoke a balance response.

2) Perturbations elicited in the roll axis will cause significantly greater increase in COP path length than that of the pitch axis.
3) Manipulating the speed in which a perturbation is received will significantly increase COP path length, evoking a greater balance response than control trials.

CHAPTER 2

Methodological Developments

A key aim of the present study was to test whether a VR and WBB combination would be a sufficient tool to deliver a perturbation, evoke a balance response, and track the recovery. For such an aim to be investigated, what first needs to be established is whether the equipment adopted is suitable, data received is sufficient, and whether such a module can be easily accessed and manoeuvred. With establishment of this, further parameters within the module can be investigated such as the optimal speed and axes to elicit perturbations.

2.1**Measurements of balance**

Balance and postural stability are interchangeable terms, both defining the body's ability to return to equilibrium after exposure to a perturbation (Karlsson and Frykberg, 2000). For balance to be assessed researchers obtain measures on either Centre of Pressure (COP), Centre of Mass (COM) or Centre of Gravity (COG) (Jančová, 2008). COM can be defined as the location of all masses within a 3D system, with the vertical projection of COM onto the ground, being the COG (Winter, 1995). This differs from COP, which is known as the point location of ground reaction force (Winter, 1995). More simply, COP represents the total of distributed force applied to a supporting surface (Jančová, 2008); when one foot is on the ground the COP is within that foot; if two feet were on the ground, the net COP would be somewhere in-between depending on the weight placed on each foot (Winter, 1995). Consequently, COP is the most common descriptor adopted when assessing balance (Winter, 1995) based on its relationship with both COG and COM (Doyle et al., 2007). Thus, COP is the measure implemented into current clinical based force platforms (Winter, 1995) and the one that will be investigated throughout this thesis.

Historically, balance assessments such as the Romberg Balance Test were not reliant on COP measurements and were simply obtained through observational analysis to subjectively assess postural dysfunctions. Development has been made since, and balance assessments nowadays are reliant on force plates to obtain valid COP measures. Whilst this provides sensitive data to assess static balance the force plate is expensive, laboratory constrained, and requires technical operation (Clark et al., 2010). Clearly, this is an unsuitable tool to adopt when seeking to develop a balance assessment tool for a pitch side scenario. This emphasises the need to investigate alternative balance modules to overcome such caveats.

2.2 **Establishing the validity of a novel balance board**

The Nintendo Wii Balance Board (WBB) (Nintendo, Kyoto, Japan) is becoming progressively more utilized as a tool in assessment of postural control; its cheap, accessible nature makes it a suitable and attractive alternative to the former force plate (Bartlett et al., 2014). The device itself is a 23 cm x 43 cm platform that weighs approximately 3.5 kg, confirming its ease and portability. Incorporated into the platform are four force transducers that can wirelessly transmit vertical ground forces. Accordingly, this can track the movement of someone stood on top of the board, providing accurate COP data. The hardware of the WBB contains an inbuilt analogue to digital convertor so the board can communicate via Bluetooth, using a chip (BCM2045) to allow for connection within any external device. This ensures that the WBB can be transported anywhere as long as a Bluetooth connection is available. However the sufficient portability, low-cost and widespread availability of WBB could be overruled by the lack of valid and reliable COP data obtained. Thus, many studies are beginning to look at whether the WBB is a sufficient platform to measure balance, making direct comparisons against the expensive, gold standard force plate.

Clark et al., (2010) assessed the reliability and validity of the WBB by making direct comparisons of COP data to the force plate (AMTI Model ORG-5). Here, subjects adopted both single and dual-leg stances in conditions where eyes were either opened or closed. In single leg stance conditions subjects stood still for 10 s, opposed to the 30 s duration for dual-leg stances. Assessments were collected from the WBB and force plate on separate occasions in a counterbalanced fashion. Results confirmed both devices exhibited good test-retest reliability with little differences displayed on COP path lengths between the devices. Pavan et al., (2015) corroborated this using a different methodological approach to compare COP data between platforms. Here, simultaneous COP measurements were obtained through placing the WBB on top of the force plate. This approach eliminated the risk of results being violated by a test-retest procedure where large differences can be displayed between trials on the same subject. Results demonstrated that the force plate is undoubtedly more accurate than the WBB, which tended to underestimate maximum oscillation along the A-P direction. However, the WBB was still able to produce sufficiently sensitive data on COP measurements. Given the ability of the WBB to overcome the caveats associated with the force plate, in terms of affordability and portability, these minimal differences in sensitivity to COP measurements are overruled. From this, it can be confirmed that for the purpose of this investigation, the WBB is a sufficiently valid tool to assess balance.

2.2.1 Calibration

A calibration procedure was implemented in order to ensure that the error rate between sampling was reduced and measurements obtained were of sufficient accuracy to be used for a valid assessment of balance. However, much ambiguity arises when deciding the precise method of calibration to adopt. Previous research has explored various point loading procedures to calibrate the WBB, allowing us to evaluate the most appropriate procedure to adopt for the present study.

Leach et al., (2014) employed a point loading calibration procedure that exploited the inverted pendulum system model, and consequently, simulated postural sway. In this investigation weights were added to each corner of the WBB and loaded to the 'tolerable weight' of 16 kg. Additional weights were then added at the base of the pendulum to stabilize the device, making the total mass of the system 58.3 kg; mimicking the weight of an average human being and upper tolerable weight of the system. Accordingly, the present study adopted a similar procedure, whereby two known masses were loaded onto predefined points on the board. These predefined points were established from the position of load cells; calculated by measuring the length and width of the board to allow for accurate establishment of each quarter. From this, measures were found for the x axis (80.6 mm) and for they axis (4.3 mm). This allowed establishment of the midpoint of the foot (67.6 mm). Each quarter was then marked on the board with tape and labelled 1,2, 3 or 4 *(figure 5a)* with a dot in the middle of each to signify a point to align the weight. Weights of 41.6 kg were then added to each calibration point accordingly *(figure 5b).* Such weights were chosen to mimic the closest weight, that was also available in the laboratory, adopted in Leach et al's., (2014) protocol. When the weight was located precisely in alignment with the respective mark a calibration trial was run through Unity, which programmed each calibration point. Once each of the four points had been calibrated additional weight was added, making a total weight of 48 kg. The same four trial sequences were performed as before but with the addition of this extra weight.

Knowing the mass of an object at a known point on the board meant sensors could be adjusted accordingly to standardised values. Moreover, an appropriate matrix could be applied to any data that was obtained, creating COP coordinates along both x and y-axes. Calibration trials were run through the computer programme Unity ensuring that individuals COP was tracked relative to the calibration point, concomitantly to relaying COP data back to the computer.

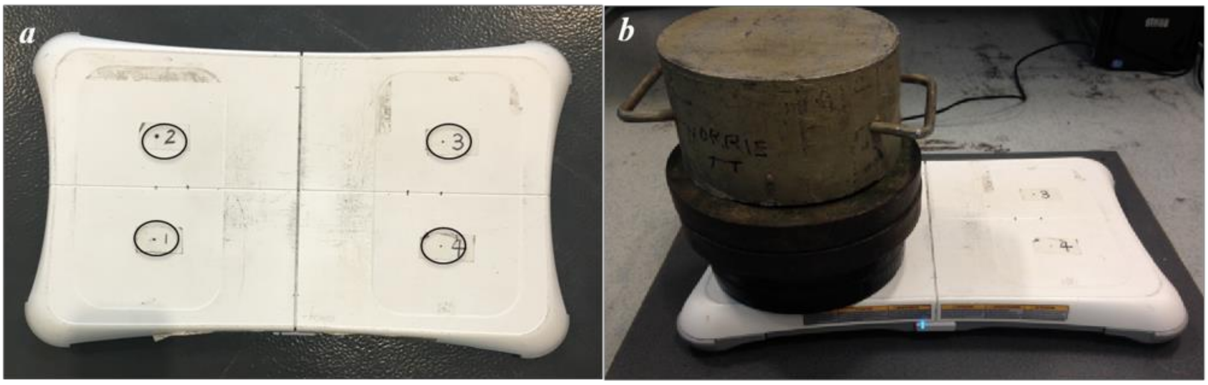


Figure 5: The calculated points to indicate the location to apply the weights for calibration (a) and an example of the 41.6 kg weight aligned at calibration point 1 on the WBB where the calibration trial started (b). This procedure was conducted in order to ensure that individuals COP response was tracked relative to a pre-defined calibration point.

2.3 **Development of a VR-WBB system**

Based on the above findings of piloting and through corroboration with previous literature, it was confirmed that the WBB produces data or sufficient sensitivity to assess balance. Whilst this ascertains a module to investigate balance, what was left to be determined is whether such a system can work in cooperation with VR to selectively perturb an individual to assess the balance response.

VR is an emerging technology that was originally developed for use in the gaming industry. More recently VR has made breakthroughs into the healthcare industry, with promising research suggesting its implication as a rehabilitation tool for balance in those suffering from neurological complications (Gil-Gómez et al., 2011). However, little has been done to implement VR as an assessment tool for balance. By manipulating the graphics within the VE, the visual-vestibular processes can be challenged; with potential to unveil deficits in neurological processes (Guskiewicz et al., 2003). Consequently, VR has been proven as an effective means to evoke perturbations and cause a balance response (Slobounov et al., 2006). Such studies have evaluated this balance response through obtaining force plate measurements on COP (Slobounov et al., 2006; Teel and Slobounov, 2015a). As discussed, the force plate poses many limitations when attempting to develop a cheap, portable device. Thus, the second stage of piloting looked at assessing whether a VR-system could be utilized alongside a WBB to produce perturbations and subsequently evoke a balance response that could be quantified.

Figure 6: An individual participant adopting a dual stance position with feet together and hands on the iliac crests of the hips. This position is maintained whilst the individual is wearing the Oculus Rift headset. The individual will see a virtual environment within the headset.

2.3.1 Establishing which VR platform to adopt

When attempting to develop a VR-system, evaluation over the different platforms of VR needs to be considered in alignment with what the overarching purpose is. There are many different VR-platforms that can be implemented, with previous studies adopting TV screens or whole room experiments as their chosen medium (Slobounov, Sebastianelli and Newell., 2011; Wright, McDevitt and Appiah-Kubi, 2015). However, these VR-platforms have been criticized for their lack of immersion, as well as their expense and insufficient portability (Chiarovano et al., 2015). Thus, for the present study alternative platforms were investigated to overcome such caveats and adopt a tool that was portable, cheap and immersive. Using a HMD as an alternative visual platform allows any head movement that individuals produce to be tracked by a detective system that is integrated into the display (Chiarovano et al., 2015). Consequently, this permits the individual to feel immersed within the environment Chiarovano et al., 2015). In addition to this, the HMD is a portable piece of equipment and thus, for the purpose of this investigation that had the aim of developing a portable device, was the most appropriate VR-platform to employ (*figure 6)*. The selected HMD for the current study was Oculus Rift (Oculus, VR, Irvine, California, USA). Data obtained from the rift can be converted into computerized data and utilized for online analysis.

For inducing perturbations within the Oculus Rift headset the computer program Unity (Unity Technologies, USA) was adopted and for the purpose of piloting, a basic custom-built 3D VR script was written. The script comprised of a visual scene that mimicked an open plan dining room with a TV, table, chairs and various other furniture incorporated (*figure 7a*). Within this script different trials could be conducted to manipulate the axis of perturbation in the visual field, such as "pitch up" (*figure 7b*) or "roll right" (*figure 7c)*, interspersed with a series of control trials.

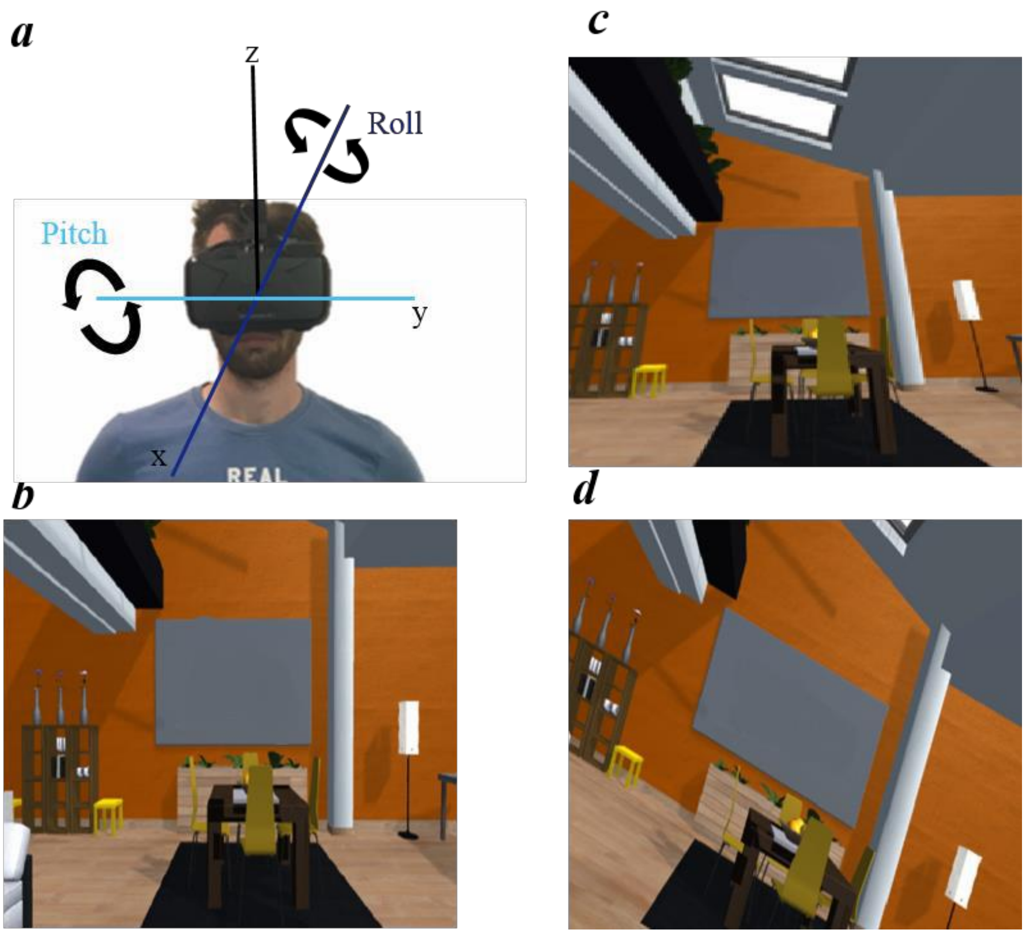


Figure 7: An illustration to show the effect of a perturbation when induced across different axes, with arrows highlighting the rotational effect in x-roll axis, and y-pitch axis (a). This is directly relatable to the screenshots taken of the visual field within the present study; showing the rotation effects experienced when perturbations are elicited through “pitch up” (c) and “roll right” (d) perturbations. These perturbation conditions directly compare to control conditions whereby no disturbance to the visual field is inflicted and thus the visual field is normal alignment (b).

Notably when individuals participated in these perturbed conditions a clear balance response was evoked. When overviewing the COP data obtained from the WBB, it was clear that perturbations caused a substantial increase in COP path length. Notably, the VR-platform adopted suitably evokes balance responses that can be detected by the WBB. However, the effectiveness of such a system could not be fully confirmed until questions were asked to the individuals regarding how much they felt immersed within this system. When using VR for any purpose it is of paramount importance that the individual believes they are in the VE, to ensure interaction with the system (Chiarovano et al., 2015). The device adopted in the present study has been promoted as the one that best ensures immersion, with images projected through the headset moving in accordance with the head (Chiarovano et al., 2015). However, on initial piloting individual's reported that they felt unengaged and not immersed with the system. As seen in figure 7 the visual scene is basic and unenticing, which could have caused individuals to get bored and undermine the belief of being in a VE. In reaction to these comments, procedures were investigated to help engage the individual and interact with the environment, these are explored below.

2.3.2Dual-task paradigm

The present study adopted a dual-task paradigm, implementing an additional cognitive task that was to be completed concomitantly with the balance assessment. This meant that whilst the individual maintained their balance (primary task) they also had to complete a variant of the Stroop, which was inputted into the virtual field (*figure 8*). The Stroop operates as a cognitive task of divided attention whereby the participant is required to read the colour of the word, instead of what the word actually says (Stroop, 1935). In figure 8 the word 'red' is written, yet the participant would have to answer 'yellow', which is the colour of the word. This dual-task was implemented to focus the individual's attention throughout the trials to ensure that they were immersed. This was based on literature emphasising the importance of immersion for efficacy of a VR-system (Chiarovano et al., 2015). However, it is important to note that such a test can also be used to assess cognition, which is of particular importance for a concussed athlete pool. Studies utilize the Stroop as an individual assessment of concussion to measure domains such as attention, executive function and reading speed (Parsons et al., 2011). Whilst the Stroop has been implemented for immersion purposes in the present study, this opens up doors for other dual- paradigm procedures to be implemented to test aspects like cognition. Furthermore, an array of different tests could be incorporated into such a paradigm encompassing domains like reaction time, or visual memory.

Figure 8: A screenshot taken after the Stroop Test had been implemented via Unity. Taken from this illustration, individuals would have to say the colour 'yellow' whilst the word written is the colour red. This is a task of divided attention, but was inputted into the design to ensure the individual felt immersed within the virtual environment.

In order to ensure that the Stroop was effective, investigation into exactly when the words would be presented, how fast, and the interval between each word needed to be established. Such specifics on Stroop delivery were established through trial and error, whereby variables could be selectively altered and implemented online through Unity. Feedback from participants that took part in piloting expressed that when words were presented too fast, immersion was compromised; individuals did not have time to vocalise the words. From further investigation that trialled different time intervals, it was deduced that a 2 s duration between each word provided optimum time for individuals to say the word: short enough time to be able to vocalise, yet not too long that attention was compromised.

From review of this piloting it could be confirmed that a valid, novel system to investigate balance was generated. Conclusively, a key aim of this investigation was met: a system had been developed that incorporated a novel balance module, VR and a test of immersion. Confirming this permits the investigation into refining the parameters of a VR for optimal assessment of balance.

2.3.3Investigation into the parameters of a VR-system

Research into refining the parameters of a VR-system for the present study was provoked by the work of others. Primarily, Slobounov et al., (2011), who was amongst the first to recognise that establishing VR parameters is integral for the rigor of balance assessment. Here, Slobounov et al., (2011) compared normal volunteers (NV) to concussed individuals, and assessed their response to perturbations in roll, pitch and yaw axes. Results deduced that roll axis perturbations were more destabilizing than pitch and profoundly more destabilizing than yaw axis perturbations that had no significant effect at all (*figure 9*). Whilst these findings are notable, this study adopted a 'moving room experiment' for their VR-platform which is neither portable nor cheap and thus, not sufficient for pitch side use. This is a key reason that underpins why the present study adopted the HMD. Given that different VR-platforms have been used previously, it may be that different responses to perturbations are effected by the particular design adopted; suggesting that investigation into refining perturbation parameters is required when using the alternative, HMD.

Whilst axis of perturbation has been loosely investigated within literature, investigation into the parameter of speed is scarce, with no studies as of yet focusing primarily on this variable. A preliminary study conducted by Wright et al., (2015) investigated the validity of VR balance system to assess mTBI symptoms. For the purpose of this study, a speed of 60 ^{0}/s was adopted for perturbation tilts. However, there was no justification as to why such a speed was used, and whether any effect was sought. This speed of 60 ^{0}/s was appropriately implemented into piloting; however, no effect on balance was displayed. Given that Wright et al's., (2015) preliminary study utilized a TV screen as their VR medium, the effect of speed of perturbation, using a more immersive VR medium such as HMD, is going to be different. Consequently, it would be insufficient to rely on previously established perturbation speeds that had been obtained using other VR-platforms. Thus, effect of tilt speed remained a parameter that had not been investigated.

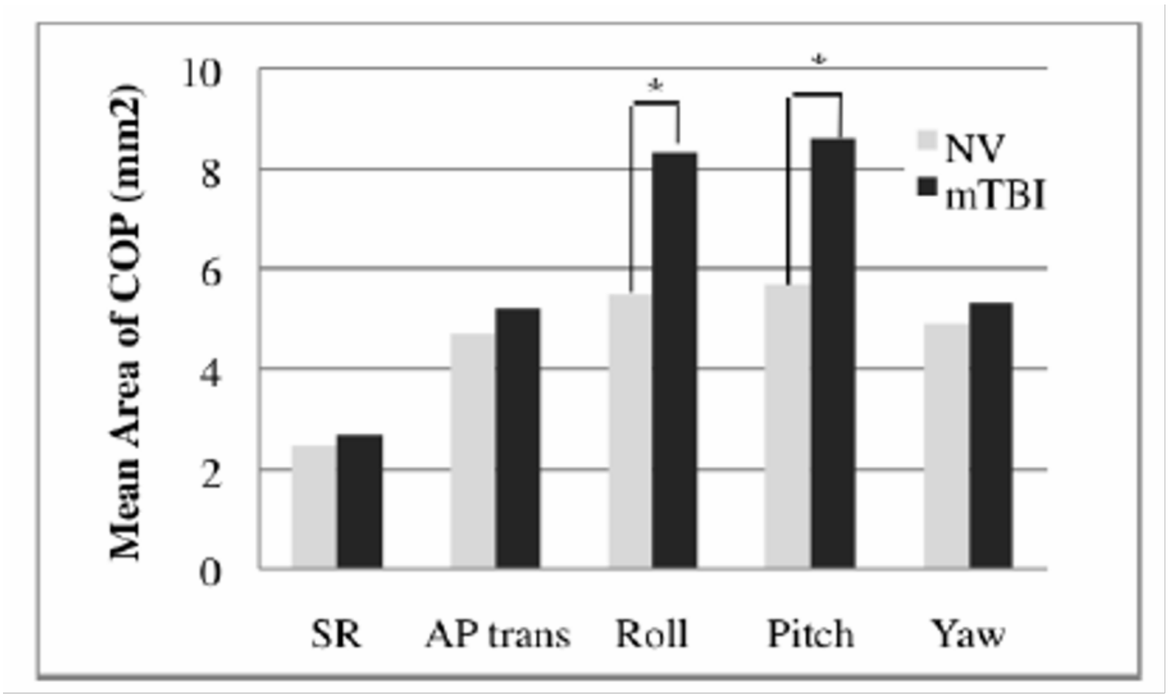


Figure 9: Taken from Slobounov et al., (2011) to show the number of successful trials (i.e. no loss of balance) in normal volunteers (NV) to mTBI subjects. Mean COP area for responses taken during both a stationary condition and perturbed 'moving room' conditions, whereby the virtual field is perturbed through roll, pitch and yaw. Perturbations elicited through roll and pitch axes caused a significantly greater increase in COP area for the mTBI population when compared to controls ($p<0.01$). However, no effect was seen for perturbations in the yaw axis.

Consequently, the second aim of this study was formed on the back of work conducted by Slobounov et al., (2011) who established an optimal angle range of 10 – 30 ^{0}. Accordingly, initial piloting procedures conducted trials to explore the intermediates of these range of angles. From this, speed parameters could be set in accordance as the angle of tilt directly affects the speed of tilt. As an outcome of piloting procedures, the optimal angle established was 22.5^0, whereby a sufficient balance response was evoked in all individual is piloted. This angle was set primarily because any angle tilt in excess caused extreme flexion of the neck to the point that individuals were unable to read the Stroop words. Thus, the Stroop limited the implementation of any angle that exceeded 22.5^0. Establishing this angle meant a range of speed parameters could be set in accordance so that the desired tilt angle was met each time, thus the adopted speed range for this study lay between 4.5 ^{0}/s to 11.25 ^{0}/s.

CHAPTER 3

Study Design

Confirming that the VR-WBB system is a suitable methodological approach meant further questions based on this design could be investigated. Thus, the second part of this thesis focused on refining the parameters of a VR-system. One of the aims of the present investigation was to investigate the influence of speed of tilt of perturbation on an individual's balance, whilst the other was to investigate the influence of axis.

This chapter will be an overview of the study design required for establishing the parameters of a VR-WBB module, including participant information, measures and the protocol. This section is applicable for the two cohorts of individuals that were recruited for the purpose of refining the parameters of a VR module for a balance assessment tool.

3.1**Participants**

63 healthy participants were recruited via email in a sample of convenience from the School of Sport, Exercise and Rehabilitation Science department at the University of Birmingham. Upon entry to the laboratory, participants were given a full briefing detailing what participation would entail. Prior to starting individuals were screened for any contraindications of a VR-system, using a pre-established screening tool – see Appendix. A. Participants were given the opportunity to familiarise themselves with the participant information sheet that was emailed previously before filling in the consent form and demographics questionnaire that was required– see Appendix B. Reassurance was given to participants to ensure they knew they could withdraw from the study at any time, without having to disclose any particular reason. The present study was approved by the University of Birmingham STEM committee (ERN11-0429) and conformed within guidelines presented by the Declaration of Helsinki.

For the purpose of this investigation participants were equally and randomly assigned to either the speed group or the axis group whereby they either received a series of axis manipulated perturbations or speed manipulated perturbations.

3 participants were excluded from analysis, which meant a total of 30 were analysed in the speed group (expressed as M ± SD) (20F, 10M, age = 19.6 ± 1.3y, height = 171.1 ± 9.1 cm, body weight = 68.1 ± 10.7 kg) and a total of 30 were analysed for the axis group (17F, 13M, age = 19.4 ± 1.17y, height = 174 ± 10 cm, body weight = 68.8 ± 13.5 kg).

3.2**Procedure**

All testing took place in the Neurorehabilitation Video Analysis Laboratory in the Sport and Exercise Sciences building at the University of Birmingham. Upon arrival, participants were asked to complete a series of forms: a participant-screening tool, a demographics questionnaire and an informed consent form. Participants were then seated and given a full debrief by one of the investigators of what participation entailed before receiving a visual demonstration. In a familiarisation period the participant practiced adopting the required position that was demonstrated by the investigator; placing their hands on the iliac crest whilst their feet were together (*figure 6).* Initially this was trialled without the participant wearing the HMD, and then again with the HMD headset on, to experience the effect of the additive weight. Once the stance was mastered with the HMD the individual had to remove any footwear and stand on marked locations of the WBB to establish an accurate position. The Oculus Rift was then secured round the head with comfortable adjustments amended to the requirement of the individual, ensuring no discomfort was felt. A washable cover was fitted around the frame of the headset, which was disinfected between each participant.

Figure 10: A screenshot taken of the calibration phase which was implemented prior to each block of new trials. This figure illustrates a red dot, which signifies an individual's COP. Individual's would shift their weight in response to the location of the red dot, aiming to get it at the cross hair in the middle. This procedure provided direct feedback to the individuals about their balance to ensure that at the start of trials, each individual was as close to their postural equilibrium as they could be.

Prior to each experiment a procedure was conducted to connect the WBB, via a Bluetooth connection, with the Microsoft computer in which the programme Unity was run. This procedure was necessary to ensure the WBB was calibrated in alignment with the VR, a note of the calibration and corresponding trial was made in the lab book for later analysis. The program Unity was then opened and the predefined 'axis' or 'speed' test was loaded. This contained the script, which either altered speed of perturbation tilt, or the axis of perturbation. A familiarisation trial was run prior to starting to ensure that individuals COP was within their BOS, finding their postural equilibrium. Here, the individual stood on the WBB and altered their balance according to the position of the red dot, which provided direct visual feedback on their COP (*figure 10*). Participants were asked to adjust their balance so that the red dot was as close to the centre of the cross hair as possible. This calibration period was conducted before each trial to act as a baseline, ensuring that any deviances in COP made after this point was more likely to be due to a perturbation and not the fact that balance was not controlled.

Both speed and axis investigations were of the same layout with each consisting of 4 blocks of 8 trials that were each 20 s long, making a total of 32 trials altogether for each participant (*figure 11*). Perturbations were induced in a randomised fashion ranging from 5 - 10 s; ensuring participants did not anticipate the type of perturbation that was going to be presented next. For each individual trial 10 words of the Stroop test were projected within the VE, with each word separated by a 2 s interval. Investigators stood beside the participant, looking for errors that occurred. There was a 10 s rest between each of the trials and a further 5-minute break between each of the blocks to prevent cognitive and physical fatigue.

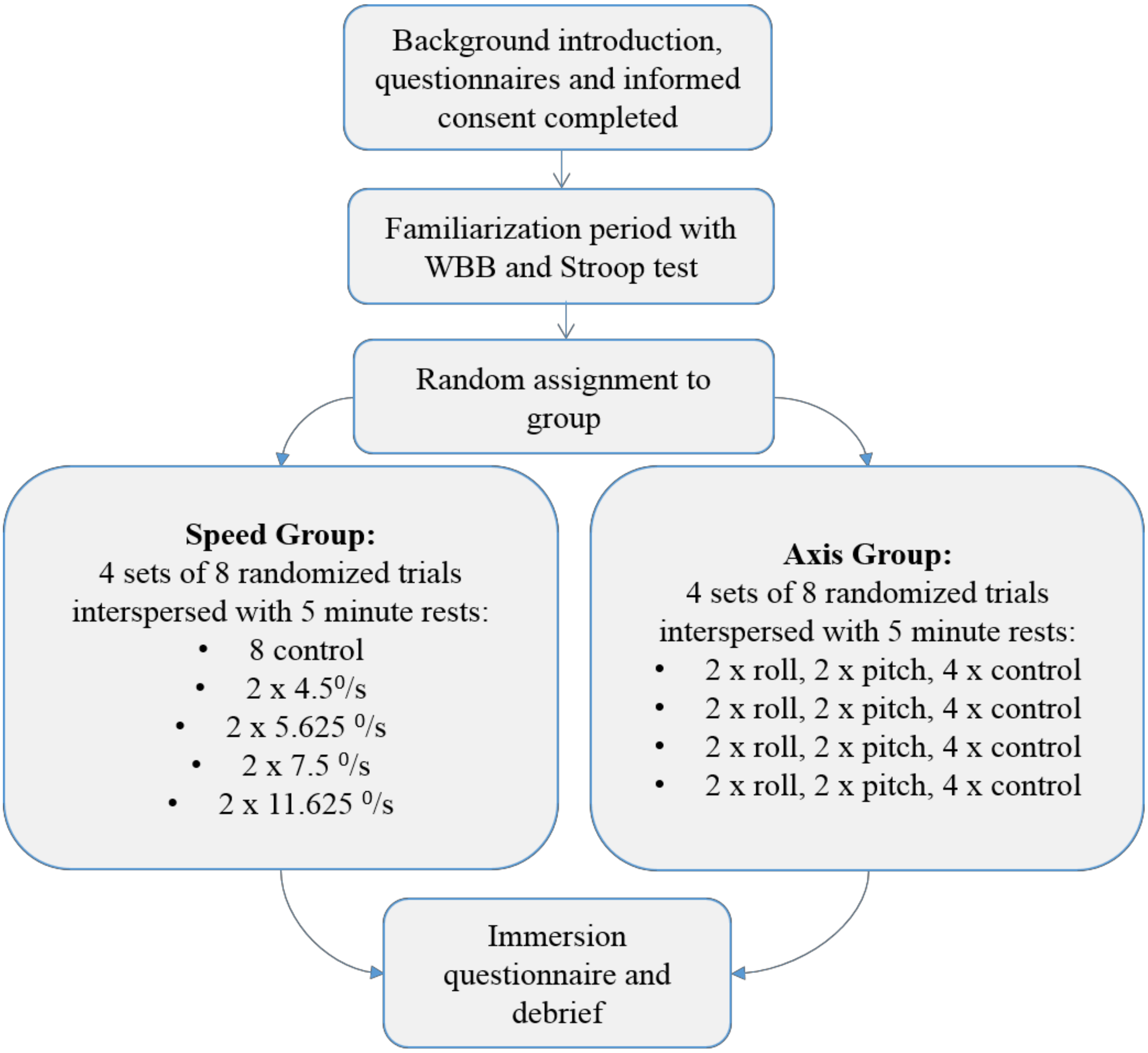


Figure 11: An illustration to give an overview of what participation entailed for each individual. This diagram shows the flow of events from as soon as the individual came to the laboratory and signed the consent form, till procedures at the end of the study where the participant was debriefed.

During trials, participants were given verbal feedback to ensure the correct stance was maintained throughout “keep your feet together”, “maintain hands on hips”. Alongside the direct visual feedback provided at the beginning of each trial *(figure 10*), verbal feedback further ensured individuals were doing their best to maintain balance. COP measures are sensitive to even slight alterations in individual's postural dispositions highlighting the importance of verbal feedback to help reinforce that balance is maintained.

After the study, individual's were administered an immersion questionnaire to evaluate how much they believed they were in the VE. This consisted of 10 questions, adapted from Gil-Gómez et al., (2013) including questions such as 'how much did you sense to be in the environment of the system' and 'to what extent were you able to control the system'- see Appendix C. The answers to questions were ranked using a 5-point Likert scale; a rating scale used to evaluate individual's opinion towards a specific subject. Questions asked about the effectiveness of the VR-system were graded on a scale from 1 – 'not at all' to 5 – 'very much', whilst questions asked regarding the difficulty of the tasked being graded from 1 – 'very easy' to 5 – 'very difficult'.

Within the study several precautions were taken to ensure the wellbeing of the participants. Prior to the study, each investigator had taken part in manual handling sessions. Manual handling is characterized as the supporting of a load by hand or by bodily force including pushing, pulling or lifting movements (Carrivick et al., 2001). These sessions made each investigator aware of what to do if an individual fell of the board. Accordingly, for every trial two investigators were stood either side of the participant.

3.2.2 Speed study

The purpose of this study was to establish whether the speed of tilt of a perturbation influences an individual's COP response. Across the 32 trials, there were 4 perturbations of each speed: 4.5 ^{0}/s, 5.625 ^{0}/s, 7.5 ^{0}/s and 11.25 ^{0}/s induced in the roll axis, with perturbations received being in both anti-clockwise and counter-clockwise directions. Each speed-perturbed trial was required to reach a perturbation tilt of 22.5^{0}. Notably, reaching this desired angle took longer for different speeds. Figure 12 exemplifies that the faster speed of 11.25^0/s took 2 s to reach the desired tilt angle, 7.5^0/s to 3 s, 5.625^0/s to 4 s and 4.5^0/s to 5 s. Thus, all speed perturbations took equal or less than 5 of the 10 s of post-perturbation analysis.

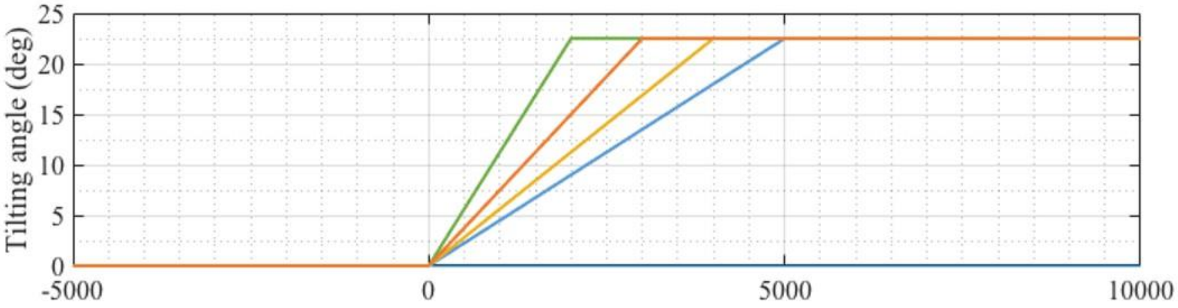


Figure 12: An illustration to show each of the speed-perturbed trials and time it took each speed to reach the desired tilt angle of 22.5^0, whereby the green line represents the fasted speed (11.25^0/s) taking 2 seconds to reach tilt angle, and the blue line represents the slowest speed (4.5^0/s) taking 5 seconds to reach tilt angle.

3.2.3 Axis study

The aim of this study was to establish whether the axis in which a perturbation is elicited has an effect on an individual's balance response. As previously illustrated in figure 7 the axis of perturbation can be easily manipulated to distort the visual field. Figure 13a demonstrates what effects are exerted rotationally on individuals when axes are manipulated. For the purpose of this study perturbations were randomly induced in anticlockwise and clockwise directions, in pitch (*figure 13d*) or roll (*figure 13b*) axis conditions. For each individual 8-roll axis perturbations were received and 8-pitch perturbations, these were interspersed with 16 control trials whereby the visual field remained normal (figure 13c). Perturbations lasted 3 s and tilted 22.5^0 at a speed of 7.5^0 p/s, for all axis-manipulated trials.

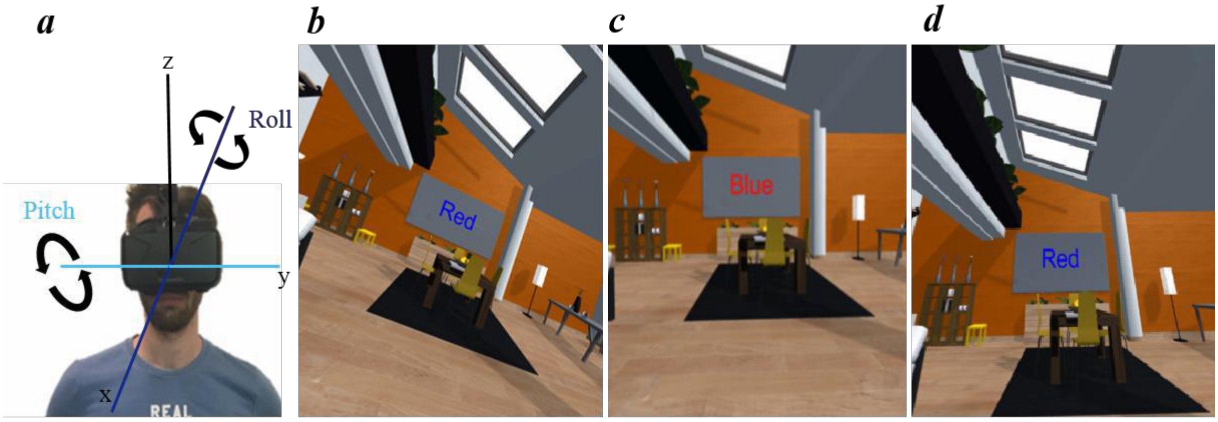


Figure 13: A guide to show how a perturbation elicits different rotational affects across different axes (a). This guide can be used to understand the effect when individuals receive a perturbation in the "roll right" condition (b), and "pitch up" condition (d), in comparison to conditions where no perturbation is elicited (c). These images (b-d) also show the implementation of the Stroop test into the virtual scene; this additive cognitive task was implemented to ensure individuals felt immersed in the virtual environment.

3.2.4Data analysis

MATLAB (MATLAB and Statistics Toolbox Release 2012b, The MathWorks, Inc., Natick, Massachusetts, United States) was the computer coding software adopted to obtain, analyse and plot measurements of COP and subsequently, assess balance.

3.2.5Statistical analysis

The statistical software adopted was SPSS (IBM. Corp. Released 2012. IBM SPSS Statistics for Mac, Version 21.0. Armonk, NYI: IBM Corp.) To analyse the effect of speed or axis of perturbation on COP response a two-way repeated measures ANOVA was adopted. This allowed appropriate analysis of both the effect of time and group (axis or speed) within the same group of individuals. Further analysis was performed to assess the effect of repeat of perturbations in either axis or speed conditions on the COP response. This was only comparing one variable (perturbation repeat) so appropriately a one-way repeated measures ANOVA was adopted. The accepted alpha level of significance for the present study was $p<0.05$. Any adjustments that were made if Mauchly's Test of Sphericity was not met, was done using the criterion of Greenhouse-Geisser, which provided an estimated epsilon to correct degrees of freedom for F distribution values. Results are expressed as means and standard deviations (M± SD).

3.2.6Data acquisition

MATLAB (TheMathWorks, Massachuseets, USA) was the software utilized to generate the code to extract the WBB board data files (.txt files) and plot respective COP coordinates. This generated a Graphical User Interface (GUI) of the COP path trajectories for each individual trial. Individual’s COP path length was extracted from the period 5 s before the perturbation was received and the 5 s after the onset of the perturbation. Selecting these time points meant that individual’s baseline balance could be assessed (quiet standing) and directly compared against their balance in response to a perturbation. This allowed for direct assessment of the change in COP path length as a result of the perturbation.

CHAPTER 4

Results

All participants recruited for the purpose of this investigation successfully completed the balance task that was required of them. Notably, the feedback obtained from questionnaires revealed that 92% of participants on average, 'enjoyed' their experience and felt at ease with what was required, confirming the wellbeing of the individuals. In addition to this, further questionnaires confirmed the effectiveness of the VR-system, with 87% of individuals reporting 'a sense of being in the VE' and 'felt it was real', indicative of a 4 or 5 score on the Likert scale. Immersion of the system was further confirmed through results of the Stroop, whereby a mean number of 2.7± 2.1 incorrect answers was established. This low number of incorrect answers reflects that the individuals were fully focused, and their attention was suitably occupied.

Whilst all participants took part with ease, some data was selectively omitted from further analysis. Within the axis group*,* 2 participants were excluded from analysis due to falling off the board multiple times. Including this data would have skewed the results in favour of the initial hypothesis made, thus any conclusions drawn from analysis would be unrepresentative of the population and be invalid. The same occurred for the speed trial, whereby one participant was excluded for further analysis due to an incomplete set of data trials being saved, a technical error. Out of the 63 participants that were initially recruited a total of 60 individual's data were utilised for further analysis. When analysing and interpreting the results from this study sections will be split into 'speed results' and 'axis results' subject to two different cohorts of individuals taking part in the studies

4.1 Speed Results

This section will analyse data to establish whether speed of perturbation has an effect on the COP response. For the purpose of this investigation the speed of tilt of a perturbation was manipulated using the speeds of 4.5 ^{0}/s, 5.625 ^{0}/s, 7.5 ^{0}/s, 11.25 ^{0}/s. The effect of manipulating these speeds on an individual's balance was examined through obtaining COP measurements 5 s before and 5 s after the perturbation was presented. The effect of speed-manipulated perturbations was compared directly to a series of control trials, whereby no perturbation was received.

All data was inputted into MATLAB and analysed using the Graphical User Interfaces (GUIs) and stabilograms that were provided (*figures 14-16*). Figure 14 is an example of one individual's raw data whereby the fastest speed-manipulated perturbations (11.25 ^{0}/s) is being directly compared to a control where no perturbation was received. Figure 14a represents these two conditions, demonstrating the 'ramp effect' that was required in the perturbed trial to reach the desired tilt angle. When used in collaboration with figures 14b and 14c it is exemplified that for the 7 s before a perturbation is presented there is minimal movement; stabilograms show little deviances in COPx and COPy trajectory paths as the individuals are engaging in quiet standing. At time point zero the perturbation is presented, and for the next 2 s there is a ramp effect until the desired tilt angle of 22.5^{0} is reached (*figure 14a*). Consequently, individuals elicit a sway response at approximately 1 s after the perturbation, revealed from the fluctuations in both the COPx (*figure 14b*) and COPy (*figure 14c*) axes. At approximately 3 s after the perturbation, individuals attempt to regain their balance; illustrated by a compensatory movement in the other direction. Whilst this compensatory effect is clearly displayed, balance is still affected up to 10 s after the perturbation is presented (when compared to pre-perturbation values).

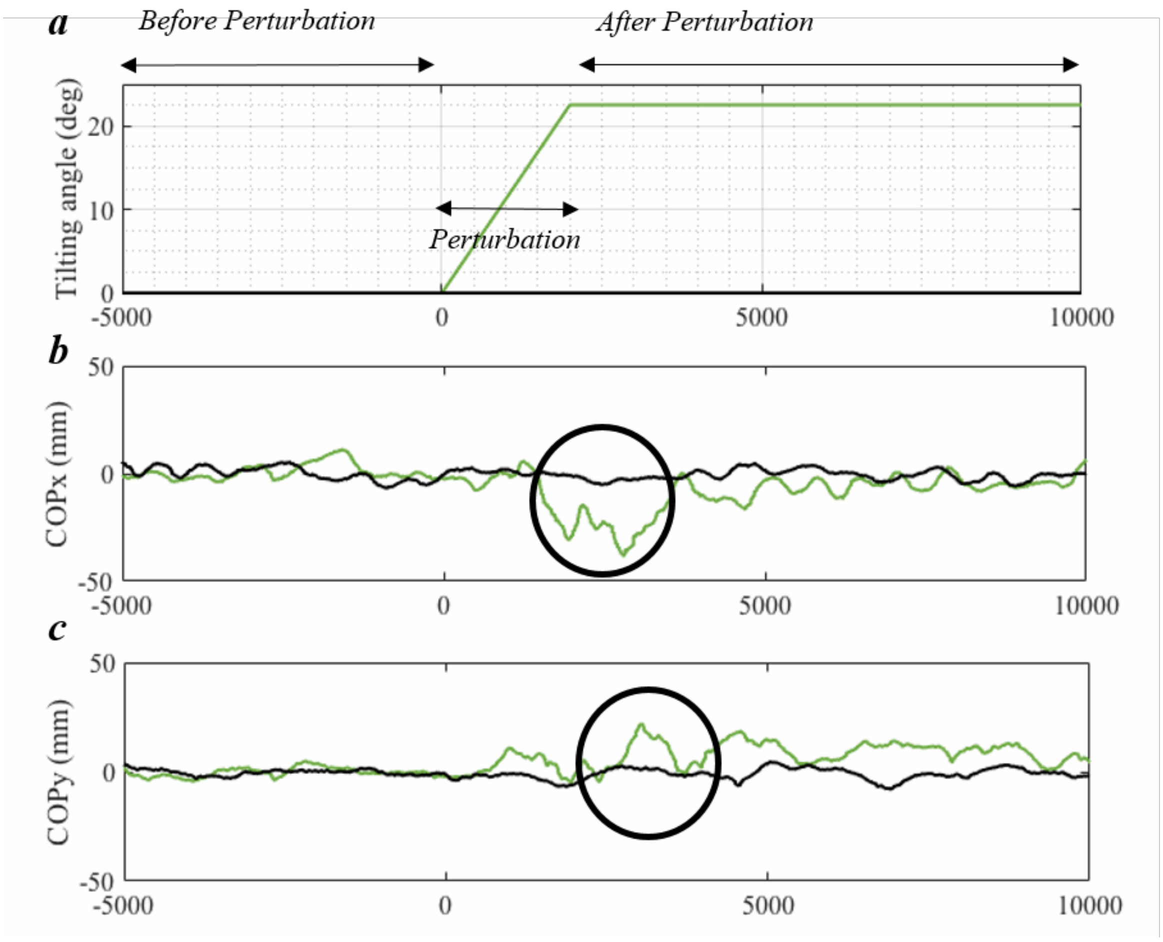


Figure 14: Raw data taken from an individual participant, directly comparing the fasted speed perturbation (11.25^0 /s) to a control trial. Figure 15a shows the time it took from the initial onset of perturbation until the desired tilt angle was reached 2 seconds after, as illustrated by arrows. The change in COP path length before the perturbation and after the perturbation is shown by stabilograms for both the x axis (b) and y axis (c). Directly shows the extent to which a perturbation can effect an individual's sway response. The annotations exemplify the substantial changes in COPx and COPy responses as a result of perturbation presentation.

The perturbation elicited in this example was in the roll axis, with greatest deviances being shown in the x axis (medial to lateral) (*figure 14b*). These stabilograms clearly illustrate the extent to which a perturbation can impede one's ability to maintain balance. This is again demonstrated in figure 15, which shows the individuals overall sway response, exemplifying how much a speed-manipulated perturbation can destabilise an individual and evoke a sway response.

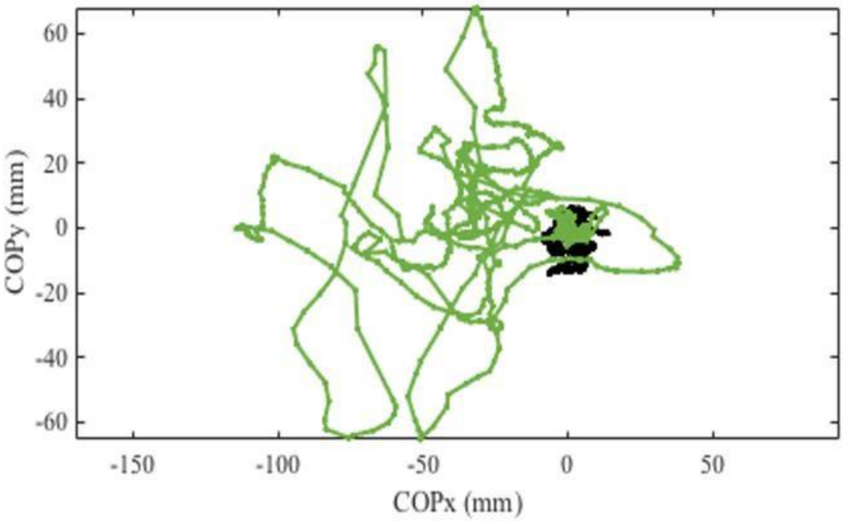


Figure 15: COP path length in both x and y axis comparing the fastest speed perturbation (11.25^0/s) to a control trial. Directly showing greater deviations from the centre (0,0) in the perturbed trial (green line) compared to the control trial (black line). This figure is formed from one individual's raw data.

The main aim of this study was to investigate whether the speed of a perturbation has an effect on COP path length. Figure 16 illustrates how long it took each of the speed-perturbed trials to reach the desired tilt angle of 22.5^0. The green line represents the quickest speed to reach the desired angle (11.25 ^{0}/s) followed by the orange (7.5 ^{0}/s) yellow (5.625 ^{0}/s) and blue (4.5 ^{0}/s). When looking at the raw data taken from one participant it is clear that COP path length is influenced by perturbation speeds, particularly when compared to control trials (*figure 17b*). This illustration exemplifies that faster speeds have a greater effect on the length on the COP path length (as seen by extreme deviances of COP in speeds 7.5 ^{0}/s and 11.25 ^{0}/s), signifying a heightened balance response.

A bespoke MATLAB script was written for the purpose of formulating the above stabilograms and GUI. By running this code, values could also be obtained on exact COP path length for both the x and y axis, alongside the standard deviation and means. These values obtained gave information on path length both before and after the perturbation was received. Therefore, statistical analysis could be performed to compare the average COP path length 5 s before the perturbation (when the individual was engaging in quiet standing) and 5 s after the onset of the perturbation.

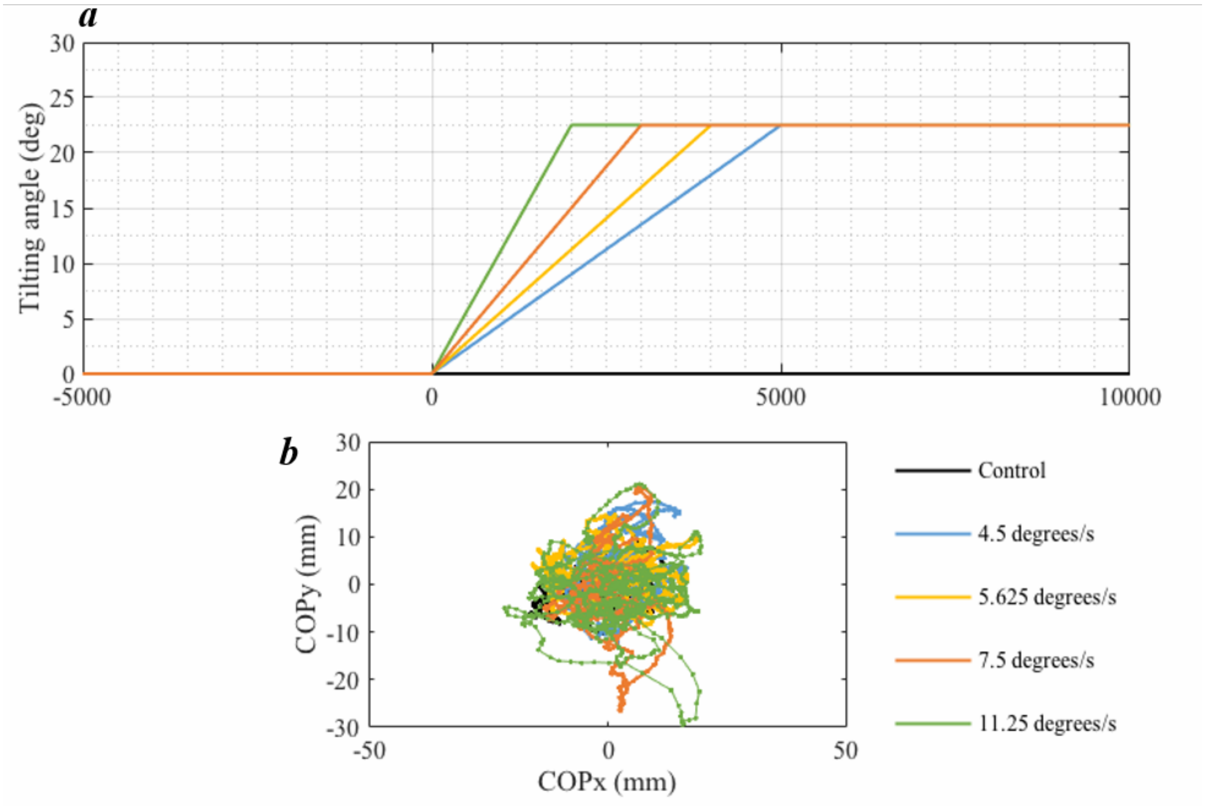


Figure 16: Illustration to show the time it took each speed to reach the desired tilt angle of 22.5^0 after onset of the perturbation at time point zero (a). This figure clearly shows that the faster speeds of 5.625^0/s (yellow line), 7.5^0/s (orange line) and 11.25^0/s (green line) have the greatest effect on an individual's balance when compared to a control trial (black line) and the speed 4.5^0/s (blue line), illustrated by the greater deviances displayed in COPx and COPy (b).

4.1.1 The effect of speed of perturbation on COP response.

Across all speed-manipulated perturbation trial, there was an average increase in COP path length from before to after the perturbation (*figure 17*), this directly compares to control trials whereby no increase in COP path length was displayed. This demonstrates that the speed of a perturbation has an effect on COP path length.

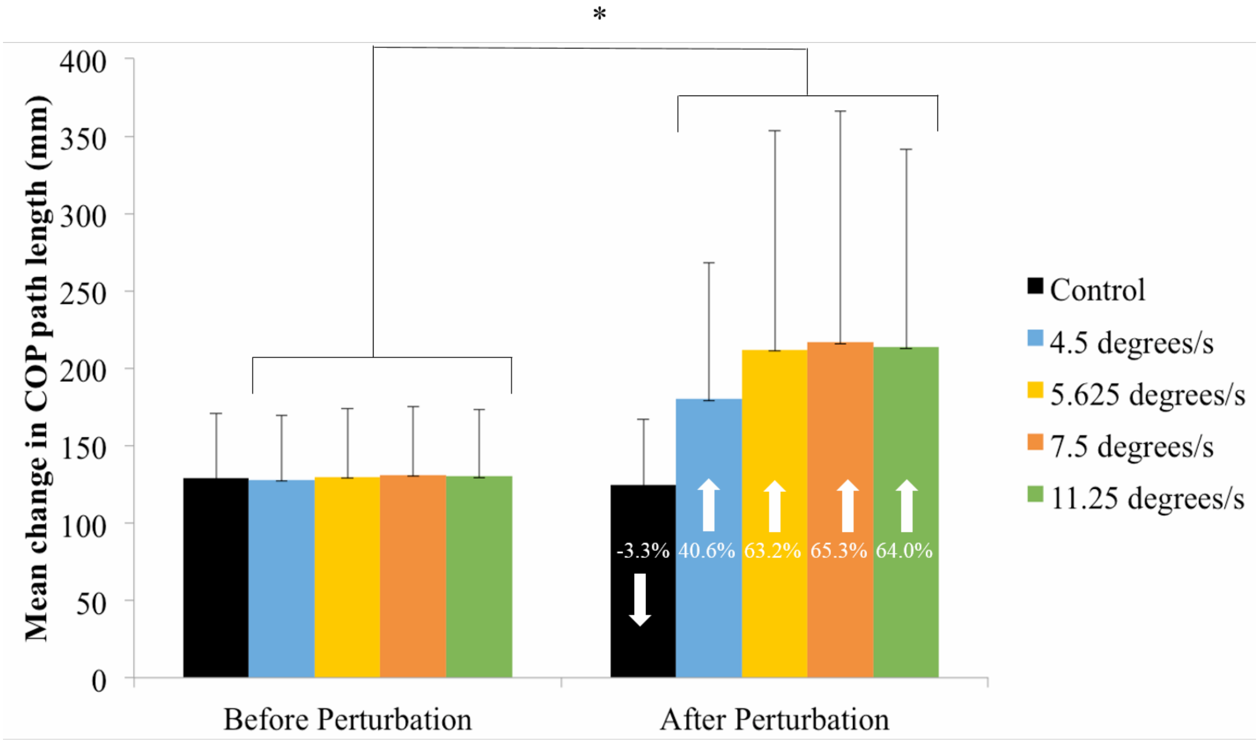


Figure 17: A graph to show the mean change in COP path length across all conditions. Showing the M ± SD (mm) COP path length values before the perturbation was received compared to COP path length values after the perturbation was received. Demonstrating the effect of speed of perturbation on COP sway ($p<0.05$). Annotations on 'after perturbation' bars show the COP mean percentage change values for each respective condition, showing the direct effect of the perturbation on an individual's balance response ($p<0.05$).

A two-way repeated measures ANOVA analysed the effect of a perturbation on COP path length across all conditions: control, 4.5 ^{0}/s 5.625 ^{0}/s, 7.5 ^{0}/s and 11.25 ^{0}/s. Across participants, a significant increase in COP path length (expressed as mean ± SD) was observed after the perturbation (190 ± 109 mm) compared with before the perturbation (130 ± 43 mm: $p<0.001$, $F_{1, 29} = 46.7$, $\eta\ ^{2}$-.617) Figure 17 illustrates that before the perturbation, COP path length is near the same across all conditions, including control. However, after the perturbation is presented an increase in COP path length is displayed across the speed-perturbed trials. What this figure also shows is that the control COP values are similar across both time points. Collectively, this confirms that perturbations have had an effect on COP values. From these results it was important to establish whether the effect of time had a significant effect on speed of perturbations. A two-way repeated measures ANOVA revealed a significant interaction effect between speed and time $p<0.001$, $F_{2.8, 80.3}= 17.453$, $\eta_p^2 =.376$. These values were obtained after adjustments had been made by the Greenhouse-Geisser adjustment criterion. This confirms that significant differences in COP path length across speed-perturbed trials only occur after the perturbation is presented.

Another way to interpret results is through calculating percentage change values. This is a suitable value to use for the present study as a direct link can be seen from the effect of a perturbation on postural stability. This more accurately accounts for individual differences as it controls for an individual's baseline postural control, providing a more insightful assessment on the influence of the perturbation. The percentage change in COP path length was looked at individually across all speeds. Annotations of figure 17 shows that speed-perturbed trials 4.5 ^{0}/s, 5.625 ^{0}/s, 7.5 ^{0}/s and 11.25 ^{0}/s, cause substantial change in COP path length increasing by 40.6 %, 63.2 %, 65.3 % and 64.0 %, respectively. A repeated measures ANOVA revealed that a significant main effect of speed was established $p<0.001$, $F_{3.2, 380.4} = 22.3$, $\eta_p^2 =0.158$, confirming that manipulating the speed of a perturbation caused a significant percentage increase in COP path length. Notably, post-hoc analysis revealed that the % increase in COP path lengths in all speed-perturbed trials was significantly greater than control.

4.1.2 The effect of repeat of perturbation on COP response.

When analysing results, it is clear that responses to perturbations depreciate across repeats of the same perturbation. Thus, the next stage of analysis evaluated whether a learning effect was present, assessing whether individuals habituate to successive perturbations after the initial one. To analyse this effect, the data from speed-perturbed trials was grouped allowing overall assessment of perturbations. As illustrated in figure 18 a trend is clearly shown; the first perturbed trial produces the greatest change in COP path length and after this, responses are attenuated. A mixed design two-way repeated measures ANOVA was performed to assess the effect of repeat of perturbation on COP response. A clear main effect of repeat was established $p<0.001$, $F_{1.6,\ 193.8} = 18.4$ $\eta_p^2 = 0.134$, confirming that repeating the same set of perturbation significantly influences the COP responses. Post-hoc analysis revealed significant differences between the first perturbation (94 ± 123 mm) with the following second (57 ± 63 mm), third (35 ± 36 mm) and fourth (42 ± 51 mm) perturbations that were presented. This confirms that the first perturbation has the greatest effect on increasing COP path length, and should be considered if this test was to be developed for diagnostic procedures.

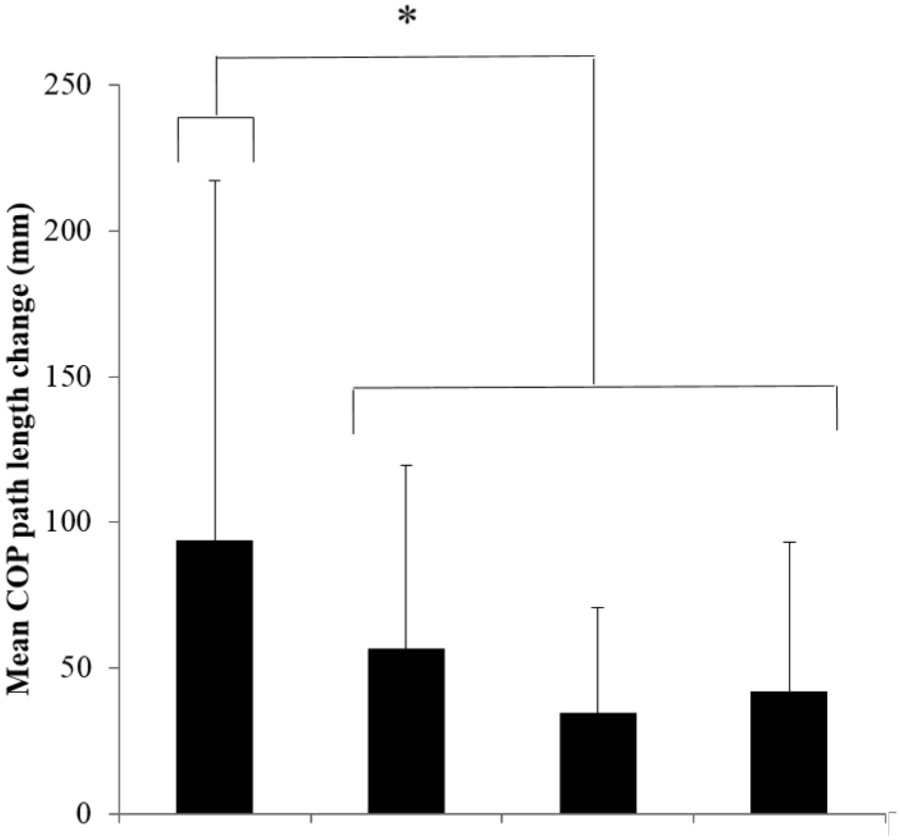


Figure 18: The effect of repeating the same set of perturbation on mean COP path lengths (mm) in speed-perturbed trials, assessing whether there is any difference from the first perturbation and the succeeding perturbations. This provides an analysis on whether habituation is occurring ($p<0.05$).

4.2**Axis results**

The purpose of this investigation was to deduce whether the axis of perturbation had an effect on the COP response. When using figure 19a as a guide we can evaluate the effect of each perturbation on the COP response. This figure clearly illustrates that it took approximately 3 s for the desired tilt angle of 22.5^0 to be reached. During the period before the perturbation the individual is engaging in quiet standing, with minimal COP fluctuations representing normal postural sway (*figure 19b*). Once the perturbation was received the individual was de-stabilized producing deviations in COP path lengths in both the x axis (*figure 19b*) and y axis (*figure 19c*). Changes in COP path length were also influenced by the type of perturbation received, which figures illustrating that roll produces greater total COP path length than pitch (*figure 20*).

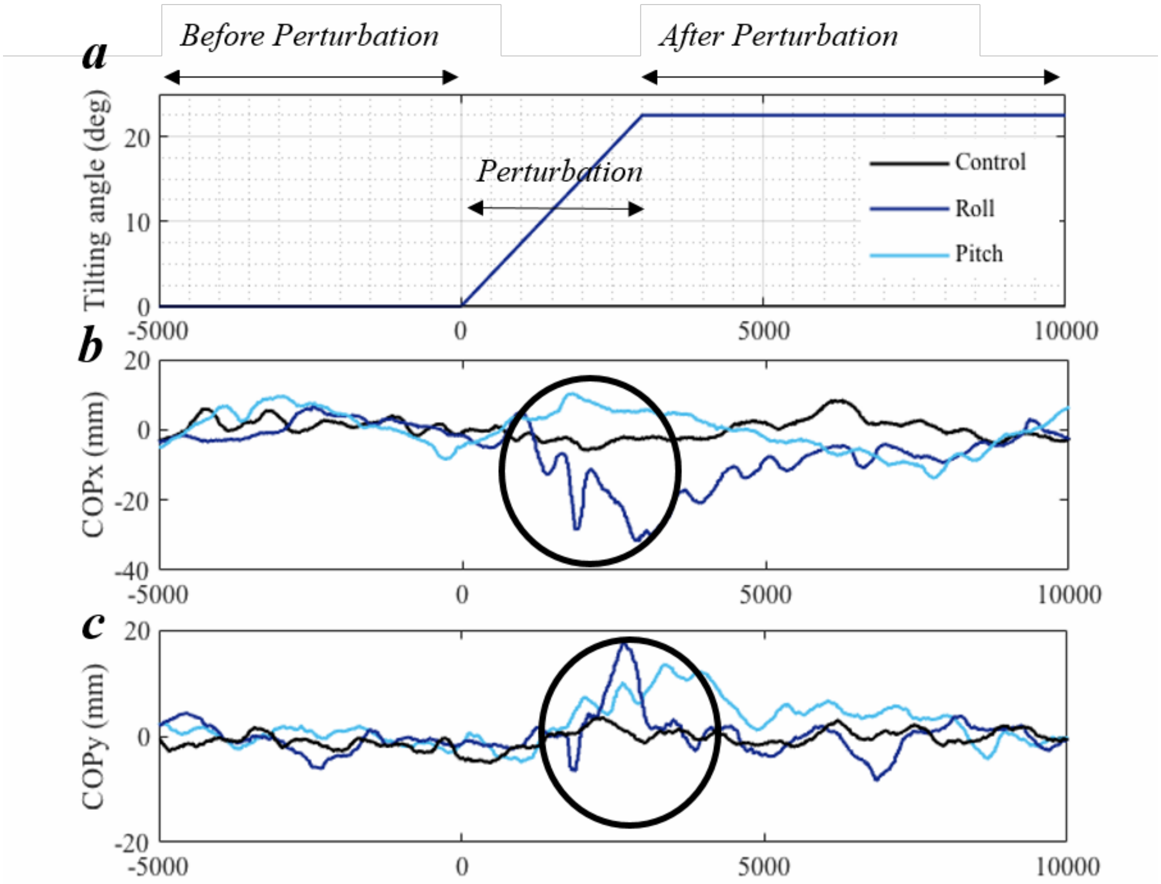


Figure 19: An illustration showing the period before the perturbation, period during the perturbation and the period after the perturbation (a). Using this figure allows one to understand why changes in COPx (b) and COPy (c) are occurring when they do. Annotations provided show that from the onset of the perturbation, there are substantial deviances in both COPx and COPy for both roll and pitch perturbations, with a more profound affect occurring in roll. This is compared to control trials (black line), whereby COP remains fairly constant.

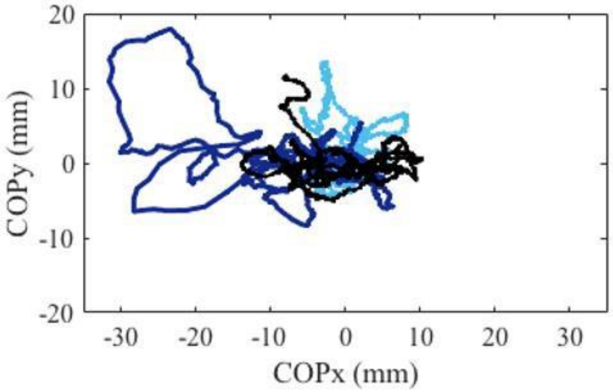


Figure 20: Total COP path length, taken from an individual participants data, comparing roll, pitch and control trials. Clearly illustrates the profound effect that roll perturbations have, over and above pitch, on COP path length.

4.2.1The effect of axis of perturbation on COP response.

In order to assess whether COP values obtained before the perturbation differed from those obtained after the perturbation in axis-perturbed and control conditions, a two-way repeated measures ANOVA was performed. COP path length increased on average from 135 ± 39 mm before the perturbation to 174 ± 90 mm after the perturbation. As shown in figure 21 all conditions have similar COP path lengths in the period before the perturbation was received, yet after the perturbation is received (pitch and roll) there is an increase in COP path length, with no effect in control conditions. A significant main effect for time was established $p<0.001$, $F_{1,87}=28.152$, $\eta_p^2=.244$ deducing that COP values obtained before the perturbation were significantly different to values obtained after the perturbation. When examining this effect closer and looking at post-hoc analysis it becomes apparent that the only significant increase in COP path length is in the roll axis, 130 ± 30 mm before to 223 ± 127 mm after. This compared to pitch perturbations where values only increased from 135 ± 32 mm before to 156 ± 51 mm after the perturbation, with the increase not meeting the accepted value of significance.

In order to establish whether time had a significant effect on axis of perturbations an interaction effect was examined. A two-way repeated measures ANOVA revealed a significant interaction between axis and time $p< 0.001$, $F_{2.87} = 17.605$, $\eta_p^2 =.288$. In collaboration with post-hoc analysis, this effect signifies that COP measurements obtained in the roll group were significantly influenced by time (*figure 21*).

Percentage change values were calculated to better demonstrate this effect, allowing assessment of the change in COP path length. Annotations of figure 21 demonstrate the effect of a perturbation on COP percent change when compared to control. An independent samples t-test (means ± SD) revealed that there was a significantly greater percentage increase in COP path length in perturbation trials (43.7 ± 81.5 %) compared to control trials (-1.5 ±14.6%), t (463) =11.5, p <0.001. Furthermore, when directly comparing pitch to roll, there is a clear difference between the groups. In roll-perturbed trials there is an increase in COP path length of 72.7%. This compares to that of the pitch axis whereby only a mere 14.6% increase in COP path length is displayed.

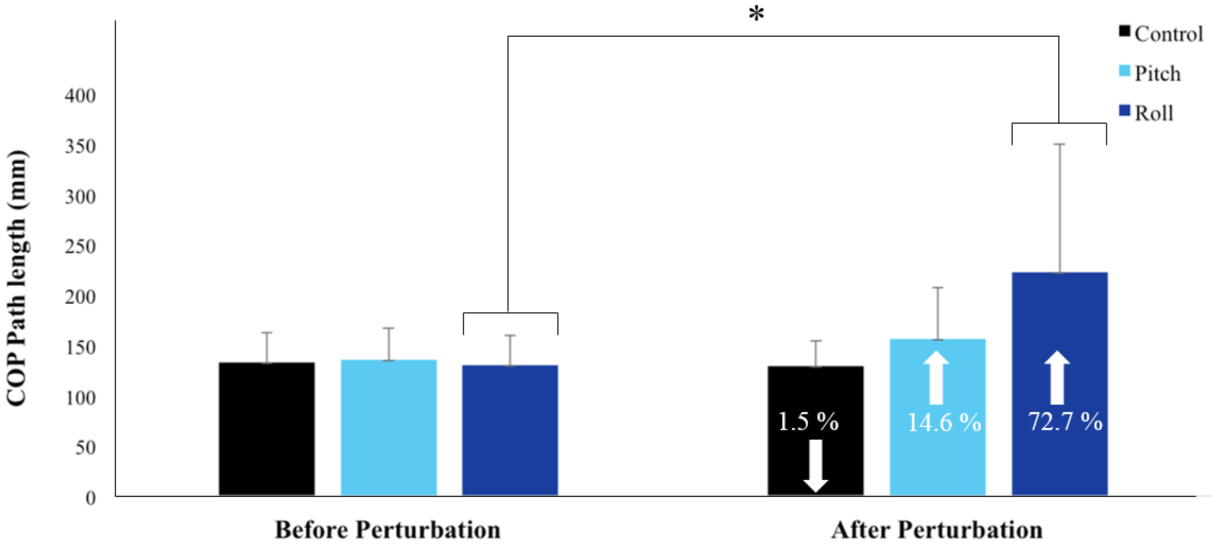


Figure 21: The effect of axis of perturbation on COP path length (mm), directly comparing control, pitch and roll trials. COP path length is measured in the 5 second period before the perturbation is presented, and then again measured from the onset of the perturbation for 5 seconds. This figure shows that the effect of perturbation was greatest for the roll condition ($p<0.05$). Annotations demonstrate the percentage change values from before to after the perturbation, with roll perturbations causing a significant percentage increase in COP path length ($p<0.05$).

4.2.2The effect of repeat of perturbation on COP response.

Inducing a postural perturbation into the individual's visual field clearly evokes a balance response, as signified by the increases in COP path length that are displayed (*figure 21*). Previously the overall effect of axis was looked at, but to pinpoint exactly when this deviation in COP path length occurs, each individual perturbation needs to be analysed. For example, in some participants it was clear from observation that the initial perturbations received in that axis created a large sway response but as exposure to repeated stimuli continued, responses tailed off. Thus, a potential effect of habituation across trials was observe.

To analyse the effect of habituation the raw COP data from all axis-perturbed trials was grouped, to give a general overview of the effect of habituation on COP responses. Responses attenuate as perturbations are repeated, with a mean COP of 136 ± 235 mm on the first perturbation, depreciating to 34 ± 47 mm on the final perturbation. In accordance with each repeat, the mean COP response decreases, and this effect are seen across all repeats. A two-way repeated measures ANOVA revealed a significant effect of perturbation repeat on mean COP responses; $p<0.001$, $F_{1,7}=5.191$ $p<.001$, $\eta_p^2=.411$. Whilst no significant differences were found between the 1st and 2nd perturbation, significant differences were displayed between the 1st perturbation and the rest that followed (3rd to 8th). This clarifies that a significant habituation effect was displayed across repeat of axis perturbations (*figure 22*). This has profound implications for refining the parameters of a VR tool, which will later be discussed, emphasizing the need to take into consideration the number of perturbations required in order to depict whether balance deficits are present.

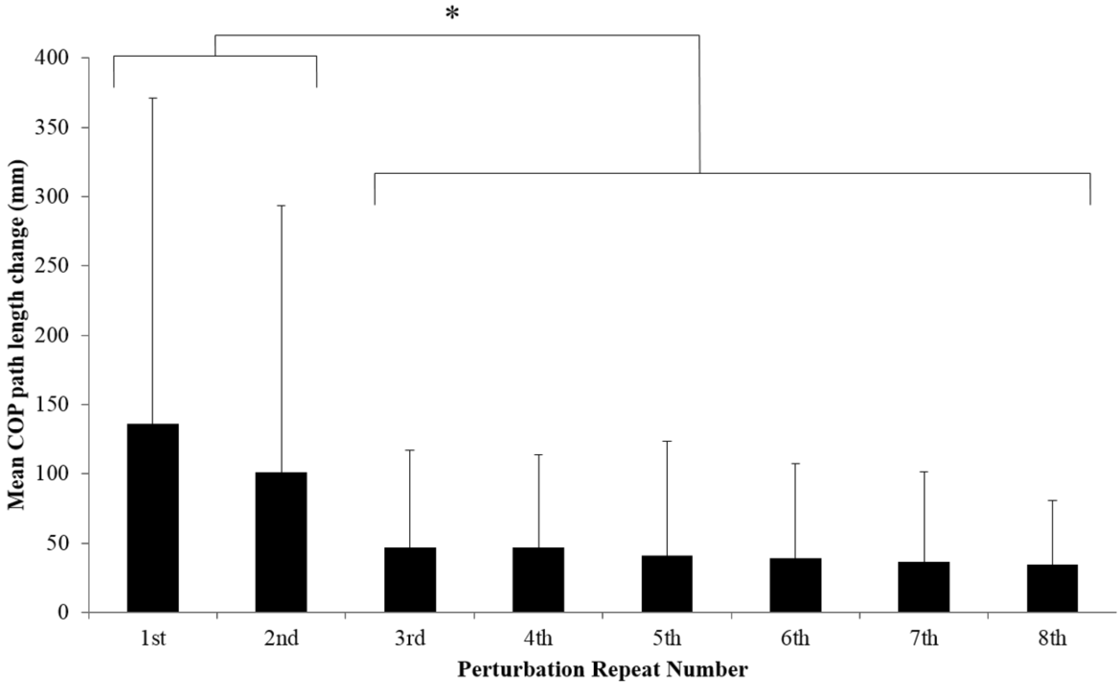


Figure 22: The effect of repeating perturbations in axis-perturbed conditions on mean COP path length (mm), assessing whether there is any difference from the 1st perturbation and the succeeding perturbations. This data is to provide an assessment of whether balance obtained data across the trails is vulnerable to the learning effect. The COP response from the 1st perturbation is directly compared to COP response of the repeat perturbations, from the 2nd through to the 8th ($p<0.05$).

CHAPTER 5

Discussion

The current study was amongst the first to investigate the use of a VR-WBB prototype for balance assessment. The research conducted further contributed and advanced previous work that has highlighted the importance of the visual system in balance maintenance (Lee and Aronson, 1974; Slobounov et al., 2006). This study developed a novel, cheap and portable platform to objectively assess an individual's balance recovery from a postural perturbation. This prototype advances previous work within the field whereby such systems, that utilised force plate or laboratory constrained VR-systems, were limited by both expense and portability (Slobounov et al., 2006; Teel and Slobounov, 2015a).

The present study corroborated previous literature and confirmed that a VR-system provided an effective means to assess and manipulate an individual's postural control (Broglio and Puetz, 2008; Slobounov et al., 2006). Once establishing that our own VR-WBB prototype was a sufficient tool to induce a postural perturbation and evoke a balance response, then meant that we could further explore the parameters to optimise such a system, providing detail on what type of perturbation elicits the greatest sway response. With continuation and development of this research tailored towards a clinical population, it would seem appropriate that this tool has the potential to assess balance abnormalities associated with a concussion.

After clarifying that impeding the visual system evokes a balance response, a key purpose of the current investigation was to deduce the most effective means to evoke this balance response, assessing the preferential axis and the preferential speed to induce a perturbation. This study confirmed the initial hypotheses, establishing that roll induced perturbations have a significantly greater effect on balance than pitch induced perturbations and further, confirming that manipulating the speed of perturbation can cause a significant increase on an individual's sway response.

5.1A novel approach to assess the role of vision in balance

Vision has long been established as one of the most important systems to maintain balance. Initial work conducted by Lee and Aronson (1974), who pioneered the moving room design to investigate balance responses to visual perturbation, highlighted the importance of the visual systems role in balance. The credible research design of the moving room was later advanced by Slobounov who adopted the same concept, but instead utilised a VR platform to evoke the perturbation and a force plate to measure the balance response (Slobounov et al., 2006; Teel and Slobounov, 2015a). Despite the ability of the force plate to detect subtle deviances in COP, it is seldom used outside laboratories, requires technical training to operate and is expensive (Clark et al., 2010), providing a sound justification as to why the affordable, portable WBB was adopted in the present study. Whilst the WBB is less sensitive in detecting subtler deviances in COP path length than that of the force plate, Pavan et al., (2015) noted that such minimal inaccuracies are quickly overcome by the feasibility of the device and ability to still obtain sufficient COP measurements. This was demonstrated in the present study through stabilograms showing sensitive COP data to a range of perturbations (*figure 15 and figure 19).*

It is important to note that the WBB was calibrated effectively prior to each of the trials. Calibration was implemented to reduce the effect of intra-individual variability skewing the results (Pavan et al., 2015), ensuring individuals COP data was tracked relative to the calibration point that had been ascertained previously. This overcomes any initial work that questioned the sensitivity of a WBB device. Consequently, the WBB provides comparable data to that obtained via a force plate when assessing COP path length, and may provide the solution that "bridges the gap between clinical assessments and laboratory testing" (Clark et al., 2010).

Moreover, the measurements obtained by the WBB confirmed the effectiveness of the VR-system to induce postural perturbations, being able to detect subtle deviations between conditions. This is exemplified by the significant differences found in COP path lengths when comparing perturbed conditions to control conditions.

The VR-WBB paradigm with the additive component of the cognitive task extends from the work of much preliminary research (Slobounov et al., 2006; Wright, McDevitt and Appiah-Kubi.,2015). This dual-task paradigm was implemented in the present study to deter individual's attention away from focusing on balance and to ensure immersion within the system. Whilst results of this test were not used as a primary measure, responses were still noted as the number of correct to incorrect answers. Accordingly, the effectiveness of this dual-task was confirmed through results, which showed minimal error rate in individual's responses (2.7 ± 2.1). This was corroborated by questionnaires administered after the trials, revealing participants felt fully immersed within the VR environment.

Whilst the Stroop was the cognitive task implemented in the present study, this research established a prototype that could accommodate for many other cognitive tasks to be implemented. Notably, a comprehensive cognitive assessment could be conducted alongside the balance task developed. If such a dual-task were to be administered to a concussed population, it would be expected that cognitive scores would be significantly lower than controls (Broglio and Puetz, 2008; Teel et al., 2013). Thus, within the present study there would be an expected increase in incorrect Stroop answers (Guskiewicz, 2011). Clearly this study provides an effective framework in which a dual-task paradigm can be implemented whereby immersion can be ensured and further, cognition can be assessed.

The design of the present study further extends the knowledge base of previous investigations on the visual control and balance within the field. Previously, much of the research into balance using VR has utilized TV screens or wall projections as a medium of VR, which can compromise an individual's sense of an immersion (Chiarovano et al., 2015). Notably, projecting perturbations through TV displays does not accommodate for tracking individuals head movements, which is integral for both sense of immersion and assessment into vestibular functioning. Thus, the VR-systems which were adopted by both Wright et al., (2015) and Slobounov et al., (2011) lacks immersive proprieties, which can compromise the individual's ability to interact within the VE. Our VR- system was comprised of an Oculus Rift headset with the VE programmed on the Unity platform. Embedded within the headset were tracking sensors, so when individuals moved their head the visual display would move in the opposite direction, - a mechanism which makes individual's feel immersed (Chiarovano et al., 2015). This immersive feel was clearly met with the present study, as confirmed by results of the Stroop and answers from questionnaires that revealed that 87% of individuals felt immersed. Adopting the HMD as our VR medium may explain why individuals reported a strong sense of immersion. Moreover, utilizing a HMD set as opposed to TV screens ensures portability. This is essential to consider given that one of the aims of the present study was to develop a portable platform that could be utilized pitch side.

Over the years VR and HMD systems have been criticized for various reasons including the restriction of movement, discomfort and their ability to induce nausea (Gatica-Rojas and Mendez-Rebolledo, 2014). VR-induced symptoms and effects (VRISE) have been reported as a key issue since the boom of VR back in the 1990's, with many papers only speculating why such symptoms arise (Nichols and Patel, 2002). In response to literature, precautions were implemented into the present study to reduce the manifestation of such symptoms. Firstly, the HMD adopted for the present study was the Oculus Rift, a lightweight alternative to more traditional-based HMD. Secondly, rigor within the protocol ensured that the potential manifestations of symptoms were addressed. Each participant had become accustomed to the stable stance they had to adopt with the additive weight of the HMD in an initial familiarization period and further asked of any discomforts they felt. Moreover, they were pre-warned for any feelings of nausea that they may experience and told to withdraw if such a symptom manifested. However, immersion questionnaires conducted after the trials revealed the wellbeing of individuals were maintained, with no such VRISE not being reported. This confirms that rigor within the protocol ensured that precious criticisms regarding the symptoms induced by VR were accommodated for.

When developing a tool to assess balance and obtain accurate COP data, it is important to evaluate what stance to adopt. Notably, the present study confirmed during piloting, that the dual-stance is the most appropriate to adopt as the stable stance for static balance assessment. Adopting this stance ensures the most reliable measures of COP, without being manipulated by horizontal forces (Pavan et al., 2015). However, employing such a stance may be questioned given the scrutiny, which has previously been evident within literature over the BESS stances (dual, single, and tandem) (Starling et al., 2015). Appropriately, the present study did not adopt a single leg stance, which eliminated much of the variability surrounding COP measurements and subsequently disregarded any criticisms that could be made (Starling et al., 2015). Moreover, following our prior pilot testing we dismissed the use of the single leg and tandem stance, because every individual piloted fell off the WBB when this was attempted. This is highly notable given that piloting was conducted on a healthy population. If a healthy population are unable to maintain balance during such stances, this defeats the point of developing a tool that can objectively prove that a concussion is present as individual’s are falling off regardless of whether an insult has been sustained. Thus, it is important to adopt a stable stance that can be maintained when individuals are healthy, to then help distinguish a balance dysfunction in the event of a concussion.

Overall, the methodological approach adopted in this study has provided great promise into the advancement of a VR-platform to objectively assess balance and has allowed us to investigate a series of other questions. Additional investigations were run to deduce the precise parameters that would be most efficacious in destabilizing an individual, which has contributed some interesting findings, to further compliment the use of VR as a balance assessment tool pitch side.

5.2**The effect of axis manipulated perturbations on an individual's balance**

Whilst previous research that adopted the moving room design concept has confirmed the importance of vision to counteract sway in response to a perturbation, our study further extended this work to see whether manipulating the effect of specific parameters (axis and speed of perturbations) could further influence the sway response. In accordance with the initial hypothesis, the present study confirmed that perturbations elicited in the roll axis produced significantly greater increases in COP path length when compared to pitch axis perturbations. Whilst perturbations received through the pitch axis still elicit greater destabilization than that of control, the effect is not significant. This confirms initial pioneering research conducted by Slobounov et al., (2011) who also established that roll elicited the greatest balance response. Presumably, this effect will be heightened when assessing a concussed population with roll perturbations having a substantial destabilizing effect (Broglio and Puetz, 2008). This finding alone has can aid the development of a more effective and refined VR module to assess balance.

Whilst it is known that the three sensory systems involved in balance maintenance are the vestibular, visual and somatosensory (Chiarovano et al., 2015; Mergner and Rosemeier, 1998) their exact roles in balance and further, how the CNS integrates the information received is poorly understood (Jeka et al., 2000). Notably, what can be confirmed is that the majority of balance dysfunction is caused by a mismatch of information received between the three systems (Guskiewicz, 2011; Horak and Kuo, 2000). Hence, why eliciting perturbations in the present study evoked a postural response. When seeking to deduce why roll perturbations elicit a greater sway response than pitch, explanations remain speculative with no literature currently focusing specifically on this concept. However, based on research from similar concepts a degree of inferences can be made, which will be discussed.

Previously, the study of posture has centered around the biomechanics of the body, with many researchers accepting the idea that the body acts as an 'inverted pendulum' that is stabilised by ankle strategies (Hsu et al., 2007; Winter, 1995). Notably, it has been established that an ankle strategy is activated when individuals are perturbed in the AP direction, i.e.: pitch axis and thus, torque of the ankle joint can oppose the perturbation and retain balance (Di Giulio et al., 2009). Given that no such ankle strategy has been documented for roll-induced perturbations, this may explain why a significantly greater sway response was seen in pitch-perturbed trials. However, this assumption must be taken with caution as more recent literature has emphasised that there are a whole range of joints required for postural stability in quiet standing, and thus maintaining balance is not dependent on one particular ankle strategy (Krishnamoorthy et al., 2005). Given that such literature is ambiguous, focusing on other, alternative mechanisms to elucidate why roll perturbations evoke a heightened balance response is required.

Perhaps a more suitable biomechanical explanation can be provided through focusing on the specific stance adopted within the present study. From as early as one can remember, the normal stance to remain upright and maintain balance was on where the feet are separated and placed approximately shoulder width apart. Notably, whenever we stop and talk to someone this will be the stance adopted; a subconscious action formed from a motor program made when we were young. The reason this stance is adopted is because it offers the greatest stabilisation; the COM lies directly within the base of support (BOS), with a wide surface area to counteract any impedance to balance. However, the present study impeded what we were accustomed to and adopted a stance whereby the feet were placed together, significantly reducing the surface area and narrowing the BOS. No longer can individuals rely on the former motor program they adopted. Instead, an adjustment is required involving individuals re-weighting sensory information to establish COM position (Creath et al., 2002; Nashner, 1982). This is not so much a problem for pitch perturbations, which operate in the AP direction where surface area is not affected by this different stance. However, it is a problem for roll perturbations, which evoke a ML sway response; the feet have been bought together so there is a reduced surface area to counteract sideways movements. This reason albeit speculative, provides a suitable explanation as to why such results were seen and is an area that should be exploited further.

Relying on purely biomechanical explanations to explain results is not appropriate, and in fact would be a massive oversight if we were to do so. Alternative explanations that could be deemed as more relevant for the present study lie internally, through analysing the visual and vestibular processes. Gresty and Bronstein (1992) investigated the differences in eye movement patterns produced when exposed to movements in the pitch, yaw and roll axes. Notably, it was established that when head movements are produced in pitch and yaw axes rotations a compensatory eye movement is activated in the opposite direction, stabilising the visual field, this is known as the Vestibular Ocular Reflex (VOR). However, when perturbed in the roll axis the compensatory reflex eye movement is inadequate. Consequently, this causes the individual to think the environment is swinging in the counter direction to the head, causing a false sense of motion and a subsequent sway response. This provides a key explanation as to why roll perturbations caused a significantly greater sway response than pitch-induced perturbations.

However, Gresty and Bronstein (1992) then went on to ask the question of how well the head is stabilised in space when perturbed through both roll and pitch. Notably, when exposed to a series of visual tasks individuals were able to stabilise their head when perturbed through roll, compensating for the lack of compensatory eye movement. Given that pitch can sufficiently stabilise the visual field through the VOR, the heightened head stabilisation as seen in roll perturbations, was not displayed. Whilst this is somewhat contradictory to the present study, whereby roll perturbation evoked a notable balance response even in the presence of a visual task, this study is highly credible and emphasizes the importance of the visual system and its ability to override other sensory information.

From above discussion it is clear that there is no definitive explanation as to why such results were displayed. In future, research should look into focusing on the specifics of roll and pitch perturbations and its effect on balance, to attempt to clarify this ambiguity surrounding why such results were displayed.

5.3The effect of speed manipulated perturbations on an individual's balance

The present study established that manipulating the tilt speed of a perturbation has a significant effect on an individual's balance response, with faster speeds causing a greater increase in COP path length. This present study provided a novel contribution to the development of a VR-WBB platform by being the first to isolate speed as an important parameter to consider for optimal perturbation delivery.

Throughout all conditions where individuals received a perturbation a balance response was evoked. This was corroborated through observations within the sessions, where a handful of individuals stepped off the board and required the help of investigators to regain balance. This was compared to a group of control trials where no perturbation was received and subsequently, no significant change in COP path length and no balance response was observed. The extent to which perturbations caused COP path length to increase from pre-perturbation values differed across the range of speeds that were examined. Perturbation tilt speed of 4.5 ^{0}/s produced smaller changes in COP path length after presentation of the perturbation in comparison to the other, faster speeds: 5.625 ^{0}/s, 7.5 ^{0}/s and 11.25 ^{0}/s. Notably, the COP response seemed to plateau at 5.625 ^{0}/s (*figure 17*) with the following speeds, 7.5 ^{0}/s and 11.25 ^{0}/s, producing similar COP path length responses. This sheds some light when deducing where the destabilizing effect may occur, i.e. between the speeds of 4.5 ^{0}/s and 5.625 ^{0}/s. The mean COP path length change for 4.5 ^{0}/s was 52 ±70 mm, compared to the speed of 5.6 ^{0}/s, which was 82 ± 121 mm. Clearly even a small increase in speed can have a substantial effect on an individual's sway response. Due to the novelty of the present study marking the first step into speed parameter investigation it was not feasible to include more intermediate speeds nor was it required to examine the relationship between individual speeds. However, both of these are extremely important avenues to peruse for future development. With such research we would be able to establish the exact point in which an individual's balance is significantly impeded, and thus be able to tailor the optimal speed of perturbation accordingly.

Given that the present study did not permit for a mechanistic understanding of the results, exploration as to why such results occurred remains speculative. One possibility that may explain results is that shorter perturbations do not allow for sufficient time for individuals to adjust their balance and recover. This is illustrated in figure 23, which exemplifies how long it took each tilt speed to 'ramp up' and reach the desired 22.5^0 tilt angle. Accordingly, 4.5 ^{0}/s correlated to a tilt duration of 5 s, 5.625 ^{0}/s to 4 s, 7.5 ^{0}/s to 3 s and 11.25 ^{0}/s to 2 s. From this it can be deduced that the slowest speed of 4.5 ^{0}/s, spent 5 out of the 10 s to reach desired tilt angle, when taken from the time the perturbation was presented to the end of the trial duration. During this 5 s period the individual may have time to adjust their posture in accordance with the delivery of the perturbation, compensating for the initial imbalance. Conversely, the fastest speed, 11.25 ^{0}/s, only took 2 s to reach the desired tilt angle, and subsequently elicited a greater increase in COP path length. This heightened COP response at faster speeds could be due to individuals having insufficient time to adapt. Markedly, it has previously been established that postural latency responses range between 70-180 ms and reaction times at 180-250 ms, this is slower than for the normal stretch reflex response (60ms) (Nashner, 1982). Given this 2 s time frame and the approximate 1.5 s delay in postural response time, this does not give the individuals sufficient time to adjust their balance response during the perturbation tilt.

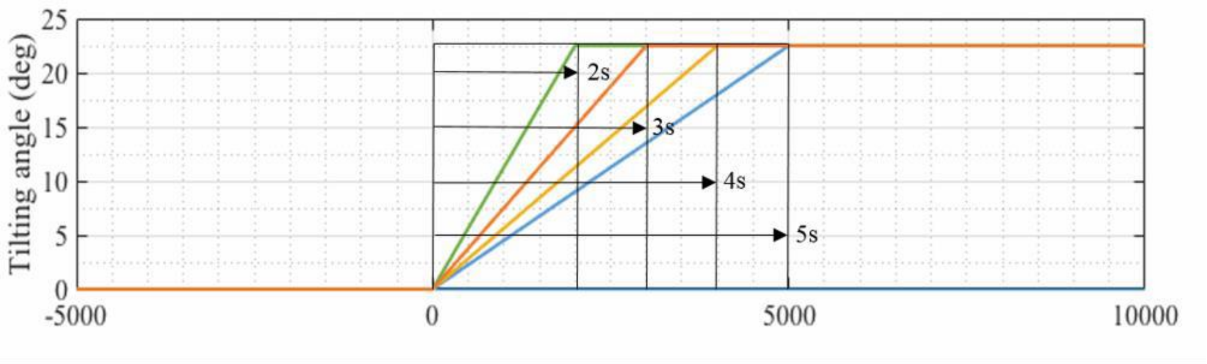


Figure 23: A visual representation of how long it took each perturbation speed to reach the desired tilt angle of 22.5^0/s. Annotations clearly represent that the speed of 11.25^0/s took 2 seconds to reach tilt angle, 7.5^0/s took 3 seconds 5.625^0/s took 4 seconds and the slowest speed, 4.5^0/s took 5 seconds. This illustration can be used to help speculate why such results were found in the present study.

After the desired angle was reached the visual field was maintained at that angle for the rest of the 10 s duration. Meanwhile, individuals had to read the Stroop words whilst the visual scene stayed perturbed. Clearly for the faster speeds the end-perturbed image would have been tilted at the angle of 22.5^0 for a longer duration than that of the slower speed trial. Consequently, more Stroop words would have had to been read whilst the visual scene was perturbed, in comparison to conditions which endured a slower speed. This additive attentional demand of the Stroop, in combination with being perturbed, would have placed strain on an individual's attentional capacity as there were two tasks the individual had to manage concomitantly. Consequently, the impedance to balance would have been exacerbated; contributing to the greater COP path length changes seen at faster speeds.

The predominant cause of balance dysfunction is due to the breakdown in communication between the three sensory modalities, causing impedance to sensory information received and the connective pathways associated with balance (Guskiewicz, 2011). When exploiting this concept, it is clear that perturbing the virtual field imposes the individual with a visual threat, which may have been heightened when elicited at faster speeds. This is dependent on how the individual perceived the perturbation, and how well it mimicked the sensation of falling. Individuals will have programmed in memory the experience of a previous fall or a time they slipped over and felt unbalanced. Subsequently, a motor program would have been formed to initiate how they responded in such an event. In the present study it may be that the faster speeds were a closer representation of that threat of a previous slip or fall, influencing the way in which they responded. Conversely, slower speeds may have appeared less of a threat as individuals could mentally process the perturbation and produce a relevant response. Thus, offering an alternative explanation as to sway responses were greater for faster speeds.

5.4**Advancing the VR-WBB system as a tool to assess the visual control of balance**

Over the years, there has been much progression to help our understanding of the visual system and its importance in balance. Notably, the research performed in the present study is now at the forefront of this. From the initial moving room experimental design carried out by Lee and Aronson (1974) through to Slobonuov and his VR induced moving room experiments, the current study has further advanced this research, contributing to our understanding of visual control and balance further. Markedly, and extending from Slobounov's work, the results from the present study have shed light into the optimal developments of VR-WBB system for balance assessment.

With the assessment of balance continuing to be explored and implemented into more and more clinical procedures, it seems fitting that this study also contributed to this advancement. Whilst we know that visual system is integral for the maintenance of balance (Lee and Aronson, 1974), we also know that more often than not, this system is impeded in the event of a concussion with the individual manifesting an observable balance deficit. Notably, and based on previous research conducted (Teel, E.F. and Slobounov, 2015) one could infer that the device designed in the present investigation could serve a purpose not only for standard balance assessments, but also in the field of concussion diagnosis. As highlighted in papers by both Wright et al., (2015) and Teel and Slobounov., (2015), administering perturbations through VR evokes a significantly greater sway response in concussed patients compared to healthy controls. Whilst the best parameters to adopt for a concussed cohort are not yet clear and will require further investigation before implemented clinically, the current study can provide some speculations, advancing from previous research.

Whilst it is clear that roll elicits the greatest COP response, this may not deduce that this is the axis most effective to detect balance abnormalities, and thus, concussion diagnosis. In fact, implementing the alternative pitch perturbations as the preferential axis may provide heightened sensitivity. The significantly smaller alterations to COP path length observed through pitch perturbations would make way for a more stringent tool to assess balance. The thought here would be that more subtle deviations in postural deficits could be detected, which would be more refining when trying to distinguish between balance abnormalities, and further, between a concussed patient and a healthy individual.

Whilst this may appear to be of benefit, a tool too stringent could lead to postural deficits, or minor concussions being overlooked, a problem that needs to be avoided implicitly. On average COP path length in the pitch-perturbed axis increased from 135 ± 32 mm before the perturbation to 156 ± 51 mm after the perturbation. Moreover, this increase was not statistically significant. In fact, this mere 15 % increase in COP path length could be attributed to other factors such as individuals balance ability, fatigue, hydration or musculoskeletal weakness and, may not actually account for any substantial increase in COP path length (Derave et al., 1998; Fox et al., 2008; Johnston et al., 1998). Collectively, this denotes that the pitch axis maybe an insufficient tool to use when trying to spot concussions on the mild end of the spectrum.

A more robust alternative may be to utilize roll perturbations, which clearly induces a substantial postural response, demonstrated by a mean increase in COP path length of 73 %. These results were obtained from a healthy cohort who had no history of concussions or neurological disorders. It is reasonable to assume that a concussed athlete would elicit an even greater response; subject to dysfunction in sensory modalities and previous literature highlighting the exaggerated effect of perturbations in concussed individuals (Broglio and Puetz, 2008). Eliciting roll perturbations would reduce the risk of overlooking any abnormalities in balance compared to if we were to use purely pitch-perturbations. Employing this type of perturbation must be done effectively; it may be that such an axis could lead to exaggerated diagnosis whereby individuals who are in fact healthy are deemed concussed. This emphasizes the need for pre-season testing to gage whether individuals have actually experienced a concussion signified by a balance deficit, or whether they just have naturally low balance abilities.

However, it maybe that neither pitch nor roll are the optimal parameter to use, but instead it could be that they complement each other when used in collaboration. For example, if this device was to be advanced to a concussed cohort, one could use roll perturbations initially to establish whether a concussion is present. From such results pitch perturbations could then be utilized to grade the severity of the injury. If an individual is finding it hard to maintain balance through pitch, the easiest axis in which to control balance within a given range, then it suggests an mTBI is likely. Consequently, utilizing additional pitch analysis can add more stringency to assessments made through roll.

Whether to use pitch or roll perturbations individually is an area that required further investigation. However, what can be speculated, based on current research, is that a concussion tool may be advanced if both perturbation types were adopted. Each insult to the brain can affect different areas; no two concussions are the same, and more specifically, no two balance responses are the same (Broglio and Puetz, 2008). Thus, investigating the effects of manipulating through purely the pitch or purely the roll axis may be an oversight as each axis may assess functioning in different areas of the brain (Riemann and Guskiewicz, 2000).

This insight has been further strengthened through research on patterns of muscle recruitment in the Central Nervous System (CNS). Küng et al., (2009) investigated the CNS and its control in pitch and roll movements during balance. Healthy individuals were perturbed in both the pitch and roll axes, and subsequent muscle responses associated with knee, trunk and arm movement were analysed through EMG traces. Over each perturbation direction, rotations through roll caused equal delays in peak COM and velocity, whereas rotation through pitch did not. In accordance with findings on timing and velocity, the EMG activity of the same muscle groups involved in coordinating the movement was also analysed, establishing that the roll response (and associated muscle initiation) occurs before compensating for pitch, as programmed through the CNS. This emphasizes how roll and pitch perturbation responses operate through reciprocal relationships, reinforcing the need to investigate both. This study also shed light into which muscle groups were activated during the respective rotations, with muscles of the lower leg being preferentially orientated for pitch and, trunk muscles for roll, corroborating previous discussion (Winter, 1995). Moreover, muscles involved in coordination of knee and arm movements, that are required to counteract roll perturbations, rely on the pitch response also. From this it can be suggested that the CNS programs the initial roll response before adjustments to the pitch response occur (Küng et al., 2009). Again, this provides a strong argument to suggest that both pitch and roll should be investigated collaboratively or alternatively, suggests that future research should be carried out within this field further.

In contrast to assessment into the influence of axis perturbations on a COP response, the influence of speed of perturbation within literature remains somewhat scarce. For progression within this area, it is paramount that the speed range adopted for the current study is tested on a concussed cohort to ensure optimization of an assessment tool. Nevertheless, inferences can be made based on the current data to provide insight as to what speed could be deemed most effective. Initially one could suggest that the speed that induces the greatest destabilizing effect would be the best to use within a concussion tool. Whilst this maybe the case, like that of roll, this conclusion is not so clear cut. If a speed was to be induced that lay in the most destabilizing ranges of 5.625 ^{0}/s to 11.25 ^{0}/s this may severely impede on a concussed individuals balance, causing them to fall over. In fact, utilizing a speed that induces the largest response in non-concussed individuals, such as the 7.5 ^{0}/s speed, may induce a ceiling effect. Therefore, analysis should be conducted on the speed that elicits that greatest difference in responses between concussed and healthy individuals. With this in mind, it may be that a slower speed like 4.5 ^{0}/s would be more appropriate to adopt to heighten the accuracy in detecting a concussion.

As balance is highly individualized, with each individual evoking different response to perturbations, it may be that more than one speed is adopted. In fact, incorporating a range of speeds could not only enhance the paradigm it may also reveal the severity of injury. For example, if the speed that caused the least destabilizing effect was used first and had no significant disturbance to balance the individual could then be assessed with a more destabilizing speed until an effect was seen. This could be used at baseline then repeated in the event of a concussion and again, to track an individual's recovery within a RTP protocol. Typically, the perturbations that provoke a response at baseline should be exacerbated in the event of a concussion. One way that this could be implemented effectively is if an individual balance profile was ascertained; establishing a threshold speed specific to each individual that elicits the most destabilizing response. This would ensure that individuals knew the upper limit of their balance responses with recovery aiming to keep COP responses within this limit.

Thresholds could be visually implemented for both axis and speed perturbations through forming specific ellipses (*figure 24)*. COP responses to a set of perturbations should be obtained at baseline and averaged over different occasions to account for day-to-day balance. An ellipse can then be formed, providing a calculated area in which an individual's balance is considered normal, any deviations made outside this ellipse would signify postural dysfunction. Whilst this is suitable for pitch side use, if the VR-WBB prototype was to be developed into clinical settings, where baseline scores are not accessible, alternative measures need to be investigated. One such possibility is to obtain a figure for the average day-to-day variation of balance in particular population cohorts. Perturbations should then be tested to ensure they evoke a response greater than the average sway response of respective populations. Establishing an average taken from population cohorts is a further study in itself, but would be a pivotal step to make for the clinical development of the VR-WBB system.

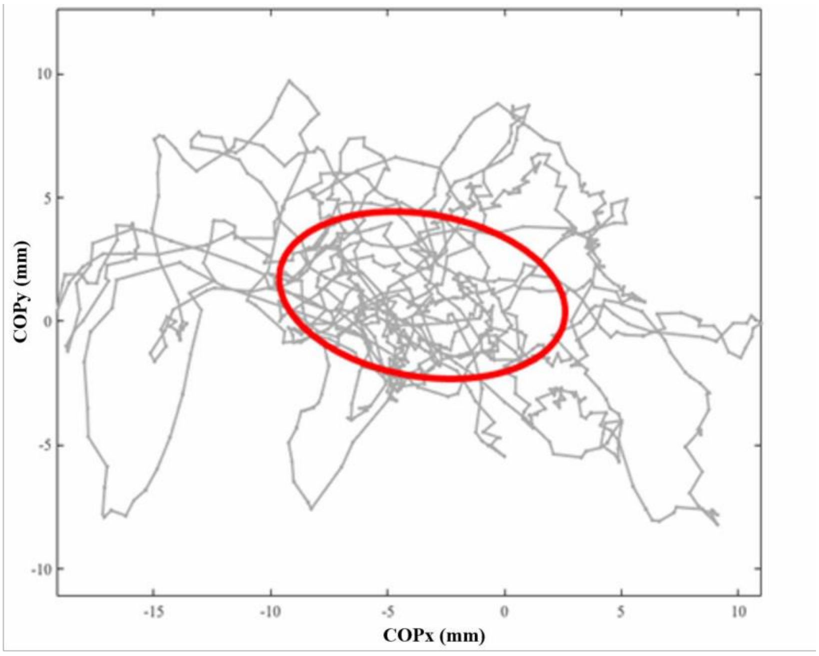


Figure 24: An illustration of an ellipse calculated from the area of an individual's mean COP sway response when perturbed in the roll axis. This image signifies a novel type of analysis that has the potential to develop for future studies when assessing individualized COP responses. Using an ellipse provides a visual representation of an individual's balance profile and could be extremely useful for assessing whether an individual can return to play.

In addition, future research could focus on implementing ellipses to illustrate and grade the severity of a concussion. For this to work an elliptical area for that individual would have had to be calculated previously. If this value was then stored online, in the event of a concussion the clinician can easily access this previously obtained value. Suitably, individual's recovery can be tracked by anyone who has access to this system and thus, not just by the clinician that established the baseline values. The individual can directly see the area in which they need to maintain balance to be considered normal. This technique provides direct visual feedback to the athlete to see if they are within the area in which their COP is controlled. With future technological advancement it maybe that such data could be stored on an app or tablet for accessibility. Not only does this implementation provide great scope for concussion assessment and RTP procedures, it maybe that active control and assessment of individuals COP could aid the rehabilitation of balance.

Overall, it is clear there is huge scope to build a comprehensive assessment of balance for a concussed cohort. Whilst it is clearly portrayed that manipulating an axis or speed of a perturbation can significantly affect an individual's postural response in healthy individuals, future work needs to investigate whether this effect will be similar in the concussed cohort. Clearly findings from the present study, which was conducted on a healthy population, cannot deduce the optimal parameters that would be appropriate for a concussed population. Nonetheless, this research established that manipulating perturbation speed and axis does have a significant effect on an individual's balance response; it can only be expected that this effect will be more pronounced within a concussed population (Broglio and Puetz, 2008; Nolin et al., 2012).

5.5Habituation

Aside from the type of perturbation influencing COP responses, a secondary finding also found a trend for repeat of perturbation influencing COP responses, inducing a habituation effect.

Habituation is an adaptive behaviour characterized as a ‘non-associative learning’ process, whereby the individual learns to adapt to presentation of the same stimulus as they realise it poses no threat. This is a natural process characterized by an activity-dependent presynaptic depression of synaptic transmission depicted by a reduction in the release of the excitatory neurotransmitter, glutamate (Breiter et al., 1996). Habituation is typical within muscles where responses attenuate following exposure to a series of identical destabilization perturbations (Bloem et al., 1998). Accordingly, habituation was displayed within the current study. Whilst this is expected in the cohort of participants recruited in the present study who had no history of concussions or neurological conditions, it is of question whether the same response would be seen in a concussed population, as individuals may not be able to identify, respond or adapt to repeated stimuli.

Regardless as to whether axis or speed of perturbation was manipulated, across all perturbed trials the first trial induced greater mean COP sway response than trials that succeeded. Previous literature has suggested this effect is typical when obtaining assessments of balance over recurrent trials. For example, McLeod et al., (2004) conducted a prospective study comparing whether the BESS and SAC are vulnerable to the effect of habituation, induced through learning. Results confirmed that the BESS elicited a significant habituation effect, yet SAC scores remained fairly stable when trials were completed over a 60 day period (McLeod et al., 2004; Valovich et al., 2003). Thus, clinicians should keep in mind that athletes may improve balance with repeated testing. Importantly this may not be due to an absence of concussion, but purely due to the effect of habituation. Whilst this is somewhat a flaw for assessing balance, this cannot be controlled due to the nature of the innate learning processes.

5.5.1Analysis of the habituation effect on COP path length

In both axis and speed-perturbed trials COP path length responses appeared to be significantly more pronounced with the first perturbation, when the participants were unaware and unfamiliar of the stimuli. As demonstrated in figures 19 and 23, it is clear that any trials that succeeded the first were significantly less pronounced, with a clear attenuation of COP path length response. This was the case in both speed and axis-perturbed trials, albeit slight different trends were exhibited.

The effect of habituation was perhaps more pronounced within 'axis' groups, given the design of the study whereby there were only two axis-perturbed groups compared to the four speed-perturbed groups. In axis-perturbed conditions, the individuals would receive eight roll perturbations and eight pitch perturbations randomly throughout the course of the trial (interspersed with control trials). Conversely, the speed group had four separate conditions whereby there were four perturbations within these conditions, receiving half the amount of the same stimuli when compared to axis trials. Thus, the greater repetition of the same stimuli in axis-manipulated perturbations may have caused the more pronounced habituation effect.

When reviewing the habituation effect in axis-perturbed conditions, it was established that the first two perturbations were not statistically different from each other, but statistically different from the succeeding trials. Over the course of eight perturbations, mean COP path length significantly decreased from the 1st to the 8th by 74.8%. Whilst the depreciation between the 1st and the 2nd was only 25.8%, with the decline being insignificant. This trend is slightly different when analysing the habituation effect in speed-perturbed trials whereby the 1st trial is statistically different from all of the succeeding trials, including the 2nd. There is an approximate average decrease of 40 % in COP path length from the 1st to the 2nd perturbation, 63 % decrease from 1st to 3rd, and a 55 % decrease from 1st to the 4th. This exemplified a less predictable trend when compared to axis conditions. As mentioned above, this effect is more likely to be due to the study design, whereby only four perturbations of a given speed were received, as opposed to eight within axis trials. In the latter cause, it would thus be expected that a more pronounced effect for the first perturbation is displayed.

The present study did not control the order in which a control or perturbed trial was received. Thus, making any valid conclusions on the effect of repeat of perturbation and further, the effect of habituation must be done cautiously. Given that sixteen control trials were interspersed with sixteen perturbed trials; the likelihood of a receiving a control trial first was 50 %. It could be that individual's first perturbation was as late as the 4th (in speed trials) or 8th perturbation (in axis trials) after a sequel of control trials, influencing how an individual habituated across trials

5.5.2 Why does the habituation occur and what are its implications?

The attenuation effect in response to repetition of the same stimuli is thought to occur through a process of self-adaptation, whereby a functional mechanism dampens the response in order to reduce energy expenditure (Keshner et al,1987). In the case where a habituation effect is not present, it could indicate the presence of a neurological condition or, a concussion. Consequently, this can shed light into refining the parameters of a concussion tool.

One way in which interpretation of the habituation effect could come in use when designing a concussion tool is by assessing how individual's respond to a sequel of repeated postural perturbations. If habituation occurs, then it can be inferred that perhaps a concussion is not present; individuals recognize that the stimulus is not a threat and can respond accordingly. Conversely, if the individuals experience difficulty in adapting to the repetitive postural perturbations it may indicate a neurological dysfunction, i.e.: concussion. Studies have expressed the importance of reducing the learning effect when conducting concussion assessments in order to depict whether the individual is fit to play (Broglio et al., 2007). Clearly it is expected that everyone responds to the first perturbation, regardless of their neurological state, it is possible that the succeeding responses are the ones that may shed light into the differences between a healthy population and those with concussion. However, an attenuation of a COP response (i.e. improvement in balance performance) as a consequence habituation could give the false illusion that an individual is not concussed. This would implicate that conditions that elicited least vulnerability to habituation may be better to use.

Any conclusions drawn about the effect of habituation in the present study should be made cautiously. The primary aim of this study was not to evaluate the habituation effect, and the methodological design utilized is not appropriate to draw any valid conclusions. Moreover, when thinking of the practical application of such a tool, employing repeated exposures to the same stimulus is a lengthy procedure and not viable for pitch side use. In most contact sports sports there is a window of time in which the individual can be assessed if they have any hope of returning to the game. Such a procedure could take up a substantial part of that assessment time in which other domains also have to be analysed. In fact, it is clear from analysis that the first two trials across axis and speed elicit the greatest effect. Thus, the first two trials are sufficient to indicate whether a balance abnormality is present. In this case, the time required to assess the individual would be shortened compared to that of the former assessment. Future studies should seek to isolate each perturbation type under investigation to pinpoint which speed, or, axis is most vulnerable to habituation.

5.6Future research

Based on the pioneering work conducted in the present study being developmental and novel, there are several drawbacks that need to be addressed if the study were to be advanced and if the prototype was to be utilized in practice.

This thesis successfully developed a tool to investigate the visual systems role in balance maintenance. Notably, such a system has potential to provide revolutionary advancements in the field of concussion diagnosis, which is what this thesis has underpinned. Whilst the implication of this thesis was to pioneer and advance a novel tool for concussion diagnosis, no sound conclusions can be drawn due to the healthy participant tool recruited. Nonetheless, this does not detract from the work that was carried out and the conclusions that were drawn. Instead, it provides the parameters for future research to investigate the visual systems role in balance, when tested on a concussed cohort. For this to be done, the following limitations that are outlined below need to be addressed and rectified.

The first limitation of the present study that needs addressing is the lack of control given over presentation of the first perturbation. Randomization of perturbations was done initially to prevent individuals anticipating responses to disturbances within the visual field. In doing so more problems were created elsewhere, particularly when trying to analyse the effect of the first perturbation. Some individuals received a perturbed trial immediately, whilst others received a series of control trials first. Clearly the former elicits a greater sway response, as the perturbation was unfamiliar and unexpected. In future, the order in which perturbations are presented should already be pre-determined: starting with initial control trials to make them feel at ease with the system and establish baseline COP values, to then be followed by perturbed trials at set points within the sequence. As long as the point at which perturbations are inflicted is kept consistent between investigations into different parameters, then a valid assessment of the effect of differing perturbations can be obtained. Moreover, change in this design would allow the effect of habituation to be looked at more effectively as assessment of the first perturbation would be comparable. Thus, this refined protocol could be implicated into a long-term assessment, whereby the same trial is run weeks later, seeing if habituation effects have influences long-term. Such a design would help to determine not just the acute symptoms of concussion but also the residual symptoms that persist over time.

Due to the novelty of the current study and the healthy cohort recruited, establishing individual baseline COP values were not feasible or required. As a result, individual variability was not accommodated for as COP values were obtained from grouped data, which produces an unrepresentative outlook on the effect of a perturbation for that individual. This is highlighted across the study by the large standard deviation values. For example, there was a mean increase in COP path length of the roll condition from 130 ± 30 mm to 222 ± 127 mm. This huge standard deviation highlights that some individual data could be distorting the results, even when clear anomalies were omitted from data analysis. Thus emphasising the need for individual balance profiles to be obtained. Balance assessments should be obtained within an individual's pre-season training, when the individual is asymptomatic, to act as a baseline for future testing. A personalized balance profile would allow for comparison to see if an individual's balance had significantly deviated from baseline and thus, indicate a concussion. Moreover, this type of assessment can be used as an RTP measure to track recovery; reduction in sway over time will indicate the individual is gradually improving. Whilst establishing a baseline was not required for the purpose of this investigation, which merely set out to investigate effect of different perturbation, it is a vital aspect that needs to be taken into consideration when implementing this module as a potential diagnostic tool for concussion.

As established in the present study and in previous work, perturbations displace the visual field distorting the quality of sensory of information available, subsequently evoking a head tilting response (Broglio and Puetz, 2008; Warren, 1976). This response is exaggerated in the current study whereby words of the Stroop were perturbed concomitantly with the visual field. It has previously been established that when individuals tilt their head, balance is compromised resulting in a state of postural disequilibrium (Paloski et al., 2006). Accordingly, it is this action that can cause individuals to feel motion sickness when within a VR-system (Smart et al., 2002). This concept is exacerbated in roll conditions whereby compensatory eye movements in response to a changing visual field are insufficient and thus, the operation of head movements in response is essential (Gresty and Bronstein, 1992). Whilst individuals COP measures were obtained, the present study could be strengthened through simultaneous obtainment of head movement. This would be a pivotal and easy advancement to the current study given that the Oculus headset already contains motion trackers that detect head movement. By gathering such information insight could also be given on whether the angle of tilt implemented was optimal, or whether future investigations should explore a different range of angles to optimise perturbation delivery.

Whilst balance can be significantly impeded in the event of a concussion, this is not the only factor that can hinder an individual's postural equilibrium. In fact, balance can become impeded by a multitude of factors on a daily basis including fatigue (Johnston et al., 1998), poor hydration (Derave et al., 1998), and physical exertion (Fox et al., 2008), all factors which can be brought on by exercise. Given that fatigue has been a factor reported to invalidate balance assessments in current pitch side concussion tools (Fox et al., 2008) it is the factor that needs to be focused on. In our study we attempted to control for fatigue by eliminating it as a factor altogether. Incorporating a 5-minute break between blocks, allowing both cognitive and physical rest, ensured fatigue was controlled. Whilst this made the protocol lengthier, previous studies had been criticized for adopting a mere 2 minute break, which may affect the individual's ability to maintain balance due to hip and ankle fatigue (Muir et al., 2014). Controlling for fatigue was fitting for the present study, however when developing a tool for pitch side use this maybe an oversight as individuals will be coming off for assessment in a fatigued state. Clearly this is an imperative a factor to consider and accommodate for when developing pitch side assessments.

Previously established balance assessments such as the BESS have also been criticized for their failure to accommodate for fatigue (Fox et al., 2008). However, it is clear that this is a vital confounding variable to consider for concussion assessment given that both the concussion and the fatigue could inflict on postural stability (Fox et al., 2008). With studies claiming that the effect of fatigue may take up to 20 minutes to subside, this questions the initial design of our study being adopted for pitch side use whereby assessments have to made within a short time-frame (Fox et al., 2008). Notably, this variable can be accommodated for with alteration to the experimental protocol. Future research should incorporate a test of physical fatigue prior to undertaking the VR-WBB experiment. Results can then be established and compared to un-fatigued values to see the effect on an individual's COP response. If an effect is seen, corroborating previous literature, then individuals should be fatigued when initial baseline COP scores are obtained in pre-season.

There is a multitude of acute exercise tests that would be considered suitable to incorporate ranging from cycle ergometers to different types of dynamometers. Johnston et al., (1998) conducted a study to determine whether lower limb fatigue affects an individual's static balance when standing on an unstable platform. The participants were fatigued through using an isokinetic dynamometer whereby antagonistic exercises on the hip, knee and trunk were inflicted. Analysis was conducted based on their balance scores in a pre-fatigued and a post-fatigued state. Results demonstrated that there were significant decreases in motor control performance following trials of fatigue (Johnston et al., 1998). This study not only confirms that fatigue impedes balance, it also provides insight into a suitable measure to inflict fatigue on individuals. Consequently, an isokinetic dynamometer, which is often utilized for strength and conditioning purposes and thus would be easily accessible, could provide a suitable tool to inflict fatigue on individuals prior to baseline testing.

The importance of an individualized balance profile has been reiterated throughout this thesis. Implicating such an approach would not only enhance the objectivity of the current VR-WBB paradigm, it would also heighten the competition against current assessment tools such as ImPACT SAC and SCAT. As established, neurocognitive assessment has been eluded as the cornerstone for concussion assessment (Aubry et al., 2002; McCrory et al., 2013). In a similar fashion to the present study, these tests have been scrutinized for not accommodating for individual differences in domains such as working memory and reaction time (McCrory et al., 2013). Notably, these tests often compare individuals to a set of previously obtained control scores rather than any baseline individualized data. This can also be the case when the SCAT is adopted, if individuals have not previously had baseline assessments when asymptomatic. Comparing individuals to a baseline value that is not their own can be deemed effectively useless; whilst some maybe good at tasks on reaction time others may struggle – this may not be anything to do with a concussion but merely how they are. Henceforth, if this current module was to enforce COP measurements to be obtained at baseline, and again at the time of an injury this would heighten the objectiveness above other measures. Moreover, obtaining balance measures through are objective and quantifiable reduces the risk of sandbagging which is a problem noted with current cognitive tests (Erdal, 2012).

A further way in which the VR-WBB platform adopted in the present study overrides current pitch side assessments is through the dual-task paradigm component. Whilst the primary reason for implementing the additive task of the Stroop in the present study was to ensure immersion, adopting such a cognitive test has greater utility elsewhere. The Stroop itself is a useful measure that can assess an individual’s current cognitive state and can indicate whether a concussion is present (Parsons et al. , 2011). However, it is not the implementation of the Stroop per se that is notable. This study has provided a platform whereby multiple cognitive-based tests can be implemented and tested concomitantly with a balance assessment, providing a tool to not only assess a physiological response but further, a tool that can more accurately assess an individual’s neurocognitive state. Whilst the Stroop focuses on one aspect of cognition, many other neurocognitive tests can be implemented to assess other domains of cognition effected in a concussion, such as tests of reaction time, spatial navigation and concentration (Teel and Slobounov, 2015b). Not only does this allow for a comprehensive concussion assessment, the VR-WBB design permits such a test to be performed in the same time frame as ascertaining balance measures; saving substantial time and cost. Notably, dual-task paradigms are the best representation of sporting scenarios whereby both cognition and postural control are required simultaneously (Teel et al., 2013). Consequently, this study has highlighted the potential to develop a revolutionary tool that can, assess multiple aspects of concussion, provide objective and quantifiable measures, and, be conducted in a suitable time frame for pitch side assessments.

The VR-WBB module in the present study was adopted for research purposes whereby assessments were conducted on a Microsoft computer within the laboratory. Given the nature of the WBB requiring only Bluetooth connection to acquire COP measurements, there are infinite possibilities for the development of the portability and feasibility of this module. In future a cost-effective, easy to use portable tablet or smart phone device could be developed which can operate the control over the initiation of perturbations. As the use of VR is becoming progressively more commonplace, equipment such as HMD are going to decrease in value. If a tool can then be developed to connect such a system with a smartphone device, the potential cost of the system would be dramatically reduced, making it an affordable system for many clubs and clinics globally.

Further to this, if individual's data was to be stored on a smartphone for online analysis not only could they visually and objectively see a balance score, they can also track their recovery. A calculated area taken at baseline, or ellipse that provides his or her own unique natural COP response can be saved and stored on this device. With access to this baseline score, individuals can see the ‘threshold’ in which their COP needs to be maintained, for them to be deemed healthy and fit to play. This proves particular promise for a graded RTP procedure as individuals and clinicians can objectively track the recovery course of symptoms. Moreover, if a more extensive range of neurological tests could be implemented within the visual scene, assessing domains such as reaction time and recall, then this prototype could make a more comprehensive RTP decision, appreciating the vast symptomology that is presented with a concussion (McCrory et al., 2009).

With implementation of the VR-WBB prototype, the current gold standard SCAT, which contains a battery of tests subjective and vulnerable to sandbagging, could be gradually filtered out. The VR-WBB system allows us to obtain objective and quantifiable COP data. Consequently, assessments are less likely to be flawed by sandbagging or the subjective interpretation of the clinician. With more investment of time and refinement of parameters such a dual-task VR paradigm could over rule many of the current diagnostic tools.

5.7Conclusion

Overall, it is clear that the combination of inducing perturbations through a VR-system and obtaining COP data from a WBB provides promising scope for the development as a newly objective concussion assessment tool. The ability of such a tool to provide quantifiable data at no expense of cost or portability unduly overcomes the limitations of current balance assessments that are either expensive, subjective or laboratory constrained. Notably, this study has established an objective balance assessment tool that can be employed pitch side; a revolutionary development that in future could help save the lives of many.

REFERENCES

Amen, D.G., Wu, J.C., Taylor, D., et al. (2011) Reversing brain damage in former NFL players: implications for traumatic brain injury and substance abuse rehabilitation. **Journal of psychoactive drugs,** 43 (1): 1-5.

Amick, R.Z., Jansen, S.D., Chaparro, A., et al. (2015) Comparison of the SWAY Balance Mobile Application to the Abbreviated Balance Error Scoring System. **Athletic Training & Sports Health Care,** 7 (3): 89-96.

Ashare, A. (2009) Returning to play after concussion. **Acta Paediatrica,** 98 (5): 774.

Aubry, M., Cantu, R., Dvorak, J., et al. (2002) Summary and agreement statement of the First International Conference on Concussion in Sport, Vienna 2001. Recommendations for the improvement of safety and health of athletes who may suffer concussive injuries. **British journal of sports medicine,** 36 (1): 6-10.

Barkhoudarian, G., Hovda, D.A. and Giza, C.C. (2011) The molecular pathophysiology of concussive brain injury. **Clinics in sports medicine,** 30 (1): 33-48.

Bartlett, H.L., Ting, L.H. and Bingham, J.T. (2014) Accuracy of force and center of pressure measures of the Wii Balance Board. **Gait & posture,** 39 (1): 224-228.

BBC NEWS. (2013). Ben robinson's rugby death. Retrieved from http://www.bbc.co.uk/news/uk-northern-ireland-23943642

Bell, D.R., Guskiewicz, K.M., Clark, M.A., et al. (2011) Systematic review of the balance error scoring system. **Sports health,** 3 (3): 287-295.

Bloem, B., Van Vugt, J., Beckley, D., et al. (1998) Habituation of lower leg stretch responses in Parkinson's disease. **Electroencephalography and Clinical Neurophysiology/Electromyography and Motor Control,** 109 (1): 73-77.

Breiter, H.C., Etcoff, N.L., Whalen, P.J., et al. (1996) Response and habituation of the human amygdala during visual processing of facial expression. **Neuron,** 17 (5): 875-887.

Broglio, S.P. and Puetz, T.W. (2008) The effect of sport concussion on neurocognitive function, self-report symptoms and postural control. **Sports Medicine,** 38 (1): 53-67.

Broglio, S.P., Macciocchi, S.N. and Ferrara, M.S. (2007) Neurocognitive performance of concussed athletes when symptom free. **Journal of athletic training,** 42 (4): 504.

Bruns, J. and Hauser, W.A. (2003) The epidemiology of traumatic brain injury: a review. **Epilepsia,** 44 (s10): 2-10.

Carrivick, P.J., Lee, A.H. and Yau, K.K. (2001) Consultative team to assess manual handling and reduce the risk of occupational injury. **Occupational and environmental medicine,** 58 (5): 339-344.

Centers for Disease Control and Prevention (2011) Nonfatal traumatic brain injuries related to sports and recreation activities among persons aged <\/=19 years--United States, 2001-2009. **MMWR.Morbidity and mortality weekly report,** 60 (39): 1337-1342

Chiavorano, E., De Waele, C., MacDougall, H.G., et al. (2015) Maintaining balance when looking at a virtual reality three-dimensional display of a field of moving dots or at a virtual reality scene. **Frontiers in neurology,** 6.

Clark, R.A., Bryant, A.L., Pua, Y., et al. (2010) Validity and reliability of the Nintendo Wii Balance Board for assessment of standing balance. **Gait & posture,** 31 (3): 307-310.

Costanza, A., Weber, K., Gandy, S., et al. (2011) Review: Contact sport-related chronic traumatic encephalopathy in the elderly: clinical expression and structural substrates. **Neuropathology and applied neurobiology,** 37 (6): 570-584.

Creath, R., Kiemel, T., Horak, F., et al. (2002) Limited control strategies with the loss of vestibular function. **Experimental brain research,** 145 (3): 323-333.

Daneshvar, D.H., Nowinski, C.J., McKee, A.C., et al. (2011) The Epidemiology of Sport-Related Concussion. **Clinics in sports medicine,** 30 (1): 1-17.

Derave, W., Clercq, D.D., Bouckaert, J., et al. (1998) The influence of exercise and dehydration on postural stability. **Ergonomics,** 41 (6): 782-789.

Di Giulio, I., Maganaris, C.N., Baltzopoulos, V., et al. (2009) The proprioceptive and agonist roles of gastrocnemius, soleus and tibialis anterior muscles in maintaining human upright posture. **The Journal of physiology,** 587 (10): 2399-2416.

Doyle, R.J., Hsiao-Wecksler, E.T., Ragan, B.G., et al. (2007) Generalizability of center of pressure measures of quiet standing. **Gait & posture,** 25 (2): 166-171.

Drew, L.B. and Drew, W.E. (2004) The contrecoup-coup phenomenon. **Neurocritical Care,** 1 (3): 385-390.

Dziemianowicz, M.S., Kirschen, M.P., Pukenas, B.A., et al. (2012) Sports-related concussion testing. **Current neurology and neuroscience reports,** 12 (5): 547-559.

Edwards, A. (1946) Body sway and vision. **Journal of experimental psychology,** 36 (6): 526.

Erdal, K. (2012) Neuropsychological testing for sports-related concussion: how athletes can sandbag their baseline testing without detection. **Archives of clinical neuropsychology : the official journal of the National Academy of Neuropsychologists,** 27 (5): 473-479.

Finnoff, J.T., Peterson, V.J., Hollman, J.H., et al. (2009) Intrarater and interrater reliability of the Balance Error Scoring System (BESS). **PM&R,** 1 (1): 50-54.

Fox, Z.G., Mihalik, J.P., Blackburn, J.T., et al. (2008) Return of postural control to baseline after anaerobic and aerobic exercise protocols. **Journal of athletic training,** 43 (5): 456-463.

Gatica-Rojas, V. and Mendez-Rebolledo, G. (2014) Virtual reality interface devices in the reorganization of neural networks in the brain of patients with neurological diseases. **Neural regeneration research,** 9 (8): 888-896.

Gibson, J.J. (1958) Visually controlled locomotion and visual orientation in animals. **British journal of psychology,** 49 (3): 182-194.

Gil-Gómez, J., Gil-Gómez, H., Lozano-Quilis, J., Manzano-Hernández, P., Albiol-Pérez, S. and Aula-Valero, C. (2013) "SEQ: suitability evaluation questionnaire for virtual rehabilitation systems. Application in a virtual rehabilitation system for balance rehabilitation", **Proceedings of the 7th International Conference on Pervasive Computing Technologies for Healthcare**ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering) pp. 335.

Gil-Gómez, J., Lloréns, R., Alcañiz, M., et al. (2011) Effectiveness of a Wii balance board-based system (eBaViR) for balance rehabilitation: a pilot randomized clinical trial in patients with acquired brain injury. **Journal of neuroengineering and rehabilitation,** 8 (1): 1.

Giza, C.C. and Hovda, D.A. (2001) The neurometabolic cascade of concussion. **Journal of athletic training,** 36 (3): 228.

Gresty, M.A. and Bronstein, A.M. (1992) Visually controlled spatial stabilisation of the human head: compensation for the eye's limited ability to roll. **Neuroscience letters,** 140 (1): 63-66.

Guskiewicz, K.M. (2011) Balance assessment in the management of sport-related concussion. **Clinics in sports medicine,** 30 (1): 89-102.

Guskiewicz, K.M. and Broglio, S.P. (2011) Sport-related concussion: on-field and sideline assessment. **Physical Medicine and Rehabilitation Clinics of North America,** 22 (4): 603-617.

Guskiewicz, K.M., McCrea, M., Marshall, S.W., et al. (2003) Cumulative effects associated with recurrent concussion in collegiate football players: the NCAA Concussion Study. **Jama,** 290 (19): 2549-2555.

Guskiewicz, K.M., Ross, S.E. and Marshall, S.W. (2001) Postural stability and neuropsychological deficits after concussion in collegiate athletes. **Journal of athletic training,** 36 (3): 263.

Halstead, M.E., Walter, K.D. and Council on Sports Medicine and Fitness (2010) American Academy of Pediatrics. Clinical report--sport-related concussion in children and adolescents. **Pediatrics,** 126 (3): 597-615.

Harmon, K.G., Drezner, J.A., Gammons, M., et al. (2013) American Medical Society for Sports Medicine position statement: concussion in sport. **British journal of sports medicine,** 47 (1): 15-26.

Heard, K. (2013) The Impact of Preemption in the NFL Concussion Litigation. **University of Miami Law Review,** 68 (1):.

Horak, F. and Kuo, A. (2000) "Postural adaptation for altered environments, tasks, and intentions" In **Biomechanics and neural control of posture and movement** Springer. pp. 267-281.

Horak, F.B., Henry, S.M. and Shumway-Cook, A. (1997) Postural perturbations: new insights for treatment of balance disorders. **Physical Therapy,** 77 (5): 517-533.

Horak, F.B. and Nashner, L.M. (1986) Central programming of postural movements: adaptation to altered support-surface configurations. **Journal of neurophysiology,** 55 (6): 1369-1381.

Hsu, W.L., Scholz, J.P., Schoner, G., et al. (2007) Control and estimation of posture during quiet stance depends on multijoint coordination. **Journal of neurophysiology,** 97 (4): 3024-3035.

Huurnink, A., Fransz, D.P., Kingma, I., et al. (2013) Comparison of a laboratory grade force platform with a Nintendo Wii Balance Board on measurement of postural control in single-leg stance balance tasks. **Journal of Biomechanics,** 46 (7): 1392-1395.

Iwasaki, S. and Yamasoba, T. (2015) Dizziness and imbalance in the elderly: age-related decline in the vestibular system. **Aging and disease,** 6 (1): 38-47.

Jančová, J. (2008) Measuring the balance control system–review. **Acta Medica (Hradec Kralove),** 51 (3): 129-137.

Jeka, J., Oie, K.S. and Kiemel, T. (2000) Multisensory information for human postural control: integrating touch and vision. **Experimental Brain Research,** 134 (1): 107-125.

Johnston, R.B.,3rd, Howard, M.E., Cawley, P.W., et al. (1998) Effect of lower extremity muscular fatigue on motor control performance. **Medicine and science in sports and exercise,** 30 (12): 1703-1707.

Karlsson, A. and Frykberg, G. (2000) Correlations between force plate measures for assessment of balance. **Clinical Biomechanics,** 15 (5): 365-369.

Keshner, E., Allum, J. and Pfaltz, C. (1987) Postural coactivation and adaptation in the sway stabilizing responses of normals and patients with bilateral vestibular deficit. **Experimental Brain Research,** 69 (1): 77-92.

Kirkwood, M., Yeates, K. and Wilson, P. (2006) **Pediatric sport- related concussion: A review of the clinical management of an oft- neglected population.** Vol.117(4) edn, , Pediatrics.

Kissick, J. and Johnston, K.M. (2005) Return to play after concussion: principles and practice. **Clinical Journal of Sport Medicine,** 15 (6): 426-431.

Krishnamoorthy, V., Yang, J. and Scholz, J.P. (2005) Joint coordination during quiet stance: effects of vision. **Experimental brain research,** 164 (1): 1-17

.

Küng, U.M., Horlings, C., Honegger, F., et al. (2009) Control of roll and pitch motion during multi-directional balance perturbations. **Experimental brain research,** 194 (4): 631-645.

Langlois, J.A., Rutland-Brown, W. and Wald, M.M. (2006) The epidemiology and impact of traumatic brain injury: a brief overview. **The Journal of head trauma rehabilitation,** 21 (5): 375-378.

Leach, J.M., Mancini, M., Peterka, R.J., et al. (2014) Validating and calibrating the Nintendo Wii balance board to derive reliable center of pressure measures. **Sensors,** 14 (10): 18244-18267.

Lee, D.N. (1980) The optic flow field: the foundation of vision. **Philosophical transactions of the Royal Society of London.Series B, Biological sciences,** 290 (1038): 169-179.

Lee, D.N. and Aronson, E. (1974) Visual proprioceptive control of standing in human infants. **Attention, Perception, & Psychophysics,** 15 (3): 529-532.

Lee, D. and Lishman, J. (1975) Visual proprioceptive control of stance. **Journal of human movement studies,** .

Levin, H.S. (2003) Neuroplasticity following non-penetrating traumatic brain injury. **Brain Injury,** 17 (8): 665-674.

Lincoln A.E., Caswell, S.V., Almquist, J.L., et al. (2011) Trends in concussion incidence in high school sports: a prospective 11-year study. **The American Journal of Sports Medicine,** 39 (5): 958-963.

Longhi, L., Saatman, K.E., Fujimoto, S., et al. (2005) Temporal window of vulnerability to repetitive experimental concussive brain injury. **Neurosurgery,** 56 (2): 364-374.

Lovell, M., Collins, M. and Bradley, J. (2004) Return to play following sports-related concussion. **Clinics in sports medicine,** 23 (3): 421-441.

Mancini, M. and Horak, F.B. (2010) The relevance of clinical balance assessment tools to differentiate balance deficits. **European journal of physical and rehabilitation medicine,** 46 (2): 239-248.

Marshall, C. (28th August, 2014) **Soccer moms' sue FIFA over 'concussion risk.** [Online]. Available from: http://www.scotsman.com/news/soccer-moms-sue-fifa-over-concussion-risk-1-3524140 [Accessed July 3rd 2016].

Martland, H.S. (1928) Punch drunk. **Journal of the American Medical Association,** 91 (15): 1103-1107.

McCrea, M., Guskiewicz, K.M., Marshall, S.W., et al. (2003) Acute effects and recovery time following concussion in collegiate football players: the NCAA Concussion Study. **Jama,** 290 (19): 2556-2563.

McCrea, M., Hammeke, T., Olsen, G., et al. (2004) Unreported concussion in high school football players: implications for prevention. **Clinical Journal of Sport Medicine,** 14 (1): 13-17.

Mccrea, M. (2001) Standardized mental status testing on the sideline after sport- related concussion. **Journal of Athletic Training,** 36 (3): 274-279.

McCrory, P., Meeuwisse, W., Johnston, K., et al. (2009) Consensus statement on Concussion in Sport–the 3rd International Conference on Concussion in Sport held in Zurich, November 2008. **South African Journal of Sports Medicine,** 21 (2):.

McCrory, P., Meeuwisse, W.H., Aubry, M., et al. (2013) Consensus statement on concussion in sport: the 4th International Conference on Concussion in Sport held in Zurich, November 2012. **British journal of sports medicine,** 47 (5): 250-258.

McCrory, P.R. and Berkovic, S.F. (2001) Concussion: the history of clinical and pathophysiological concepts and misconceptions. **Neurology,** 57 (12): 2283-2289.

McLeod, T.C.V., Perrin, D.H., Guskiewicz, K.M., et al. (2004) Serial administration of clinical concussion assessments and learning effects in healthy young athletes. **Clinical Journal of Sport Medicine,** 14 (5): 287-295.

Mergner, T. and Rosemeier, T. (1998) Interaction of vestibular, somatosensory and visual signals for postural control and motion perception under terrestrial and microgravity conditions—a conceptual model. **Brain Research Reviews,** 28 (1): 118-135.

Monsell, E.M., Furman, J.M., Herdman, S.J., et al. (1997) Computerized dynamic platform posturography. **Otolaryngology--head and neck surgery : official journal of American Academy of Otolaryngology-Head and Neck Surgery,** 117 (4): 394-398.

Mucha, A. (2012) **Augmenting neurocognitive assessment in the evaluation of sports concussion: how vestibular and ocular issues impact recovery.** 9 (1):12-16 edn, .

Muir, B., Lynn, A., Maguire, M., et al. (2014) A pilot study of postural stability testing using controls: the modified BESS protocol integrated with an H-pattern visual screen and fixed gaze coupled with cervical range of motion. **The Journal of the Canadian Chiropractic Association,** 58 (4): 361-368.

Mulligan, I.J., Boland, M.A. and McIlhenny, C.V. (2013) The Balance Error Scoring System Learned Response Among Young Adults. **Sports Health: A Multidisciplinary Approach,** 5 (1): 22-26.

Murray, N.G., Ambati, V.P., Contreras, M.M., et al. (2014) Assessment of oculomotor control and balance post-concussion: a preliminary study for a novel approach to concussion management. **Brain injury,** 28 (4): 496-503.

Nashner, L.M. (1982) Adaptation of human movement to altered environments. **Trends in neurosciences,** 5 358-361.

Nashner, L.M. (1977) Fixed patterns of rapid postural responses among leg muscles during stance. **Experimental Brain Research,** 30 (1): 13-24.

National Federation of State High School Associations (1980) **National Federation of State High School Associations Handbook.** National Federation of State High School Associations.

Nichols, S. and Patel, H. (2002) Health and safety implications of virtual reality: a review of empirical evidence. **Applied Ergonomics,** 33 (3): 251-271.

Nolin, P., Stipanicic, A., Henry, M., et al. (2012) Virtual reality as a screening tool for sports concussion in adolescents. **Brain injury,** 26 (13-14): 1564-1573.

Omalu, B.I., DeKosky, S.T., Minster, R.L., et al. (2005) Chronic traumatic encephalopathy in a National Football League player. **Neurosurgery,** 57 (1): 128-134.

Paloski, W.H., Wood, S.J., Feiveson, A.H., et al. (2006) Destabilization of human balance control by static and dynamic head tilts. **Gait & posture,** 23 (3): 315-323.

Parsons, T.D., Courtney, C.G., Arizmendi, B.J. and Dawson, M.E. (2011) "Virtual Reality Stroop Task for neurocognitive assessment.", **MMVR** pp. 433.

Paulson, O.B. and Newman, E.A. (1987) Does the release of potassium from astrocyte endfeet regulate cerebral blood flow? **Science (New York, N.Y.),** 237 (4817): 896-898.

Pavan, P., Cardaioli, M., Ferri, I., et al. (2015) A contribution to the validation of the Wii Balance Board for the assessment of standing balance. **European journal of sport science,** 15 (7): 600-605.

Peerless, S.J. and Rewcastle, N.B. (1967) Shear injuries of the brain. **Canadian Medical Association journal,** 96 (10): 577-582.

Peterson, C.L., Ferrara, M.S., Mrazik, M., et al. (2003) Evaluation of neuropsychological domain scores and postural stability following cerebral concussion in sports. **Clinical Journal of Sport Medicine,** 13 (4): 230-237.

Prentice, W.E. and Kaminski, T.W. (2004) **Rehabilitation techniques for sports medicine and athletic training.** McGraw-hill New York:.

Prins, M.L., Lee, S.M., Cheng, C.L.Y., et al. (1996) Fluid percussion brain injury in the developing and adult rat: a comparative study of mortality, morphology, intracranial pressure and mean arterial blood pressure. **Developmental Brain Research,** 95 (2): 272-282.

Resch, J.E., May, B., Tomporowski, P.D., et al. (2011) Balance performance with a cognitive task: a continuation of the dual- task testing paradigm. **Journal of athletic training,** 46 (2): 170.

Riemann, B.L. and Guskiewicz, K.M. (2000) Effects of mild head injury on postural stability as measured through clinical balance testing. **Journal of athletic training,** 35 (1): 19-25.

Rugby World Cup (12th September 2015) **Hawk-Eye to clarify close calls and aid player welfare.** [Online]. Available from: http://www.rugbyworldcup.com/news/90525 [Accessed June 5th 2016].

Shaw, N.A. (2002) The neurophysiology of concussion. **Progress in neurobiology,** 67 (4): 281-344.

Signoretti, S., Lazzarino, G., Tavazzi, B., et al. (2011) The Pathophysiology of Concussion. **PM&R,** 3 (10): S359-S368.

Slobounov, S., Sebastianelli, W. and Newell, K.M. (2011) "Incorporating virtual reality graphics with brain imaging for assessment of sport-related concussions", **Engineering in**

Medicine and Biology Society, EMBC, 2011 Annual International Conference of the IEEEIEEE pp. 1383.

Slobounov, S., Slobounov, E. and Newell, K. (2006) Application of virtual reality graphics in assessment of concussion. **Cyberpsychology & Behavior,** 9 (2): 188-191.

Smart, L.J.,Jr, Stoffregen, T.A. and Bardy, B.G. (2002) Visually induced motion sickness predicted by postural instability. **Human factors,** 44 (3): 451-465.

Starling, A.J., Leong, D.F., Bogle, J.M., et al. (2015) Variability of the modified Balance Error Scoring System at baseline using objective and subjective balance measures.

Stroop, J.R. (1935) Studies of interference in serial verbal reactions. **Journal of experimental psychology,** 18 (6): 643.

Talavage, T.M., Nauman, E.A., Breedlove, E.L., et al. (2014) Functionally-detected cognitive impairment in high school football players without clinically-diagnosed concussion. **Journal of neurotrauma,** 31 (4): 327-338.

Teel, E.F., Register-Mihalik, J.K., Blackburn, J.T., et al. (2013) Balance and cognitive performance during a dual-task: preliminary implications for use in concussion assessment. **Journal of Science and Medicine in Sport,** 16 (3): 190-194.

Teel, E.F. and Slobounov, S.M. (2015) Validation of a virtual reality balance module for use in clinical concussion assessment and management. **Clinical journal of sport medicine : official journal of the Canadian Academy of Sport Medicine,** 25 (2): 144-148.

Thurman, D.J., Alverson, C., Dunn, K.A., et al. (1999) Traumatic brain injury in the United States: A public health perspective. **The Journal of head trauma rehabilitation,** 14 (6): 602-615.

Valovich, T.C., Perrin, D.H. and Gansneder, B.M. (2003) Repeat administration elicits a practice effect with the Balance Error Scoring System but not with the Standardized Assessment of Concussion in high school athletes. **Journal of athletic training,** 38 (1): 51.

Warren, R. (1976) The perception of egomotion. **Journal of Experimental Psychology: Human Perception and Performance,** 2 (3): 448.

Willer, B. and Leddy, J.J. (2006) Management of concussion and post-concussion syndrome. **Current Treatment Options in Neurology,** 8 (5): 415-426.

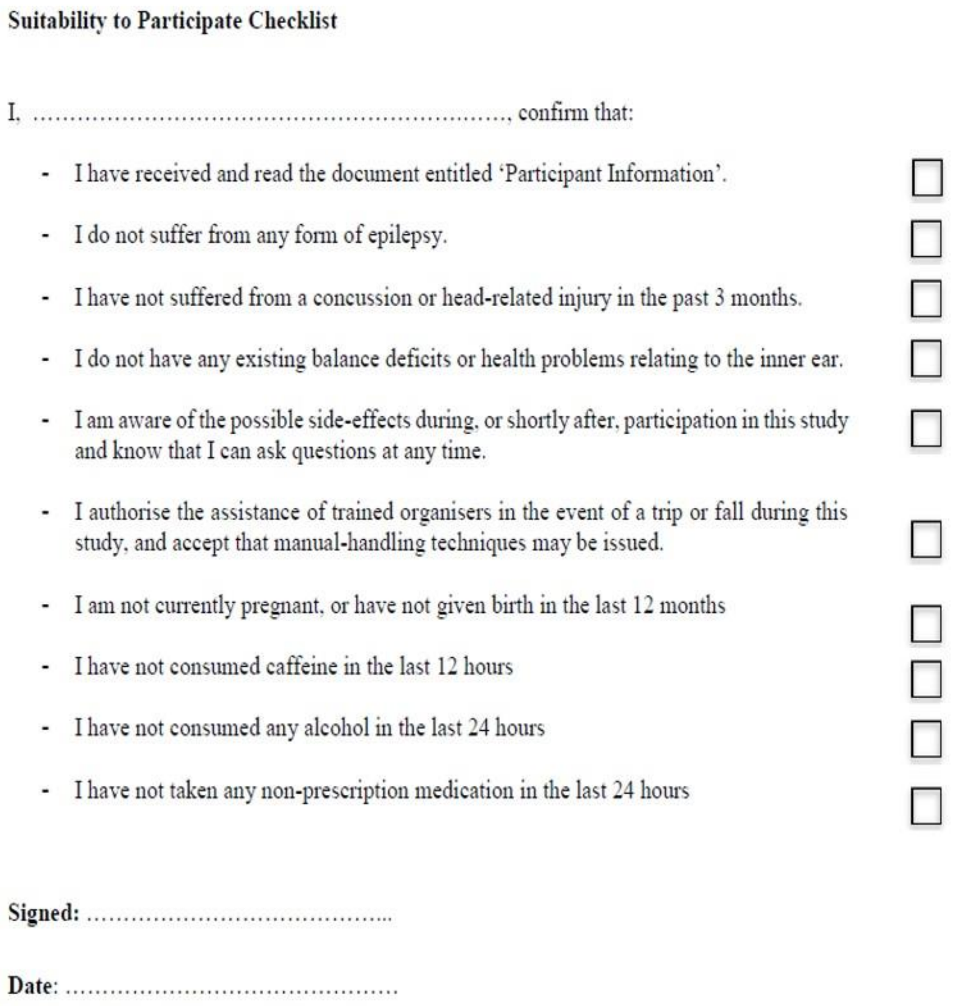
Winter, D.A. (1995) Human balance and posture control during standing and walking. **Gait & posture,** 3 (4): 193-214.

World Rugby (15th May, 2015) **Head injury assessment adopted into law.** [Online]. Available from: http://www.worldrugby.org/news/70796 [Accessed May 29th 2016].

Wright, W.G., McDevitt, J. and Appiah-Kubi, K.O. (2015) "A portable virtual reality balance device to assess mild traumatic brain injury symptoms: A pilot validation study", **Virtual Rehabilitation Proceedings (ICVR), 2015 International Conference on**IEEE pp. 72.

APPENDICES

Appendix A – Participant screening tool



Suitability to Participate Checklist

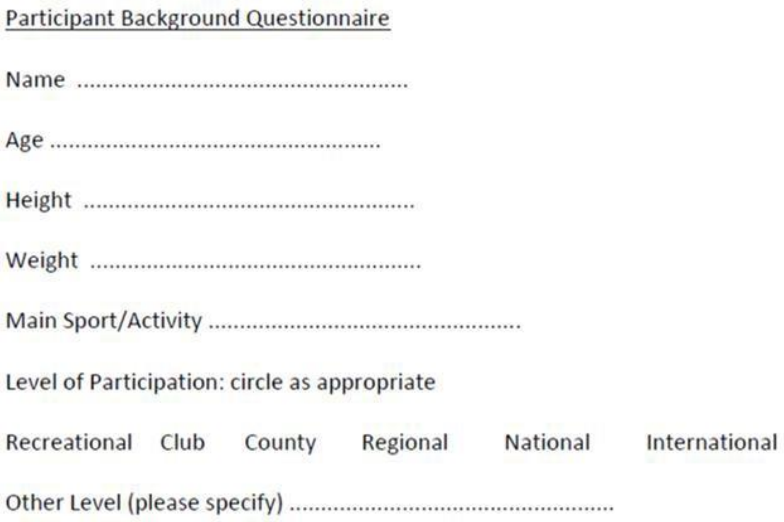
I, ……………………………………………………………, confirm that:

- 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 have not consumed caffeine in the last 12 hours ☐
- I have not consumed any alcohol in the last 24 hours ☐
- I have not taken any non-prescription medication in the last 24 hours ☐

Signed: …………………………………..

Date: ………………………………………

Appendix B – Participant questionnaire, informed consent, participant information sheet



Participant Background Questionnaire

Name …………………………………………

Age …………………………………………

Height …………………………………………

Weight …………………………………………

Main Sport/Activity …………………………………………

Level of Participation: circle as appropriate

Recreational Club County Regional National International

Other Level (please specify) …………………………………………

UNIVERSITY OF
BIRMINGHAM

Neuroplasticity and Neurorehabilitation Laboratory
School of Sport, Exercise and Rehabilitation Sciences

INFORMED CONSENT

Participant Identification for this study:

Virtual Reality based concussion management

Name of Researcher:

Please initial

I confirm that I have read and understood the information sheet detailing the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reasons. ☐

I understand that where it is relevant to my research participation, data acquired may be analysed by responsible individuals from the University of Birmingham, or from regulatory authorities. I give permission for these individuals to have access to my data records. ☐

I agree to have transcranial magnetic stimulation (TMS) in different study sessions as outlined in the participant information sheets. ☐

I agree to attend one session at the Neuroplasticity and Neurorehabilitation Laboratory at the University of Birmingham's School of Sport, Exercise and Rehabilitation Sciences. ☐

I understand that All information collected about me during the course of the study is kept strictly confidential. ☐

I agree to take part in the above study. ☐

Name of Participant ____________ Date ________ Signature ________

Researcher Name ____________ Date ________ Signature ________

(File: 1 for participant, 1 for researcher)

All information collected will be stored in accordance with the Data Protection Act 1998
Consent Form Version 2 (single session)
29 October 2013

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. Therefore, we aim to apply our results to aid in the development of future pitch side concussion diagnosis.

If you agree to participate in this study, you will be required to complete a short balance test in a laboratory environment. The entire visit should last no longer than 1 hour. You will be required to complete a short background questionnaire, which you should bring with you to the lab. On arrival you will be introduced to the equipment and procedure 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, details of which are enclosed.

Firstly, we will measure your height and weight. The tasks will take place barefoot, and you will be required to stand on a balance platform throughout the tasks. In addition, during the virtual reality protocol, you will be required to wear a set of goggles to watch an animation on the built-in display.

Your participation in this study is entirely voluntary, and as such, you are entitled to withdraw from participation at any point before, during or after the testing protocols. 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. Any information obtained from the visit may be held in secure conditions for up to 5 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.

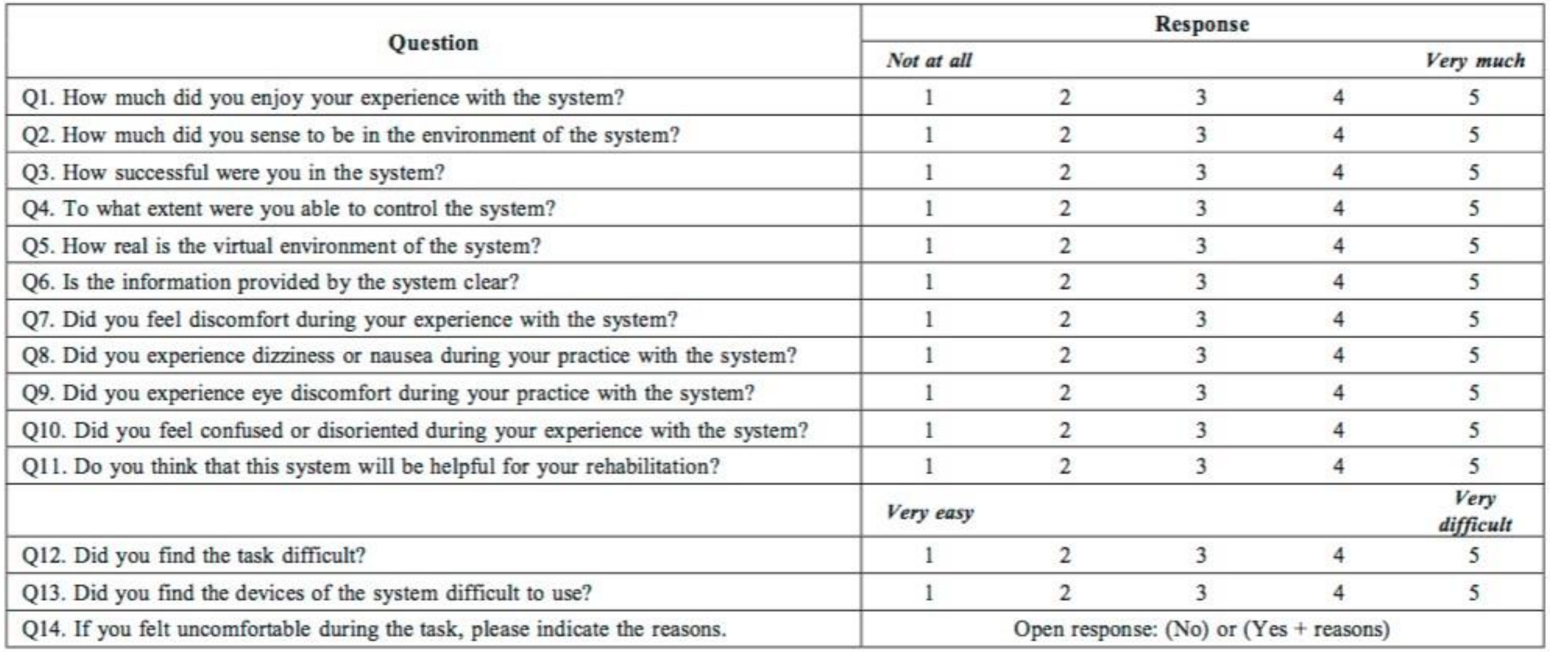
Although participation is voluntary, we are happy to compensate any student requiring 'subject pool' hours with 1.5 research hours. This will be awarded upon completion of the visit, or in the case of an incomplete visit, research hours will be awarded on a pro-rata basis according to the duration of the visit.

Further information is available on request, so please do not hesitate to contact us if you have any questions or concerns.

Appendix C – Immersion questionnaire

Adapted from Gil-G**ó**mez et al., (2013

TABLE I. SUITABILITY EVALUATION QUESTIONNAIRE (SEQ)



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 of the system?	1	2	3	4	5
Q3. How successful were you in the system?	1	2	3	4	5
Q4. To what extent were you able to control the system?	1	2	3	4	5
Q5. How real is the virtual environment of the system?	1	2	3	4	5
Q6. Is the information provided by the system clear?	1	2	3	4	5
Q7. Did you feel discomfort during your experience with the system?	1	2	3	4	5
Q8. Did you experience dizziness or nausea during your practice with the system?	1	2	3	4	5
Q9. Did you experience eye discomfort during your practice with the system?	1	2	3	4	5
Q10. Did you feel confused or disoriented during your experience with the system?	1	2	3	4	5
Q11. Do you think that this system will be helpful for your rehabilitation?	1	2	3	4	5
	Very easy				*Very difficult*
Q12. Did you find the task difficult?	1	2	3	4	5
Q13. Did you find the devices of the system difficult to use?	1	2	3	4	5
Q14. If you felt uncomfortable during the task, please indicate the reasons.	Open response: (No) or (Yes + reasons)				