THE DEVELOPMENT OF A NOVEL PITCH-SIDE CONCUSSION BALANCE ASSESSMENT: A COMPARISON BETWEEN A VIRTUAL REALITY BASED BALANCE TOOL AND THE MODIFIED BALANCE ERROR SCORING SYSTEM

by

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ABSTRACT

Background: Balance deficits are a key measurable marker of concussion injuries. An objective pitch-side concussion balance assessment needs to replace current subjective, insensitive, unportable tests. A novel pitch-side dual-task VR test has been developed to evoke perturbations, and measure COP path length changes, via a WBB.

Aims: To establish whether a VR WBB system is effectively able to assess postural stability, by evoking perturbations, and to measure subsequent changes in COP path length. To establish whether mBESS error scores, or objective mBESS COP path lengths correlate with changes in COP path length post-perturbation.

Methods: 14 female University of Birmingham hockey players aged 18-21 performed both the mBESS and the VR WBB assessment at the pitch-side.

Results: The mean COP path length post-perturbation was significantly greater than pre-perturbation, as the tilt induced a compensatory sway response. SL error scores significantly correlated with SL COP path length, and COP path length percentage change from pre to post-perturbation.

Conclusion: The dual-task VR WBB system effectively assesses postural stability by measuring subsequent changes in COP path length. The objective nature and plethora of information provided by the VR WBB system, heightens its appeal over the mBESS, as an assessment of postural stability.

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ABBREVIATIONS

TBI – Traumatic Brain Injury

LOC – Loss of Consciousness

RTP - Return to Play

SIS - Second Impact Syndrome

CTE – Chronic Traumatic Encephalopathy

PCS – Post-Concussive Syndrome

HIA – Head Injury Assessment

SCAT – Sport Concussion Assessment Tool

mBESS – Modified Balance Error Scoring System

ImPACT – Immediate Post-Concussion Assessment Tool

BESS – Balance Error Scoring System

CNS – Central Nervous System

SOT – Sensory Organisation Test

COP – Centre of Pressure

WBB – Wii Balance Board

VR - Virtual Reality

EEG – Electroencephalogram

DL – Double leg

SL – Single leg

TL – Tandem leg

ICC – Intra-class correlation

CHAPTER 1. INTRODUCTION

1.1 Background

The term concussion stems from the Latin verb concutere, meaning to shake violently (Maroon et al., 2000). Prior to the 1980's mild traumatic brain injuries such as concussion were seen as no more than an inconvenience to many physicians and to the health care community alike (Barth et al., 2001). However, in more recent years' concussion, particularly in a sporting context has been highlighted as the most common and puzzling type of traumatic brain injury (TBI) (Shaw et al., 2002). This is somewhat due to the vast ambiguity seen within the healthcare community in the defining of concussion. The most recent and widely recognised definition, as described in the Berlin consensus of 2016, defines a concussion as a TBI that is induced by biomechanical forces (McCrory et al., 2017). However, it is vital to consider that no two concussions are alike in terms of their initial symptomatology (McCrea et al., 2003). Subsequently, a concussion results in a range of clinical signs and symptoms ranging from the neurological, to the physical, and emotional, and that may or may not involve loss of consciousness (LOC) of the individual. Therefore, the assessment and management of concussion injuries should be carefully considered on an individualised basis. In addition to this no one single test is able to fully diagnose and assess concussive injuries, therefore, it is essential that a multi-faceted approach is implemented. Importantly, balance deficits seen post-concussion are one of the only symptoms that can be objectively measured and can be done so at both baseline and post-injury. Despite this, current tests are unable to provide valid objective measures of balance instability post-concussion. This thesis will aim to develop and test the effectiveness of a novel Virtual Reality (VR) balance tool in a pitch-side environment on healthy individuals. Furthermore, the VR system will be tested against the currently accepted standard balance assessment tool known as the modified Balance Error Scoring System (mBESS).

1.2 Concussion – The Problem

The notion of head injuries has been debated as early as Hippocrates, who noted that intelligence and sensation stems from the brain, which in turn is associated with speech, sight and hearing. Observations by the Arabic physician Rhazes further identified that blows to the head resulted in an abnormal physiological state (Seymour, 2013). Following centuries of observational work within the field it was not until 1989 that the first large scale study on concussion was published by Barth and colleagues. Barth et al. (1989) reported that the neurocognitive performance of college footballers was significantly poorer following a sustained concussion in comparison to their baseline scores. The floodgates then opened for the advancement of concussion research, truly marking the genesis of the field of Sports Neuropsychology (Barth and Broshek, 2015).

More recently, concussions in sport have become a much greater part of the public health dialogue, as increasingly more cases are published in the press and opinions widely debated on social media (Barth and Broshek, 2015). As Goff (2015) explains, the use of misleading terms in the media such as mild, minor or slight concussion are commonplace. The use of misleading vocabulary in the literature and the media may both underplay the significance of a concussive event or create hysteria over the dangers of sustained injuries. Much of the previous literature has also heavily focused on severe TBI's, which problematically may lead individuals to believe that mild TBI's such as concussions are indicative of a less serious event with insignificant post-injury symptoms. Regardless of the wording used in the categorising of TBI's, a concussion is still an insult to the brain and should be treated with great consideration and urgency in care. It is important to note that not all concussion injuries are the same displaying varying levels of severity.

Many papers fail to adhere to one unified interpretation of the definition of concussion and everything that it encompasses. This makes the work of physicians and healthcare professionals very difficult, in turn exacerbating the concussion problem further. The definition of concussion has evolved greatly over time, as much of the earlier literature such as the Cantu Grading scales in the early 2000's typically relied on LOC as a key grading element of concussion (Echemendia et al., 2015). LOC represents a state of brief coma in which an individual's eyes are typically closed and they are unresponsive to external stimuli. However, this is rare and only occurs in less than 10% of concussions (Lovell, 2004). Although, Castile et al. (2012) highlighted that recurrent concussions demonstrate a greater likelihood of LOC than individuals who have only sustained a single concussion. It is important for one not to assume that just because an individual did not lose consciousness that they are not in fact concussed. This has been identified as one of the biggest mistakes commonly seen in concussion diagnosis, in that LOC is imperative for diagnosis and is not indicative of the severity of concussion (Kissick and Johnston, 2005). This may lead to the under-reporting of concussive events by individuals who believe they are not concussed, as culturally they are led to believe LOC is an imperative marker of concussion.

Progress is still lacking in the acceptance of an operational definition of concussion that can be effectively utilised to evaluate injuries during game situations (Helmy et al., 2013). However, a nongovernmental and non-advocacy panel known as the Concussion in Sport Group meet every few years with key sporting bodies such as FIFA and the Olympic Association, in order to discuss and give objective and balanced views to the topic of concussion. This panel forms the most widely used and recognised definition of concussion, as described in the Berlin Consensus of 2016. Whereby, a concussion is defined as a complex pathophysiological process affecting the brain, induced by biomechanical forces, and resulting in a graded set of clinical symptoms that may or may not involve LOC (McCrory et al., 2017). The work of bodies such as the Concussion in Sport Group are going someway into aiding clinicians and healthcare professionals in sporting environments to unify the defining of concussion, which will ultimately aid clinical diagnosis.

Head injuries are a public health concern both financially and socially due to high incidence levels and the accompanying morbidity and mortality rates (Nance, 2011). Figures published by the Centre for Mental Health estimate that the cost of TBI's in the UK alone has reached £15 billion annually, with premature death, loss of work contributions and the rising costs of health and social care just some of factors contributing to this yearly cost (Parsonage, 2016). However, these figures do not consider the human costs on quality of life and wellbeing which is ultimately the biggest cost (Parsonage, 2016). There is little evidence within the literature on the specific cost of concussion injuries alone in comparison to TBI's as a whole. Nonetheless, concussive injuries are becoming a much greater part of our public health rhetoric. Further barriers to optimal patient care both clinically and in a sporting context include lack of awareness on the part of the patient, parent, coach and clinicians, lack of appreciation of clinical significance and a lack of human resources (Nance, 2011). Many of these wider problems associated with concussion may be partly attributed to the lack of education and objective assessment and diagnostic tools at both a sporting and healthcare level.

In terms of incidence, young children have the greatest rates of concussion, with bicycle accidents and sporting activities accounting for the majority of injuries between the ages of 5-14 (Ropper and Gorson, 2007). Increasing numbers of adolescents are participating in contact sports every day, with reports in the US stating 7.5 million engaged in contact sports at school from 2011-2012 (National Federation of State High School Associations). The rise in participation figures may go some way into explaining the vast numbers of concussions seen in younger individuals. Across all age groups, Headway, The Brain Injury Association, have reported statistics stating the total head injury admissions for 2013 was 162 554, equating to roughly 445 head injury admissions per day to UK hospitals (Headway, 2014). Furthermore, there has been a 10% increase from 2005 to 2013 in hospital admissions for those with an acquired brain injury (Headway, 2014). Outside of sport, falls and vehicular accidents are the most common causes of head trauma in adults (Ropper and Gorson, 2007). The coupling of increasing contact sport participation levels and incidence levels are just two factors that contribute to the concussion problem.

The reported incidence of concussion in a sporting context has also increased, particularly in elite rugby union, whereby the reported incidence of concussion has increased from ~4 to ~13 injuries per 1000 player-match-hours over the last 10 years (Fuller et al., 2015). This increase in incidence may either be due to actual increases in the incidence of concussion, or the greater reporting of injuries, which may stem from better education-driven awareness and knowledge. Regardless of the increased incidence figures there still remains a large problem in the world of both amateur and elite sport regarding the reporting of concussion and its symptomatology. In the UK alone it has been estimated that 50% of sport concussions are not reported to medical personnel, with the general notion among professionals, that the rate of concussion in contact sports is greater than the incidence of the injuries that are recorded (McCrea et al., 2004).

Fraas et al. (2014) studied 4 professional rugby union clubs over one season and asked players to recall any incidence of concussion they had experienced. 45% of the 172 players involved reported at least one concussion, of which, only 46.6% were reported to medical personnel. One of the two main reasons players did not report their concussion was that they did not believe their injury was serious enough to warrant medical attention, a reason similarly reported by McCrea et al. (2004). Furthermore, players also stated a further reason for not reporting their concussion was not wanting to be removed from the game. Subjective symptom recall is highly problematic in the diagnosis of concussion, with individuals failing to remember the seriousness of the events, and under-reporting their symptoms in order to accelerate their return to play (RTP). Athletes should be considered a unique population group with its own risk factors and culture (Sahler and Greenwald, 2012). Different pressures surround athletes when reporting and rehabilitating from a concussive injury, such as pressure from the coach, management, or peers to accelerate their RTP. Henceforth, it is essential that objective tests are undertaken both at the pitch-side and in clinical settings in order to completely remove this element of guesswork and subjective nature on the reporting of symptomatology.

The pressure of a cup final or important game in the season may further exacerbate the issue of symptom under-reporting. Additionally, medical staff within a sporting environment are commonly under great amounts of pressure from the team or coach to get the athlete back on the pitch as soon as possible. The main issue surrounding early RTP within the same game, or even a return to training in the following week post-concussion, exposes the athletes to the chance of sustaining a second concussive insult while still experiencing symptoms from their initial head injury. Many players may fail to appreciate the severity in the downplaying of their symptoms, and it is important to consider the problems that may arise if RTP is accelerated and premature, or initial concussive impacts are not properly diagnosed and treated.

Second Impact Syndrome (SIS), a term first coined by Saunders and Harbaugh (1984), occurs “when an athlete who sustains a head injury – often a concussion or worse injury, such as cerebral contusion – sustains a second head injury before symptoms associated with the first have cleared” (Cantu, 1998), and may not only occur in individuals who are symptomatic. This in turn can lead to diffuse cerebral swelling, brain herniation, and death (Cantu, 1998). This very rare but devastating condition can occur in young and healthy individuals, such as 14-year old Benjamin Robinson (Bull, 2013). He experienced 3 concussive insults during a single game of rugby, in which the last insult resulted in him collapsing unconscious and he later died. The autopsy later revealed he had suffered from SIS, whereby the multiple insults to the brain had caused vulnerable concussed cells to become irreversibly damaged by swelling (Cantu, 1998). The syndrome is considered to be more serious in children. This often fatal syndrome, albeit rare, highlights the damage multiple concussions can cause in the short term such as in a game or training session, if the initial insult is not assessed and the player not removed from play. The initial assessment of concussion injuries is vital in ensuring symptoms are not downplayed and players are immediately removed from game situations. The development of an objective test is vital to aid medical staff in making a well informed decision, which will ultimately prevent the sustaining of further injuries. In this instance, it is of primary importance that players are removed from the game, as without this, an objective test is merely rendered obsolete.

The first documented case of long-term neurodegenerative changes in a retired NFL player were seen in Mike Webster, in which his symptoms were consistent with Chronic Traumatic

Encephalopathy (CTE) (Omalu et al., 2005). CTE is evident with multiple diffuse amyloid plaques and neurofibrillary tangle or neuropil threads in the hippocampus or entorhinal cortex (Omalu et al., 2005). A CTE diagnosis can only be diagnosed post-mortem and relies on the progressive evolvement of neuropsychiatric symptoms which can be attributed to a repeat TBI, and not any other pathological process (Costanza et al., 2011). Specifically, post-concussive syndrome (PCS) denotes a group of symptoms such as headaches, dizziness and problems with attention which persist for more than 3 months post-injury (Erlanger, 2015). The removal of players from the field and the subsequent assessment of initial insults to the brain are essential. The development of an objective testing procedure is vital to aid medical staff in making a well-informed clinical decision, which will ultimately prevent the sustaining of further injuries.

Over the last few decades concussion has developed into both a global sporting and healthcare problem. To combat the range of problems plaguing the assessment of concussion and subsequent rehabilitation from the injury, the diagnostic process must include suitable multi-faceted, multi-time point assessments that are both appropriate for pitch-side and clinical environments for both amateur and elite athletes. The development of an objective concussion assessment tool is essential in the accurate diagnoses of a concussion and must consider the often puzzling pathophysiological processes that underpin the injury. To consider a concussion as a mild TBI essentially undermines the severity of the cascade of molecular changes which affect performance and increased vulnerability for repeat injury (Barkhoudarian et al., 2011).

1.3 Mechanisms and pathophysiology of concussion

1.3.1 Mechanisms

An experiment performed by the military surgeon Gama in 1830 was the first to shed light on the mechanism of concussion injuries, using a flask which held a gelatinous substance resembling the consistency of the brain. By hitting the walls of the flask this caused the movement of thin wires within the gelatinous material, resembling the spread of forces within the brain (Feinsod, 2002). It is precisely these biomechanical forces that inflict a concussion injury to the brain, which is deemed a highly complex pathophysiological process. Sport concussions are typically obtained via a direct or indirect blow to the head, face, neck or body (Aubry et al., 2002), due to a fall to the ground, collisions with other players or being hit by an inanimate object (Seifert and Shipman, 2015).

Diffuse injuries are characterised by accelerative or decelerative forces which tear and stretch tissues, in turn causing brain injury. These rotational forces on the midbrain and thalamus transiently disrupt the reticular activating system resulting in LOC sometimes seen in concussive events (Ropper and Gorson, 2007). This exposes the brain to rapid acceleration, deceleration and rotational forces when one experiences a concussion. This then instigates the stretching and distortion of axons, glial cells, dendrites, blood vessels, and neuronal cell bodies (Seifert and Shipman, 2015).

1.3.2 Pathophysiology

Following a mechanical insult to the brain, the acceleration and deceleration forces cause a complex cascade of metabolic events to ensue known as a neurometabolic cascade. This includes neuronal depolarisation, release of excitatory neurotransmitters, ionic shifts, changes in glucose metabolism, altered cerebral flow, and impaired axonal function (Giza and Hovda, 2014). These changes in metabolic functioning seen post-concussion can be correlated with vulnerability periods and neurobehavioural abnormalities, which may last for days in animals and weeks in humans (Giza and Hovda, 2014). The neurometabolic cascade can largely be separated in to two key event pathways; the axonal events, and the cellular events.

1.3.2.1 Time course of effects

The first key pathway of the neurometabolic cascade of concussion involves axonal injury, which is induced by the acceleration and deceleration forces on impact. Impaired axonal functioning involves initial axolemmal disruption and calcium influx, followed by neurofilament compaction via phosphorylation or sidearm cleavage (Barkhoudarian et al., 2011). This is followed further by microtubule disassembly, accumulation of axonally transported organelles, leading to axonal swelling and eventual axotomy (Barkhoudarian et al., 2011). Axonal degeneration caused by a TBI may induce long-term neurodegenerative processes such as Alzheimer's disease (Johnson et al., 2013). The stretching of the neuronal and axonal membranes post-concussion induces a variety of cellular events.
Barkhoudarian et al. (2011) describes how the initial mechanical forces of a concussive insult to the brain results in cellular changes. Specifically, the deformation of the neuronal membrane which in turn results in a spike of neural activity. Consequently, excessive amounts of potassium are released into the extracellular spaces. The same membrane impairment also results in the indiscriminate release of neurotransmitters specifically known as excitatory amino acids. Glutamate is a specific excitatory amino acid that subsequently binds to NMDA and AMPA receptors. The activation of NMDA receptors causes additional depolarisation and a subsequent influx of calcium ions, coupled with an efflux of potassium (Barkhoudarian et al., 2011). The resulting depolarisation results in neurone suppression, resembling extensive spreading depression of neurones (Giza and Hovda, 2001).

Importantly, without a concussion the brain is able to maintain potassium levels through the action of glial cells, whereby excessive extracellular potassium is taken up by surrounding glial cells. In turn this prevents the potential mass efflux of potassium into the extracellular space (Paulson and Newman, 1987). Therefore, the concentration of potassium in the intra-cellular potassium is typically high. However, when one experiences a concussion the glial cells and arteriole regulation is complicated by ischaemia (Paulson and Newman, 1987). The sharp increase in potassium causes neuronal depolarisation, which acts as a to initiate further glutamate release, and in turn, the release of more potassium (Giza and Hovda, 2001). In order to combat the depression and restore homeostasis ATP-dependent Na+/K+ pumps are activated, which need high levels of glucose metabolism. Similarly, in the absence of a concussion the Na+/K+ pumps work under aerobic conditions. However, post-injury the intracellular energy stores are diminished and neurones are forced to undergo inefficient glycolysis (Seifert and Shipman, 2015). Experimental studies in rats has shown that this large increase in glucose metabolism occurs instantly and may last anywhere between 30 minutes to 4 hours (Yoshino et al., 1991). The activation of NMDA channels by glutamate after a concussion also results in a significant calcium influx which accumulates in the mitochondria. This in turn causes concomitant glucose oxidative dysfunction (Verweij et al., 1997). Barkhoudarian et al. (2011) also highlights how oxidative metabolism is further disrupted due to mitochondrial dysfunction and an increase in lactate production leading to acidosis, cerebral oedema and an increase in membrane permeability. An energy crisis then ensues due to increased amounts of calcium in the mitochondria, which can lead to longer-term issues. In a fluid percussion injury study in rats, McKee and Robinson (2014) highlighted that hyper-metabolism occurs alongside a decrease in cerebral blood flow creating a discrepancy between glucose supply and demand, underpinning the energy crisis. In turn, more of the concussed cells then enter a state of vulnerability.

1.3.2.2 Second Impact Syndrome

If the brain experiences a second concussive event the already vulnerable cells may become irreversibly damaged by swelling (Signoretti et al., 2011). This concept of concussion-induced brain vulnerability is the underlying pathophysiology of the phenomenon known as SIS (Signoretti et al., 2011). This highlights the importance of immediate removal from game situations and suitable recovery times prior to RTP, in order to prevent further brain cell vulnerability.

The pathophysiological process of a concussive event in a child differs from that of an adult, as children are actively developing organisms that respond different physically during and post-concussion (Kirkwood et al., 2006). Initially, the physical concussive impact dynamics involve the rotational acceleration or deceleration forces. In turn, these cause great stress on the neural and vascular components of the brain, which are similar in both children and adults (Barth et al., 2001; McCrory et al., 2013). However, it is the compositional and mechanical properties of a child's brain that differ profoundly, such as brain water content, cerebral blood volume, level of myelination, skull geometry, and suture elasticity (Kirkwood et al., 2006). McCrory et al. (2013) highlights that children's brains may require greater force to become symptomatic post-injury, although their brains are likely to respond poorer to insult to the brain. Children have a reduced resilience of the shoulder and neck muscles, more impact is transmitted to the brain, as it cannot dissipate mechanical energy as well as the adult brain (McCrory et al., 2013). Children are particularly susceptible to the cumulative effects of multiple insults to the brain, the differences in the pathophysiology of a child's brain compared to that of an adult may go some way to explaining this.

Prins et al. (1996) used a fluid percussion technique to mimic a TBI in both adult and young rats. The physical responses to TBI in young developing rats were more pronounced, with a higher mean arterial blood pressure and higher mortality rates. Furthermore, an experimental closed head injury study performed on juvenile rats with low mortality taxes and absence of gross pathology, has been shown to produce measurable cognitive deficits (Prins et al., 2010). The removal of all athletes from sporting environments whereby they have sustained a potential or diagnosed concussion is vital to ensure no further potential injury is acquired. However, it is important not to consider children and adults in the same bracket concerning both the mechanisms and pathophysiology of concussion. The RTP, learning and daily activities is a vital component of concussion management. Importantly, changes to game rules at a youth level also need to be considered to take the differing pathophysiology of a child's brain in to account. Often in youth and amateur level games there is often a lack of available and sufficient medical staff, the adoption the approach of 'if in doubt sit them out' is one that should be recognised and utilised universally (The Football Association, 2015). It is also essential to develop an objective concussion assessment that is both appropriate and engaging for both children and adults to complete.

1.3.2.3 Pathophysiological effect of concussion on balance

The specific pathophysiology that underlies balance and visual deficits post-concussion is poorly understood. The areas of the brain that are affected by a concussion or TBI have been reported to be those responsible for the maintenance of postural equilibrium (Riemann et al., 1999). In order for an individual to maintain their standing balance, the central nervous system (CNS) must integrate visual, vestibular and somatosensory information. An investigation by Guskiewicz et al. (2001) proposed one theory, in that athletes recovering from concussion had postural stability deficits that were most likely linked to a sensory interaction breakdown immediately after the injury. Consequently, there is incoherence between afferent information received from the sensory modalities, and the processing of this information through the CNS is disrupted. Therefore, individuals are unable to re-weight the afferent sensory information, resulting in balance instability (Guskiewicz et al., 2001). Damage to internal receptors or processing structures, will ultimately prevent the integration of information from the different modalities, and renders the body ineffective in producing an appropriate muscle response.

Alternatively, the literature has also proposed that the vestibular system is the most vulnerable to damage following a concussive impact. The purpose of the vestibular system is to maintain the eyes fixed on a stationary target during head and body movements, and to maintain postural stability alongside visual and somatosensory information (Guskiewicz & Broglio, 2011). Two key sensors are housed within the vestibular system; the otolith organs are responsible for the detection of horizontal and vertical movement, whereas the semi-circular canals detect rotational movement.

The weakening of vestibular function post-concussion is proposed to be underpinned by two mechanisms. Firstly, damage to the peripheral receptors may provide the brain with an inaccurate sense of acceleration, hence reducing its ability to orient itself within space (Mucha et al., 2012). Secondly, central damage could occur inhibiting the sensory integration of information within the CNS (Guskiewicz and Broglio, 2011). The failure to integrate and weight afferent information from key systems will prevent the ability of the CNS to maintain postural stability.

Researchers have proposed varying theories that they believe underpin the pathophysiology of postural instability following a concussion. It is inconclusive as to whether this is due to a communication breakdown between the sensory modalities, or more specifically damage to sensors within the vestibular system. However, the manifestation of balance deficits post-concussion is undeniably due to damage inflicted on the sensory systems. When visual or somatosensory information is disrupted, post-concussive individuals often show impairments in the perception and processing of vestibular system information, often demonstrating a visual preference for the maintenance of standing balance (Zylka et al., 2013; Starling et al., 2015). Many balance assessments are based around this concept by reducing the influence of either the visual, vestibular or somatosensory information.

1.4 Signs and symptoms

The signs and symptoms experienced following a concussion are key components in the defining of concussive injuries. Concussion results in neuropathological changes, but the acute signs and symptoms of injuries largely reflect functional pathophysiological disturbances rather than structural injuries (McCrory et al., 2017). Concussion also results in a range of clinical symptoms which may or may not involve LOC. Acute concussive symptoms, in the minutes to hours' post-concussion, include headaches, lack of concentration, attention deficits, irritability and sleep disturbances. These early symptoms are representative of a global energy crisis (Ellis et al., 2015).

It is also important to consider the notion that even if individuals are asymptomatic during rest, post-concussive symptoms may surface during exertion (Johnston et al., 2004). Henceforth, graded RTP protocols are essential in progressively bringing athletes back to low intensity exercise through to full match situations. Concussion diagnosis is often based on subjective reports of player's symptoms. Many players either do not report or under-report their symptoms in order to accelerate their RTP (Frommer et al., 2011). During the assessment of concussive symptomatology, it is important to consider that reporting may be influenced by sex, current illness, musculoskeletal injury, socioeconomic factors, and moderate-to-high intensity exercise (Mickevičienė et al., 2004). Gender differences are seen in the types of reported symptoms, as Frommer et al. (2011) highlighted that males reported more cognitive symptoms, whereas women reported more neurobehavioural or somatic symptoms. Although males are more likely to sustain concussions, Conder and Conder (2015) highlight that females may be more willing to report their injuries and associated symptoms. Although types of symptoms and reporting may differ between sexes, symptom resolution time and time until RTP does not differ (Frommer et al., 2011). It is important to take these factors into consideration during subjective symptom recall. This further highlights the great need for an objective test in order to reduce the influence of factors such as age, sex and exercise.

Concussion symptoms can be broadly categorised into 4 different sections; cognitive, emotional, sleep and physical (*Table* 1). It is vital to remember that no two concussions are alike in terms of symptomatology, therefore not all individuals demonstrate the same pattern of recovery in symptoms, cognition and balance (McCrea et al., 2003). This highlights the idea that concussion produces a constellation of symptoms and impairments that differ from one person to the next, and its effects are not confined to one domain. Henceforth, concussions are best managed with a multi-faceted and multi-time point approach.

Table 1. Signs and symptoms of a concussion (adapted from (Halstead et al., 2010)).

Physical	Cognitive	Emotional	Sleep
Headache	Feeling mentally 'foggy'	Irritability	Drowsiness
Nausea	Feeling slowed down	Sadness	Sleeping more than usual
Vomiting	Difficulty concentrating	More emotional	Sleeping less than usual
Balance problems	Difficulty remembering	Nervousness	Difficulty falling asleep
Visual problems	Forgetful of recent information		
Fatigue	Confused about recent events		
Sensitivity to light and noise	Answers questions slowly		
Dazed	Repeats questions		
Stunned			

1.4.1 Cognitive

Cognitive deficits are not immediately displayed post-concussion as there is a several hour delay (Bloem et al., 1998; Aubry et al., 2002). Sub-concussive blows in football have been shown to result in changes in cognitive function, which are consistent with mild TBI's in the frontal lobes (Zhang et al., 2013). Post-concussive changes in cognitive function include declines in the speed of mental processing and attention. Understandably these declines in cognitive function can disrupt an individual's functional state. Henceforth, it is essential that cognitive testing is undertaken in clinical concussion management. Testing of cognitive function post-concussion typically takes the form of either self-report measures and performance-based psychometric tests. Clinicians and healthcare professionals should be wary of the self-report process as individuals may be willing to underplay the significance of their symptoms in order to accelerate their RTP. Athletes may even go to extreme lengths by deliberately performing poorly on pre-season baseline testing, in order for their post-concussion assessments to appear somewhat unchanged. This process is known as sandbagging and highlights why a combination of self-report measures and psychometric tests are essential for accurate symptom evaluation. The use of checklists detailing symptoms that individuals may be suffering from have been shown to elicit significantly more symptoms in comparison to interview-based assessments with clinicians (Iverson et al., 2010). Alongside the specific methods of cognitive assessment, it is also important not to consider symptomatic groupings such as cognitive deficits in isolation. The assessment of concussion injuries must be a broad medical and psychological evaluative process in order to aid clinical decision making (Goldberg and Madathil, 2015).

1.4.2 Emotional

Emotional signs and symptoms are often seen in the long term development of PCS. PCS consists of a group of symptoms that persist beyond the expected time frame, for example 10-14 days in adults and over 4 weeks in children (McCrory et al., 2017). Specifically, these are a constellation of non-specific symptoms which may be linked to coexisting or confounding factors that don't necessarily reflect the ongoing physiological injury of the brain (McCrory et al., 2017). Such emotional symptoms range from anxiety and sadness, to emotional lability. Extreme cases of persistent long-term symptoms have been seen recently in numerous NFL players. These long-term symptoms included paranoia, panic attacks, and major depression (Cantu, 2007).

1.4.3 Physical

Physical symptoms range vastly from headaches to visual problems and balance deficits. Headaches are commonly reported as the most persistent concussive symptom and may be seen in up to 70% of cases (Gasquoine, 1997). Alongside this, visual sensory symptoms are potential indicators of concussion, these include double vision, blurriness and abnormal peripheral vision (Clark et al., 2017). It is essential that sufficient cognitive and physical rest is taken following a concussion in order to negate these symptoms.

1.4.3.1 Balance

Within the physical domain, deficits in balance are commonly seen following a concussion. Balance can be defined mechanically, as the “state of an object when the resultant force acting upon it is zero” (Bell, 1998). Centre of Mass describes the location of all masses within a 3D system, with the vertical projection of one’s centre of mass onto the ground being the centre of gravity. In order for the body to remain upright and steady, all forces that act upon the body must be balanced, in turn resisting external forces such as gravity. Postural control is defined as the “act of maintaining, achieving or restoring a state of balance during any posture or activity” (Pollock et al., 1999). Postural control shows the ability of the body to return to an equilibrated state following a perturbation (Karlsson and Frykberg, 2000).

A postural perturbation is a sudden change in conditions that displaces the body posture away from equilibrium (Horak et al., 1997). Disturbances in single body segments such as the head due to a perturbation can result in small muscle changes and responses throughout the body (Horak and Diener, 1994). For larger displacements of the whole body centre of mass, large enough responses are needed to exert directionally specific forces on the contact surfaces in order to return centre of mass to equilibrium (Fung et al., 1995). The visual, vestibular and somatosensory systems, are able to detect such displacements, integrate and interact to produce an appropriate stabilising response. Information from the three sensory modalities is sent to the CNS, where it is integrated and combined with learned information from the cerebellum and cerebral cortex, in order to calculate an appropriate motor response (*figure 1*). The musculoskeletal system uses the information formulated by the CNS to engage the appropriate muscles to retain postural control, via the selection of balance synergies and strategies.

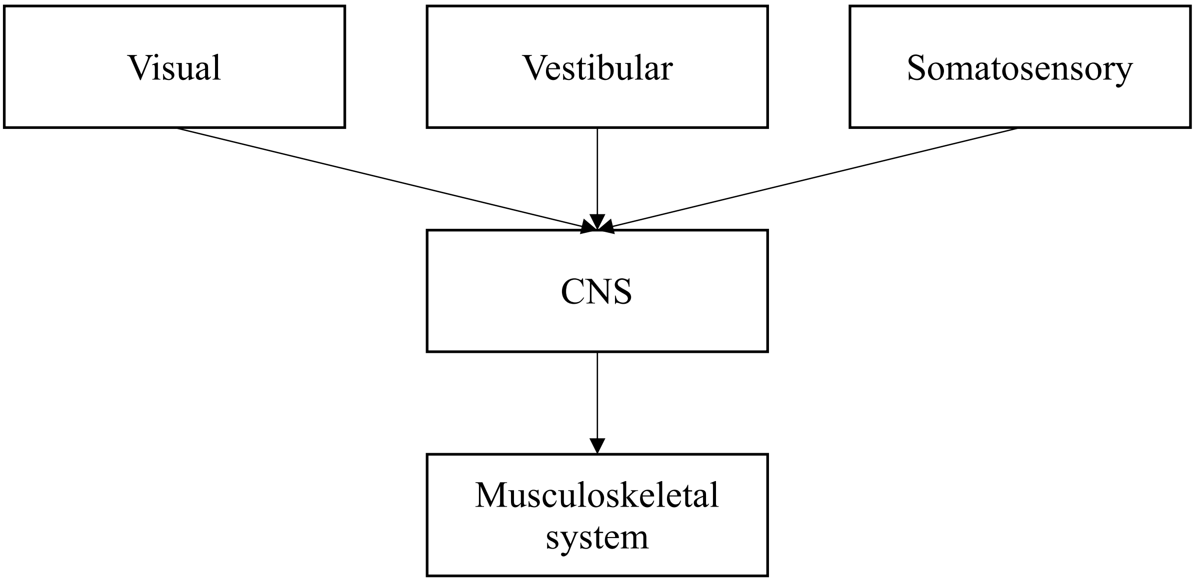

Figure 1. Adapted from Iwasaki and Yamasoba (2014) highlighting the mechanisms involved in the maintenance of postural control. Information is obtained via sensory receptors in the three sensory modalities, detecting any changes in the surrounding environment. This information is sent from sensory receptors to the CNS whereby the information is processed and integrated. Subsequent relevant information is the directed to the musculoskeletal system via motor neurons, in order to engage the appropriate muscles to initiate a balance response.

The CNS is vital in the maintenance of postural equilibrium. The CNS must process and integrate visual, vestibular and somatosensory afferent information, in order to perform precise and coordinated musculoskeletal movements (Guskiewicz, 2011). Internal sensory receptors contained within the three sensory modalities are able to detect environmental changes. Following stimulation of these receptors, information is then sent to the CNS where it is processed, and relevant information is then sent via motor neurons in order to stimulate appropriate muscles. The CNS is highly complex, consisting of specialised neural networks. These networks interact at multiple levels of the craniospinal axis, and this in turn regulates gait, co-ordinates eye movements, and importantly maintains balance and postural control (Ellis et al., 2015).

The vestibular system is important in the perception of self-motion and the provision of sensory information for the neuromotor control of balance (Dieterich and Brandt, 1999; Horak, 2010). In turn, the vestibular system has strong reciprocal inhibitory connections with the visual system (Dieterich and Brandt, 1999). The system contains numerous special sense organs such as semi-circular canals, otolithic organs, joint mechanoreceptors and the retina. These organs contain primary processing units that share rich direct, indirect and reciprocal projections to the spinal cord, autonomic nervous system, cerebellum, brainstem nuclei, basal ganglia, thalamus and cerebral cortex (Armstrong et al., 2008). Two important components of these systems include the vestibulo-ocular reflex and the vestibulo-spinal reflex. The vestibulo-ocular reflex regulates the stabilisation of gaze during head acceleration, and the vestibulo-spinal reflex co-ordinates head, neck and trunk positioning during dynamic bodily movements (Ellis et al., 2015). Post-traumatic dysfunction within these neurological sub-systems can have profoundly adverse effects on the related sub-system, which are difficult to pinpoint to a single specific neural substrate (Ellis et al., 2015). Various muscular strategies are able to provide sensorimotor solutions in order to control postural stability which is characterized by contact forces, patterns of movement and torque (Horak et al., 1997).

These solutions, such as the hip and ankle strategies, are proposed to underpin the maintenance of the body's biomechanics. Older research, such as Winter (1995) accept the notion of an inverted pendulum idea regarding the body, which is considered to be stabilized by ankle strategies. The inverted pendulum is particularly important when the body sways in the antero-posterior direction in that the body behaves like an inverted pendulum pivoting about the ankle joint (Horak and Nashner, 1986; Winter et al., 1993). The proposition of the ankle strategy is that balance is maintained by rotating the body as a rigid mass about the ankle joints, resulting in a smaller displacement of centre of gravity, compared to alternative strategies such as the hip strategy (Nashner, 1977; Horak and Macpherson, 1996). During standing, body sway is correlated highly with ankle joint rotation, henceforth, muscles which cross the ankle joint provide sensory information needed in the maintenance of balance (Di Giulio et al., 2009). When an individual is perturbed, ankle strategies are enforced in order for the centre of mass to be maintained via the generation of torque around the ankle joint in order to shift COP beyond COM (Horak and Kuo, 2000). When an individual is perturbed, contractions in the ankle joint are enforced in the direction opposite to the sway perturbation (Horak and Nashner, 1986). There is much debate regarding the precise strategy that the body utilises in order to maintain postural equilibrium. The ankle strategy of balance maintenance is not the only proposed theory.

An alternative theory proposes the hip strategy underpins the maintenance of postural control. The hip strategy involves flexion and extension of the hip muscles, opposing ankle dorsiflexion and plantarflexion (Chow et al., 2016). The hip strategy theory has less support than the proposed ankle strategy. The hip strategy is not deemed effective by Chow et al. (2016) as the displacement of the centre of gravity is substantial, and in turn induces greater postural instability. Alternatively, other research negates both the hip and ankle strategies, as Krishnamoorthy et al. (2005) proposes the idea that in order for one to be mechanically stable, COM needs to fall within the individual’s base of support, making the COM or projection, the gravity line, a vial task variable in postural control. Therefore, this opposes the hip and ankle strategy notions, as during quiet standing, other joints are required to cohere and stabilise the body. Regardless of the multitude of proposed theories, it is important to consider that the body is able to integrate key visual and vestibular information to provide sensorimotor solutions, in order to stabilise balance when exposed to a perturbation.

The different roles and contributions of the three different sensory modalities may change dependent on the environmental situation and the availability of the sensory information (Horak et al., 1989). For example, if vision is impaired, a greater reliance is placed on the somatosensory and vestibular modalities. Likewise, standing on an unstable surface, greater reliance is placed upon the vestibular and visual systems, as sensory input from the somatosensory system is greatly reduced. Although the availability and quality of the information of one of three sensory modality systems may be rendered ineffective, the balance system as a whole is able to accommodate for this compromised.

Within the physical domain, balance deficits are less vulnerable to individual symptom reporting, and are one of the only symptoms that can be objectively measured (Mancini and Horak, 2010). Balance deficits are commonly seen acutely post-concussion, but have also been identified to persist in the hours and days after the injury, longer than cognitive or emotional symptoms (Muir et al., 2014). Furthermore, even within the balance domain, it is important to consider each concussion in its own entity and that individuals may differ in the types and severity of the symptoms that present themselves.

1.5 Assessment of concussion

A multi-faceted approach to the assessment and management of concussion injuries is essential due to the plethora of signs and symptoms that may ensue post-concussion. The assessment of concussion must cover both the acute and long-term signs and symptoms. Importantly, the wide range of symptoms that may present themselves differ from one person to the next, meaning that the assessment of concussion must also be an individualised process.

1.5.1 Simple tests of alertness

Numerous simple tests of alertness are conducted in the SCAT 5 assessment following the sustaining of a suspected concussion in a sporting situation (Davis et al., 2017). A team physician or member of the medical staff will conduct an initial first aid assessment in order to rule out any other injuries, such as neck and spinal cord damage. Any red flag signs such as neck pain, seizures, vomiting or double vision, are checked for by the clinician. The individual is then asked to answer a series of Maddocks questions such as ‘What venue are we in today?’, and ‘What team did you play last week/game’ (Davis et al., 2017). The Glasgow Coma Scale neurological assessment is also performed to assess the conscious state of the individual (Teasdale & Jennett, 1974). Following this initial first aid assessment, the athlete can then be taken off the field in order to undergo further standardised concussion assessments. In the event that a suspected concussion occurs in the absence of a medical professional, the player should be removed from play immediately and taken to hospital (Davis et al., 2017).

1.5.2 Standard concussion assessments

1.5.2.1 SCAT

The SCAT has been developed and amended over the last 15 years, building on previous statements using an expert consensus-based approach from the Concussion in Sport Group. The SCAT is an internationally recognised compendium of concussion assessments, endorsed by sporting bodies such as FIFA, the Olympic Organisation, and the RFU. The SCAT is highly useful immediately after injury in differentiating between concussed and non-concussed athletes (Davis et al., 2017). However, it shows a decreased utility 3-5 days post-concussion (McCrory et al., 2017). The SCAT5 is the most well established and rigorously developed tool for the sideline evaluation of athletes (Echemendia et al., 2017), and also contains an appropriate version for children known as the Child SCAT (Davis et al., 2017). The on-field SCAT5 assessment includes the simple tests of alertness, as described in section 1.5.1 of this thesis. This is then followed by a symptom evaluation checklist, cognitive screening including the Standardised Assessment of Concussion, and a neurological screening involving the mBESS. The SCAT5 is an excellent tool for the evaluation of those with a suspected but perhaps a less obvious concussion following a collision or head impact.

1.5.2.2 HIA

Game-specific changes are evident in Rugby Union, who have implemented the use of head injury substitutions alongside a head injury assessment (HIA) procedure. The HIA is a multi-faceted, multipoint-in-time assessment, which aims to identify players with confirmed or suspected concussion (Fuller et al., 2017). The first stage of the HIA involves a four point procedure, including immediate removal criteria, the SCAT 5 off-field screening tool, pitch-side video review, and the clinical evaluation by a doctor. Following a player being led unaided to a medical room, the second stage of the HIA involves the repeat testing of the athlete within 3 hours of impact on the SCAT procedure. This includes the Maddocks' and Standardised Assessment of Concussion questions, a tandem gait test, and the assessment of any symptoms or clinical concussion signs. The HIA 3 assessment involves the repeat medical evaluation of the athlete 36-48 hours following the impact. Additional time has also been allocated for the assessment of pitch-side concussion injuries, as the initial 5 minute allocation for the HIA was hardly sufficient to effectively examine a potentially concussed individual.

The time in which an initial HIA assessment can take place is extremely limited. Whilst great strides have been taken in Rugby Union and other sports to address the problem of acute concussion assessment, it is often the subtle concussions that may still go unaddressed and unmanaged, as players may attempt to downplay their symptoms. The desire to remain in the game often overcomes the ability of the player to make a rational decision regarding their signs and symptoms of a suspected concussion. Additionally, the medical staff themselves may also be under great pressure from the team, coach, or administration to get a player back on to field, regardless of their injury. Environmental pressures can often lead to poor clinical decisions, in turn jeopardising the individual's long-term recovery. It is vital that medical staff have reliable, objective tools and assessments to assist in clinical decision making, and to ultimately remove and assess those players who may have sustained a suspected concussion. Research has shown that prior to the implementation of the HIA in Rugby Union 56% of concussed players returned to play during the same game, however with the use of the HIA this figure is now less than 12% (World Rugby, 2015).

A recent study by Fuller et al. (2017) evaluated World Rugby's HIA concussion management process during the Rugby World Cup in 2015. Following on-field assessments of alertness, the SCAT3, without the Glasgow Coma Scale and Maddocks' questions, was performed within 3 hours of sustaining the acute injury. This was then proceeded by an expanded SCAT 3 test performed between 36-48 hours post-injury. It is vital that the concussion management procedure is a multi-point assessment which not only assesses players pitch-side for their acute concussion symptoms, but also includes a 36-48-hour post-concussion assessment and a 3-month follow up. 49 players were evaluated by Fuller et al. (2017) for suspected concussion injuries, with a total of 24 being medically diagnosed with concussion. These multi-point assessments are vital as concussions were seen to be presented at varying timeframes from the minutes during games, to at least 48 hours post-trauma. Additionally, and perhaps most importantly, five players who did not exhibit any signs or symptoms during matches were later diagnosed with concussion. It has previously been noted that a multi-faceted approach is essential in aiding clinicians to accurately assess and diagnose concussive injuries. However, Fuller et al. (2017) highlighted that a multi-time approach to the concussion assessment process is also vital to ensure both immediate and later developing concussions are effectively recognised. The development of an appropriate pitch-side objective diagnostic tool is essential in supporting these great advancements in the HIA process and game-specific changes seen in Rugby Union.

Technological advancements may also be able to aid medical staff in the initial diagnoses of head injuries during matches. A multi-camera Hawk-Eye system providing 360° coverage of the pitch was utilised at the 2015 Rugby World Cup. Pitch-side real-time videos and medical room video reviews undertaken at the Rugby World Cup in 2015 identified or confirmed 11 out of 19 head contact events which led to immediate and permanent removal of the player from the game (Fuller et al., 2017). This equipment allowed clinicians to replay any sequences of play that may have led to a potential concussion injury, and to review the video recordings in slow motion. Importantly, video reviews can be used to assist clinicians and multiple stages of the concussion management process, ranging from the identification of the initial injury, to assessing those returning normal HIA results and individuals who may display delayed symptoms. This method of evaluation must not be used alone, but rather in conjunction with traditional observational pitch-side methods. Furthermore, the use of video technology may go some way into helping medical personnel with the identification of concussion but does not solve the problems associated with concussion diagnosis. Time and financial resources must be invested into the development of technological methods to aid in the objective diagnosis of concussion.

1.5.2.3 RTP

Table 2. Graduated return-to-sport (RTS) strategy adapted from McCrory et al. (2017).

Graduated return-to-sport (RTS) strategy			
Stage	Aim	Activity	Goal of each step
1	Symptom-related activity	Daily activities that do not provoke symptoms	Gradual reintroduction of work/school activities
2	Light aerobic exercise	Walking or stationary cycling at slow to medium pace. No resistance training	Increase heart rate
3	Sport-specific exercise	Running or skating drills. No head impact activities	Add movement
4	Non-contact training drills	Harder training drills, e.g., passing drills. May start progressive resistance training	Exercise, coordination and increased thinking
5	Full contact practice	Following medical clearance, participate in normal training activities	Restore confidence and assess functional skills by coaching staff
6	Return to sport	Normal game play	
NOTE: An initial period of 24-48 hours of both relative physical rest and cognitive rest is recommended before beginning the RTS progression.			
There should be at least 24 hours (or longer) for each step of the progression. If any symptoms worsen during exercise, the athlete should go back to the previous step. Resistance training should be added only in the later stages (stage 3 or 4 at the earliest). If symptoms are persistent (e.g., more than 10-14 days in adults or more than 1 month in children), the athlete should be referred to a healthcare professional who is an expert in the management of concussion.			

Following the initial assessment of concussion, players must then undergo further assessments in a clinical setting, which may include the repeat assessment of the SCAT5. Concussions are highly individualised injuries and as with the acute signs and symptoms, the longer term signs and symptoms may also differ profoundly. The time period of recovery of concussion symptomatology also differs greatly between individuals. Repeat assessments are vital in order to monitor a player's RTP progression and to aid in clinical decision making. A multi-faceted approach as seen in the SCAT 5, must be taken in both initial and repeated concussion assessments. A variety of tools ranging from neurocognitive tests to balance assessments are vital in determining when an individual is fit to RTP. It is essential that this is an objective process that does not solely rely on symptom reporting. Accelerated RTP whilst individuals are still experiencing ongoing symptoms, places them at greater risk of further injury and further exacerbation of their existing symptoms (Helmy et al., 2013). Only those athletes who have steadily progressed through a step-wise RTP protocol, such as the Graduated return-to-sport strategy (*Table 2*), and are asymptomatic are ready to RTP (Kissick and Johnston, 2005). Table 2 notes that following a brief period of initial rest, activity staying below physical and cognitive exacerbation threshold may be conducted (McCrory et al., 2017). Providing the athlete meets all of the criteria, without the development or recurrence of concussion symptoms they may progress to the next level of the step-wise graded RTP protocol. It is suggested that each step take 24 hours, therefore it would take one week to complete the full rehabilitation protocol when they are asymptomatic at rest (McCrory et al., 2017). The time frame for RTP is specific to the individual and is dependent on a number of different factors such as concussion history, age, and sporting level.

1.5.3 Neurocognitive tests

Neurocognitive tools are one of the key cornerstones in the assessment and management of concussion injuries. Neurocognitive assessments provide an in-depth evaluation of an individual's post-concussive functional state (Aubry et al., 2002). Neurocognitive deficits are not immediately displayed following concussion, henceforth, the assessment of such deficits is vital in long-term concussion management. Symptoms including loss of memory and concentration are common post-concussion (McCrory and Berkovic, 2001). Traditional pen and paper tests have been gradually replaced with computerised tests such as Cogsport or Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT). ImPACT is a computer-based assessment of cognitive function, whereby 6 modules are mathematically combined to produce 4 composite scores for verbal memory, visual memory, reaction time and visual-motor speed (Broglio et al., 2007). Computerised assessments are easier, faster and less expensive to administer compared to traditional methods, and allow for the fast availability and analyses of results (Cole et al., 2013). Concussed individuals have been shown to have lower verbal and visual memory scores, slower processing speed and reaction time, alongside a higher quantity of reported symptoms (Iverson et al., 2003).

Fazio et al. (2007) examined the differences in neurocognitive performance between symptomatic concussed individuals, concussed individuals with no subjective symptoms, and a non-concussed group of controls using ImPACT. The concussed asymptomatic group demonstrated a significantly better performance on the test batteries than the concussed symptomatic group. Furthermore, the study highlighted that concussed athletes who denied having subjective symptoms demonstrated poorer performance than controls on all four composite scores of the ImPACT batteries. This identified that concussed individuals who were deemed asymptomatic had not fully recovered from their injury, as evidenced by neurocognitive testing. Objective neurocognitive assessments are vital in aiding clinicians with the difficult RTP decision making process by uncovering residual symptoms that athletes may be underplaying or believe that they have already subsided. However, no one single testing parameter can fully diagnose and manage concussion injuries. A multi-faceted approach combining neurocognitive testing alongside other parameters such as symptom evaluation and balance testing is greatly required.

1.5.4 Balance assessments

The assessment of postural control post-concussion is based on the idea that human balance is dependent on an ensemble of complex mechanisms, such as cortical and subcortical pathways (Ingersoll and Armstrong, 1992; Degani et al., 2017). Information from the three sensory modalities, the visual, vestibular and somatosensory systems, is sent to the CNS, where it is integrated and combined with learned information from the cerebellum and cerebral cortex, in order to calculate an appropriate motor response (*figure 1*). The musculoskeletal system uses the information formulated by the CNS to engage the appropriate muscles to retain postural control, via the selection of balance synergies and strategies. Subsequently, even small changes to this mechanistic pathway will produce deficits in postural control. These postural control deficits range from abnormalities in body sway and the strategies utilised by the CNS to coordinate the activation of a variety of postural muscles (Degani et al., 2017). Henceforth, the assessment of balance is considered an important cornerstone in the assessment of concussion, as post-concussion, one's cortical processing is disturbed which may result in the slowing of the central nervous system. The assessment of postural stability provides a very useful tool for the objective measurement of the motor domain of neurological function (Hunt et al., 2009). Postural control is defined as one's ability to maintain centre of gravity within the base of support (Shumway-Cook et al., 1997). Postural stability assessments were clinically introduced in order to aid healthcare professionals in determining when concussed individuals who had experience balance deficits were able to RTP (De Beaumont et al., 2011). Many of the current and widely used balance assessment tools are often plagued by their subjectivity.

1.5.4.1 Romberg test

The Romberg test was one of the first static balance tools to be utilised in a clinical setting (Riemann et al., 1999). The premise of the Romberg test is that an individual requires at least two out of the three sensory modalities to maintain upright postural stability. Its purpose is to assess an individual's balance when they experience reduced sensory input (Murray et al., 2014). As this test reduces an individual's visual input, the vestibular and somatosensory components of balance are exaggerated. The Romberg test is able to test and evaluate post-concussive balance deficits, whereby individuals are asked to stand with their feet together, hands by their sides, and their eyes closed. The number of seconds the individual is able to stand in the prescribed stance is recorded. Examiners are required to stand by the side of the individual for balance support if required. If one is deemed to sway involuntarily during the test, whereby they have diminished vision, then that is a positive test. Specifically, a positive test is recorded if an individual sways more than normal or falls without being supported by the examiner. In the repeat implementation of the Romberg test, if the individual is able to stand for longer periods of time with their eyes closed, their balance deficits are deemed to have decreased (Black et al., 1982).

The Romberg test is simple, easy to administer and requires no equipment set up. It also aided by its flexibility to test a wide variety of patients. However, the Romberg test is deemed too insensitive and subjective for the long-term assessment of concussion (Guskiewicz and Broglio, 2011). The test is deemed subjective as the outcome measure relies on the interpretation of a single individual, deeming whether the participant has swayed enough to suggest the presence of a postural deficit. The test is rendered ineffective for the testing of balance deficits post-concussion in athletes, as this population group tends to score higher than the general public on specific tests of coordination. In terms of assessing balance dysfunction in concussed populations, the Romberg test also lacks data on its reliability and validity.

1.5.4.2 Sensory Organisation test

Similar problems seen with the Romberg test also arise with the NeuroCom Sensory Organisation Test (SOT) where dual force plates are used to record an individual's antero-posterior sway. It is used to assess one's ability to integrate key balance components; such as visual, vestibular and proprioceptive cues in order to maintain postural control. The SOT does this by systematically disrupting afferent sensory information via the reduction of spatial awareness cues by visual or somatosensory elements, whilst individuals aim to maintain a steady quiet posture. For example, the visual system is perturbed in the eyes closed condition, in comparison to the sway referenced condition when there is a heavier reliance on the vestibular system (Resch et al., 2011). A composite balance score and an equilibrium performance score is calculated via 6 different combinations. This is deduced by 3 sets of 20 second trials per combination. Scoring is conducted on a 100-point scale, whereby higher scores are correlated with better postural maintenance. Guskiewicz et al. (2001) evaluated the performance of concussed patients on the SOT test. Within 24 hours of concussive injury all individuals performed worse than the healthy control participants. However, within 3 days, the deficits seen in the concussed individuals were resolved, as their postural stability scores returned to baseline levels.

Undoubtedly the SOT test is robust in the assessment of posturography, which is able to quantitively assess the ability of an individual to use sensory cues to maintain postural stability (Clendaniel, 2000). However, the SOT may be useful in the short term evaluation of balance deficits, but may fail to identify longer-term deficits (King et al., 2014). Furthermore, due to the use of laboratory-graded force plates to provide COP measurements, the cost of the SOT ranges between $80000-$180000, which prohibits it for use in many sporting environments, particularly at the amateur level (Broglio and Puetz, 2008). Moreover, the SOT lacks portability making it highly impractical for pitch-side use. The SOT has a moderate level of reliability in healthy populations, however it also lacks generalisability for its use in injured populations. The SOT cleverly utilises the quantitative measure of COP to assess balance but is unsuitable for use at the pitch-side in the post-concussive assessment of balance due to its high cost and unportable nature.

<u>1.5.4.3 Modified Balance Error Scoring System</u>

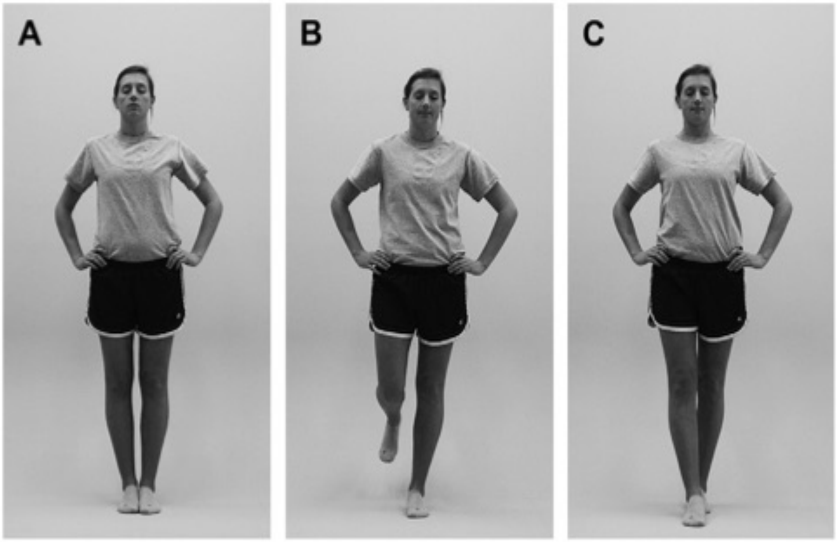

Figure 2. Example mBESS stances (Iverson et al., 2011). Participants must keep their eyes closed and hands on their hips throughout all of the trials. The double leg stance is represented by panel A whereby feet are placed together. Panel B illustrates the single leg stance where individuals stand on their non-dominant foot, with the hip flexed to approximately 30° and knee flexed to approximately 45°. The non-dominant foot is defined as the opposite leg to the individuals preferred kicking foot. Panel C illustrates the tandem leg stance; individuals stand heel to toe with the non-dominant foot behind the dominant foot. The heel of the dominant foot should touch the toe of the non-dominant foot.

Perhaps the most common, widely used and cost-effective balance assessment tool is known as The Balance Error Scoring System (BESS), which is featured in the SCAT5. The BESS uses modified Romberg stances performed firstly on a non-compliant support surface and then followed on a foam surface (Amick et al., 2015). The modified version, known as the mBESS, only uses the non-compliant surface in order to reduce the duration of the test. The mBESS has been shown to be more sensitive than the BESS in the detection of balance deficits both acutely and following a period of recovery (Buckley et al., 2018). Participants are required to complete 3 stances, the double leg (DL), single leg (SL), and tandem leg (TL), each for 20 seconds with their eyes closed and hands on their hips. The number of errors made during the 20 second trials are counted, and such error classifications are reported in

Table 3. A higher error score performed by an individual during the trials is indicative of poorer postural maintenance. If more than one of the error classifications are performed simultaneously, for example as the participant steps out of position they also open their eyes, this is simply categorised as one error score. In the DL stance task, by standing with the feet directly together individuals must adjust by re-weighting sensory information in order to establish centre of mass (Creath et al., 2002). In order to flexibly control upright stance this re-weighting of sensory information provided by the visual, vestibular and somatosensory system is vital (Creath et al., 2002).

The aim of the mBESS assessment is to isolate each component of the balance system (Guskiewicz, 2003). Closing the eyes eliminates the visual input, whereas standing on a compliant foam surface reduces the orientation accuracy of the information from the somatosensory system. For example, increased postural stability in conditions when the eyes are closed, and visual input is eliminated, suggests that the other sensory modalities are not adequately compensating for the loss of visual input (Guskiewicz, 2003). The nervous system is responsible for providing necessary visual input, vestibular mechanisms, and the proprioceptive reflex activities, that are essential for the maintenance of balance (Guskiewicz, 2003). The BESS is undeniably cost-effective, easy to administer and portable in nature due to the little equipment required in its set-up, all elements which heighten its appeal for use as a pitch-side concussion assessment.

Table 3. Adapted from Guskiewicz et al. (2003) to demonstrate the types of errors within the mBESS test.

Balance Error Scoring System (BESS)
Errors
Hands lifted of iliac crests
Opening eyes
Step, stumble, or fall
Moving hip into more than 30° of flexion of abduction
Lifting forefoot or heel
Remaining out of position for more than 5 seconds

Riemann et al. (1999) compared the composite scores and sway measures of the BESS and SOT tests, which resulted in moderate to high correlations. The BESS and SOT tests are valid and sensitive in detecting deficits in postural stability when large differences are apparent, such as fatigue and concussion (Bell et al., 2011). Both the BESS and the SOT tests typically indicate that postural control is worst 24-hours post-concussion, with balance scores then returning to baseline within 3-5 days (Guskiewicz et al., 2001). Additionally, the BESS or mBESS is aided by its relative simplicity and ease of use and is highly cost effective. Furthermore, its short duration, high specificity and reliable individual components of the BESS aid its appeal (Dziemianowicz et al., 2012).

An investigation by McCrea et al. (2003) assessed 94 concussed athletes alongside 56 non-injured controls on a multitude of concussion assessments, including the BESS. The BESS was administered immediately following the concussion injury on the sideline, 2-3 hours post-concussion, and on days 1, 2, 3, 5, 7 and 90 post-concussion. In the acute phase immediately following the injury, the concussed group scored a mean 5.81 error marks more than the control group. However, by day 5, the mean error score for the concussed group had reduced to -0.51 in comparison to the control group. Most individuals were deemed to have returned to normal postural stability within days 3-5 post-concussion. McCrea et al. (2003) noted the vast individual variability in the resolution of symptoms within the concussed athletes. Concussions cannot be diagnosed on a blanket basis; each individual case must be carefully considered. Although McCrea et al. (2003) noted that the BESS showed a reduction in balance deficits in the days following a concussion, the repetition of BESS assessments performed in such a short space of time may be cause for concern. Rather than the BESS scores highlighting an improvement in postural stability post-concussion, this investigation may be plagued by a learning or practice effect. Whereby, the participants may be becoming better at the assessment simply due to the number of repeats performed. Furthermore, the BESS assessors used in McCrea et al. (2004) were not blinded to the nature of study, which may have also afflicted the subsequent results.

Valovich McLeod et al. (2004) assessed if serial administration of the BESS assessment would elicit a learning effect in healthy young athletes. They found that the repeat testing of the BESS over a period of 60 days elicited a learning effect. Total error scores were found to have significantly decreased on days 5, 7 and 60, compared to baseline. This identified that the BESS is plagued by the presence of a significant learning effect. This limits the reliability of the BESS over multiple administrations, whereby decreases in postural stability may be due to the presence of a learning effect, rather than an actual improvement in postural stability.

In addition, the subjective nature of the BESS assessment plagues its reliability. It is essentially a low-technology balance assessments which are ultimately dependent upon an individual's interpretations of balance errors. This is a significant problem which hampers the use of the BESS, as its highly subjective scoring system often leads to vast variations in the proposed error scores of the assessors. Henceforth, the subjective nature of the test may lead to poor inter-rater reliability values (Finnoff et al., 2009). Furthermore, all the advantages of the BESS are merely irrelevant if no accurate baseline BESS test is performed on individuals when they are totally asymptomatic (Dziemianowicz et al., 2012). As concussions are highly individualised injuries producing differing and varying severities of associated symptoms, it is important for baseline testing to be conducted to allow for tests to be analysed on an individualised basis.

Further problems arise within the BESS test, as the SL stance task induces vast variations in postural control even in healthy individuals at baseline (Starling et al., 2015). This severely limits the use of the BESS as a post-concussion balance assessment tool, as it may be unable to detect changes in postural control secondary to concussion. This problem is further exacerbated when the BESS is completed by concussed individuals. Additionally, the BESS has been found to only be useful if administered within the 48-hours immediately post-concussion, therefore it cannot be utilised as a sole balance assessment, as it does not reliably assess long-term balance control (Burghart et al., 2017).

BESS scores are also known to increase with concussion, ankle injury, external ankle bracing, fatigue, sport played and age (Bell et al., 2011; Dziemianowicz et al., 2012). These factors must be taken into consideration when individuals are performing repeat BESS assessments over the course of a season. The idea that fatigue may increase the number of errors performed on the BESS is extremely important to consider, as performing the BESS test post-concussion, in line with the SCAT 5 assessment, can be undertaken at any time point during a game. If BESS scores increase with fatigue alone, it is difficult to interpret the test scores if an individual has also sustained a suspected concussion. The difficulty lies in determining how much fatigue increases BESS scores above and beyond that of a concussion injury, which may lead to exacerbated error scores. Furthermore, if the heightened error scores are complicated by fatigue, the following assessment that an individual may perform in a rested state may seem much lower than that of their initial score. This can lead to further complications with RTP measures, henceforth it is essential that an objective test is developed that can withstand the problematic factor of fatigue. Nonetheless, it is important to note that all balance assessments may be impacted by fatigue, as postural stability is known to decrease after isolated muscle fatigue, and whole-body fatigue (Wilkins et al., 2004). Importantly, the balance component of concussion assessments is not standalone, but rather in conjunction with a multitude of other testing batteries. Practical solutions to fatigue have been suggested by researchers, whereby other elements of the comprehensive assessment of concussion injuries, such as symptom checklists, are completed prior to any balance tests in order to attempt to negate any effects of fatigue.

This highlights a further problem compounding the use of the BESS or mBESS in World Rugby's HIA, whereby a 10-minute period is allocated to allow medical staff to make important clinical decisions. If the BESS is affected by fatigue, it is not ideal that such a test is utilised in a high pressured environment and in such a short time frame. Previous recommendations by Fox et al. (2008) have noted a post-exercise recovery period of 20 minutes is required to negate the effects of injury and fatigue, making this more comparable with baseline testing in order to enhance validity. It is simply not feasible to expect athletes to rest prior to the undertaking of a pitch-side balance assessment. The aim of a pitch-side assessment tool such as the HIA is to determine if athletes are fit to undergo immediate RTP. As well as ensuring those who have sustained a concussion are removed from play, it is vital to preserve the integrity of the sport, allowing those individuals who are not concussed to be permitted an immediate RTP. If diagnostic tools such as the BESS, which may not be able to accurately distinguish between concussion injuries or mere fatigue, are continued to be used in pitch-side environments, this may lead to the inaccurate evaluation of athletes. This could ultimately lead to incorrect RTP decisions being made. An objective and sensitive test must be developed in order replace current existing tools to aid clinicians in making informed decisions for both potentially concussed and non-concussed athletes.

All the tests have various positive elements which heighten their appeal as the current gold standard assessments of postural stability. However, for the specific assessment of postural stability post-concussion at the pitch-side, all the current tests, the Romberg, SOT, and the BESS can be deemed inappropriate. Measures such as the BESS are highly subjective and may also be incompetent at detecting both subtle and residual balance deficits post-concussion. Regardless of the plethora of associated problems, the mBESS still remains the currently accepted standard and most widely used concussion balance assessment tool, as featured in the SCAT5. At present there is no current objective replacement for these inadequate tests. Henceforth it is essential that an objective, pitch-side and portable assessment is developed in order to negate these issues, such as fatigue and subjectivity, to essentially aid clinical decision making.

1.5.4.4 Measurement of balance

Balance deficits are one of the only post-concussion signs that can be objectively measured. Centre of Pressure (COP) is a commonly utilised measurement of postural stability. It describes the point of location of the ground reaction force (Winter, 1995). For example, if only one foot is on the ground the COP is within that foot, however, if two feet are placed on the ground the net COP is dependent on the weight placed on each foot (Winter, 1995). COP is considered the main index of postural stability (Teel and Slobounov, 2015). It can be measured via a variety of balance platforms such as the force plate.

The force plate has long been used in the objective measurement of postural stability. Although laboratory-grade force plates are regarded as the gold standard for the measurement of balance modules, they are greatly limited to a clinical or laboratory setting due to their great expense and unportable nature (Pavan et al., 2015). The current and widely used subjective tests highlight why there is a great need within the field to create an inexpensive balance assessment tool with widespread and pitch-side usability (Clark et al., 2010).

Modern balance modules such as the WBB are becoming ever more commonplace in the management and rehabilitation of balance abnormalities (Wikstrom, 2012). The ease of use and portability of the WBB is explained by its 23 cm x 43 cm platform which weighs approximately 3.5 kg. The WBB consists of a platform with four uni-axial vertical force transducers in each of the four corners of the board (Bartlett et al., 2014). Each of the transducers is a load cell which contains a cantilevered metal bar with a strain gauge that converts applied force to a digitised voltage that can be wirelessly transmitted (Bartlett et al., 2014). Therefore, the WBB is able to track an individual's movements stood on the platform and is able to produce reliable COP measures. The WBB hardware contains an inbuilt analogue to digital converter, allowing the board to provide information to any external device using a Bluetooth connection.

Clark et al. (2010) completed one of the first studies to assess the effectiveness of the low-cost WBB in the assessment of balance deficits. The validity and reliability of the WBB in the assessment of balance was tested against a laboratory grade force plate. Participants completed both SL and DL standing balance tests with eyes open and closed. Clark et al. (2010) deduced that the WBB exhibited excellent test-retest reliability for COP path length and had concurrent validity with a laboratory grade force plate. Ultimately, this highlighted the potential of the WBB for use in standing balance assessments, which is further aided by its portability, widespread availability and low cost.

Limitations of the WBB include a low sample rate and large amount of noise, however, its low cost and portability largely overcome these minor issues. Clark et al. (2010) identified that the WBB is deemed a satisfactory tool in the assessment of standing balance and has the potential to bridge the gap between laboratory testing and clinical balance assessments. Due to the low cost nature and widespread availability of the WBB, it may be obtained in great quantities to be utilised at a clinical, amateur sporting and elite sporting levels.

In a recent study completed by Merchant-Borna et al. (2017), the feasibility of the WBB to assess postural stability at baseline, 3 days post-concussion and 7 days post-concussion, was tested in comparison with the BESS. Baseline data was collected during the preseason from 403 student-athletes, of which 19 undertook further testing following the sustaining of a concussion. The WBB is able to track COP measurements using internal components, which are similar to that in laboratory-grade force plates. DL, SL and TL BESS stances were assessed on both a firm and foam surface. Alongside the BESS, participants were required to perform 4 stances on the WBB for 10 seconds: DL-eyes open, SL-eyes open (dominant limb), DL-eyes closed, and SL-eyes closed. Data was collected for 10 seconds during the SL trials and for 30 seconds during the DL-leg trials, with 15 seconds rest taken between each of the trials. The WBB software was able to calculate the motion of the participants COP throughout the trials and sampled points from this path at 40 Hz frequency, similarly seen in Clark et al. (2010). Merchant-Borna et al. (2017) identified that the WBB demonstrated mean changes in concussed individuals from baseline to day 3 post-concussion, and between days 3 and 7 post-concussion. Furthermore, the COP measures from the WBB correlated with the BESS and ImPACT tests for several measures, and even identified two cases of balance abnormalities post-concussion that the BESS failed to identify. The objective data that the WBB is able to provide via COP measurements may provide an alternative to the subjective BESS test.

1.5.4.5 Virtual Reality Balance Assessment

The clinical management of balance deficits associated with concussive injuries has remained largely unchanged over the last few decades. However, the advancement of VR technologies provides an exciting advancement and prospect within the field (Teel and Slobounov, 2015). VR has been defined as "the process by which a human viewer interprets a patterned sensory impression to be an extended object in an environment other than that in which it physically exists" (Ellis, 1991). VR has been described to induce both egomotion and vection. Egomotion describes any environmental displacement of the observer with regard to visual motion (Warren, 1976). Vection is regarded as sensations or illusory postural self-motion which is induced by a moving background (Nakamura and Shimojo, 1999). The use of various visual kinaesthetic tasks within a virtual environment allows for an interactive and immersive setting to be created that stimulates a real world situation through the medium of a computer (Keshner and Kenyon, 2000; Teel and Slobounov, 2015). The incorporation of varying perturbations within a virtual environment has been shown to evoke balance deficits in concussed individuals (Broglio and Puetz, 2008). In comparison to traditional balance testing, VR is able to immerse individuals within an engaging and purposeful task. Research adopting VR perturbations has been effectively utilised in the training and enhancing of balance post-injury, such as in stroke patients. However, little research has been conducted to assess the effect of visual VR-evoked perturbations on balance.

The first study to assess the use of VR in the objective measurement of balance was performed by Slobounov et al. (2006). The use of VR as a balance assessment tool was assessed in a student athlete population prior to concussion injury, and at 3, 10 and 30 post-concussion. The experimental set up involved the participants standing on a force plate with motion sensors attached to their body, whilst wearing a VR headset. The subjects viewed the VR projector screen through a VR headset and were stabilised using a harness. They experienced a moving room experiment in which three different visual scenes were induced. Prior to their concussion injuries, all participants were able to maintain postural stability during the moving room trials. However, on day 3 post-concussion none of the participants could maintain postural stability throughout the trials. Balance deficits had resolved by day 10 post-concussion, however some abnormal balance responses will still evident up to 30 days following the injury. Slobounov et al. (2006) demonstrated the usability of a VR balance system, specifically the significantly destabilising effect of virtual motions on concussed individuals. VR technology has the ability to detect both acute and long term balance deficits following concussion. The experimental set up involving a projector screen and force plate prevents its applicability in pitch-side use, and also heightens the expense of the study. Nonetheless, it is evident that insensitive mBESS and SOT tests need to make way for advancing VR balance technologies to ensure subtle deficits are detected and allow athletes to undergo correct RTP protocols.

The medium of which the VR experience is provided to the user is also important to consider. In an investigation by Wright et al. (2015), they opted to use a large screen television to immerse their participants, as opposed to a head mounted display (HMD) device. In comparison to a HMD device, a television screen display is not changed adaptively according to a participant’s head movements, therefore the perception of immersion within the visual field is absent (Chiarovano et al., 2015). In terms of usability at the pitch-side, a large screen television would not be suitable. The use of a portable HMD is more appropriate, in which the display is modified by the wearers head position, which is detected by sensors within the goggles (Chiarovano et al., 2015). In the past VR HMD's have been criticised for having lower spatial and temporal resolution than that of the human visual system, with small delays causing movement illusions and motion sickness (Nichols and Patel, 2002). However, over the last few years the quality and variety of HMD's available to purchase seems to be ever increasing. The visual display screen moves to the opposite direction to the wearer's head movements, therefore perceiving themselves to be immersed inside the visual field (Chiarovano et al., 2015). Furthermore, the weight and interface of a HMD such as the Oculus Rift does not influence balance assessment performance (Mihalik et al., 2008). The Oculus headset provide excellent immersive VR qualities, but the appeal of their use is also highlighted by their relative low cost and portability.

A preliminary conference paper by Wright et al. (2015) tested the reliability and sensitivity of a VR WBB combination, in order to develop this new methodological approach to concussion testing. The VR WBB combination was found to be highly efficacious in the detection of subtle balance deficits in a small number of both healthy and concussed individuals. Those individuals who had suffered a concussion were shown to have performed significantly worse on the VR balance system in comparison to the healthy individuals. This coheres with the earlier work of Slobounov et al. (2006), in that a VR system is reliable in the detection of subtle postural deficits seen in concussive injuries. However, the use of a large screen projector by Slobounov et al. (2006), or a large screen television utilised by Wright et al. (2015), would not be appropriate for pitch-side use. Furthermore, earlier research in the field such as that of Slobounov et al. (2006), utilised an experimental setup in which the participants were stabilised by a harness. In the acute assessment of balance post-concussion, it is essential that not only an objective test is employed, but also one that is appropriate for a pitch-side environment.

Within a VR system, individuals can be perturbed in a variety of directions. A pitch perturbation involves the tilting of the VR scene along the y-axis, either forwards or backwards. Perturbations within the pitch antero-posterior axis direction, involve an ankle strategy being activated and the ankle joint is able to oppose perturbations and maintain balance. Alternatively, a roll perturbation, involves a tilt of the VR scene along the x-axis, in either the left or right direction. Gresty and Bronstein (1992) describe that in the roll condition head movement may be increasingly important, as poor eye movement is atoned for by superior head stability. During pitch conditions, reflex eye movements are able to stabilise the eyes, however, in the roll condition the eye movements are inadequate which in turn cause visual instability (Gresty and Bronstein, 1992). Slobounov et al. (2011) highlighted that perturbing the participants along medio-lateral x-axis, the roll condition, within a VR environment was regarded as more destabilising to balance than the pitch condition.

Perturbations can be induced in a variety of different ways, such as visual perturbations as evoked by VR systems, or physical perturbations, such as those induced by the mechanical tilting of a platform. Mechanical support surface perturbations elicit rapid, automatic and coordinated postural responses which are primarily triggered by somatosensory afferents (Diener et al., 1988). Visual input was once thought to be irrelevant to sudden stance perturbations, since the sensation of motion induced by moving visual fields has a relatively long latency (Nashner, 1978). However, subsequent experiments have shown visual information conflicts with those arising from other sensory channels can have a rapid and profound effect on postural responses (Bugnario & Fung, 2007). The influence of moving visual fields on postural stability depends on the characteristics of the visual environment, and of the support surface, including the size of the base of support, its rigidity or compliance (Keshner & Kenyon, 2004). A recalibration process within the body is able to produce an appropriate response in the presence of sensory conflict (Bugnario & Fung, 2007), for example, when the visual perception of the surrounding environment is discordant with the proprioceptive information from the support surface.

It is important that such visual perturbations within a VR system are unexpected to the individual, so they cannot anticipate and prepare an appropriate balance solution. In a study performed by Slobounov et al. (2013), a novel VR and electroencephalogram (EEG) paradigm was utilised to examine the effects of visually induced perturbations on postural response dynamics. Testing was completed on 12 healthy individuals, whereby they were exposed to either a predictable change in direction of a moving room to the right or left, or an unpredictable random change in direction of the moving room. Participants experienced significantly stronger modulation of their frontal-central EEG theta activity prior to the onset of the unpredictable postural perturbations. Slobounov et al. (2013) postulated that this enhanced EEG activity in unpredictable postural perturbations is reflective of an increased effort to recruit additional brain resources, in order to meet to demands of the postural tasks. It is essential that perturbations within the VR environment are unexpected and randomised. Individuals are unable to anticipate the perturbations within the virtual scene, using greater resources to adjust their postural stability. By retaining the objective nature of the VR environment, it sets itself apart from the current, widely used and subjective post-concussion balance assessment. Furthermore, this aspect of the VR environment allows for the development of further tests and continually new and unexpected experiences within the system.

Single-task paradigms are able to effectively measure either an individual's cognitive functioning or postural stability (Teel et al., 2013). Single-task paradigms are heavily limited as they are unable to evaluate any domain interaction across a pair of synchronous tasks. This is particularly relevant in a sporting context, as sporting situations require simultaneous processing of motor, sensory and cognitive information (Broglio et al., 2005). A single task paradigm within a virtual environment is incapable of integrating both cognitive and balance components. Within a dual-task scenario, postural stability can be challenged and underlying balance deficits revealed, due to the simultaneous demands placed on both cognition and balance (Brauer et al., 2004).

An aspect of the novelty in the current study lies in the utilisation of a dual task approach, through the integration of both cognitive and balance components, using a VR system. A dual-task paradigm is created by integrating a cognitive task into the system, such as the incongruent cognitive Stroop Task, to give individuals a focal point whilst aiming to retain their balance. The Stroop task requires the participant to say the colour of the word, rather than the word itself (Stroop, 1935) (*Figure 6)*. Many other tasks are deemed too simplistic in their level of difficulty compared to the Stroop task, as it involves both inhibitory and interference processes (Monsell, 2003). More complex tasks have demonstrated inconsistent interference in those suffering a mild TBI (Brauer et al., 2004). It is vital that the neurocognitive aspect of the dual-task assessment is of sufficient difficulty and is both age and mentally appropriate for the selected cohort.

Teel et al. (2013) highlighted that combining the SOT test with the Stroop induced slower reaction times and moderate to high levels of reliability for cognitive balance tasks. In terms of COP measures, if balance and cognition are assessed simultaneously, subtler deficits in cognition and COP sway can be detected (Guskiewicz and Broglio, 2011). In healthy individuals, there is an added cost to cognitive functioning via the incorporation of the Stroop task alongside a balance task. The integration of a dual-task paradigm further adds to the heightened sensitivity in the detection of subtle and residual post-concussive balance deficits similarly seen in the VR component. The present study merely adopts the use of the Stroop as an immersive measure. However, the adaptable aspect of the VR system allows for other dual task assessments such as neurocognitive tasks to be integrated. The addition of a dual task alongside the assessment of COP measures through the use of a VR based approach heightens the novelty of the assessment.

1.6 Development of the VR WBB system

1.6.1 Pilot testing of the WBB

Piloting procedures were implemented in the development of the VR WBB test to assess the validity and reliability of the WBB, whereby 6 healthy volunteers were recruited from the University of Birmingham (20.5 ± 0.5 y, 2 males, 4 females) (Wilkinson, 2017). COP measurements were obtained from a force plate (Kistler Type 9281) and WBB both as single boards, both as individual balance modules and as a stacked system, similarly performed by Pavan et al. (2015) and Clark et al. (2010). 5 x 30 second trials were completed in both DL and non-dominant SL stances, as shown in Figure 2. Participants were asked to keep their eyes closed and stand as still as possible throughout the trials, with each trial separated by a 30 second period in order to deter fatigue. This was similarly seen in the study by Pavan et al. (2015), whereby the WBB was placed directly upon the force plate, with the two systems centrally aligned. The stacking design eliminates the risk of results being compromised by a test-retest procedure, whereby vast differences are displayed between the same individual's trials (Pavan et al., 2015).

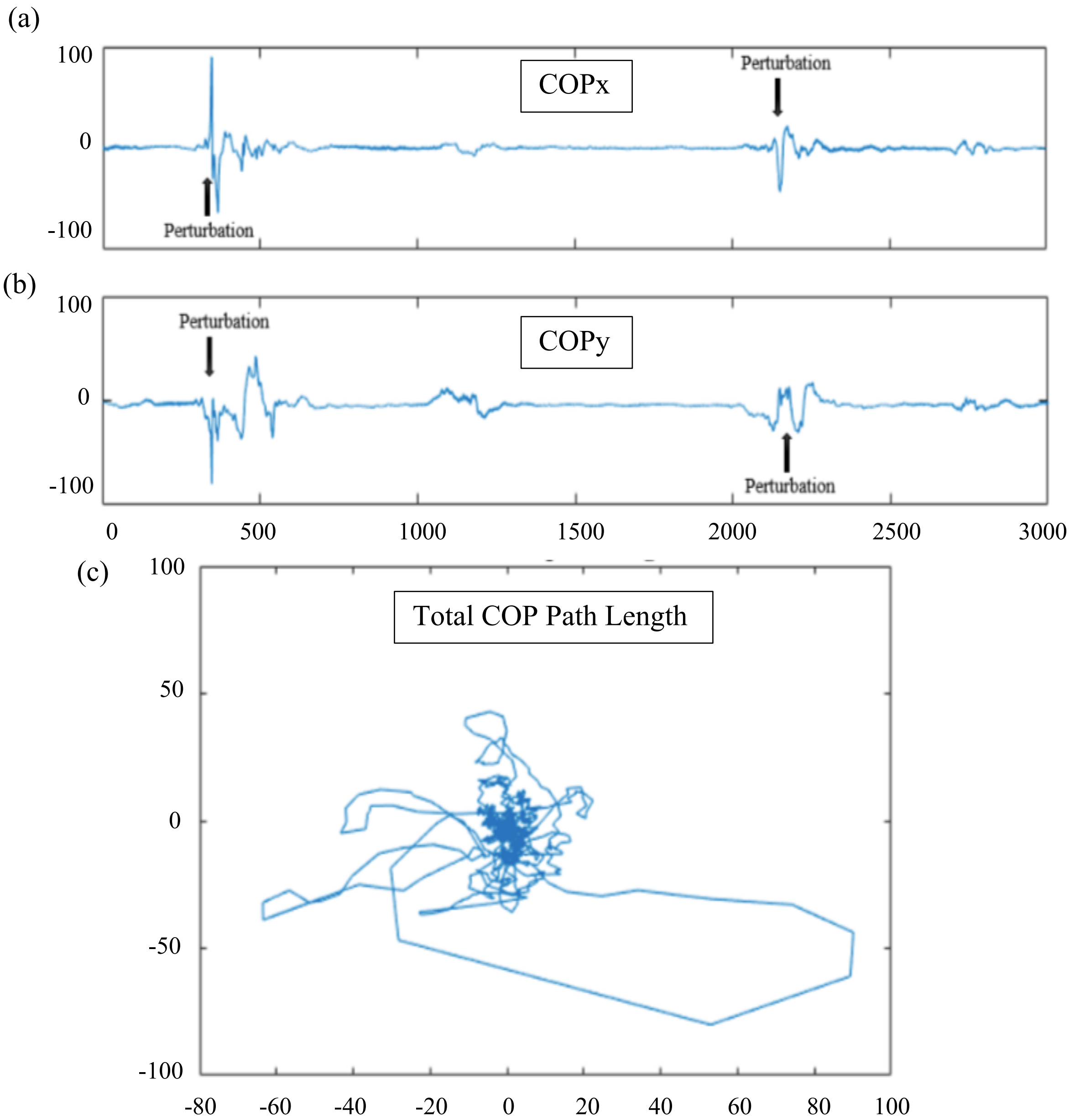

Figure 3. An example of a subject's COP data obtained from pilot testing of the WBB, adapted from Wilkinson (2017). Participant performed the DL stance on the WBB, stabilograms highlight the COP response of the individual to a perturbation. Manual perturbations were induced by lightly pushing the shoulder of the individual to destabilise their balance, at 3 seconds and 22 seconds, as denoted, inducing deviations in COP path length, in both the x axis (a) and y axis (b). (c) Total COP path length concentrated around 0, the centre of the board, with large deviances in COP shown in response to the perturbation. Pilot testing of the WBB shows the ability of the WBB to detect deviances in COP in response to perturbations.

Manual perturbations were induced by lightly pushing the shoulder of the individual randomly throughout the trial to destabilise their balance, as evidenced by the increases in COP deviations in Figure 3. The piloting measures outlined by Wilkinson (2017) deduced that the WBB was effective in detecting the deviances in COP path length following a perturbation (*Figure 3*). Piloting assessments corroborated the work of Clark et al. (2010) in deducing that the WBB had good to excellent between-device test-retest reliability for the measurement of COP path length. This identified that the WBB can be utilised as a valid tool in the assessment of standing balance, as the WBB was able to detect subtle balance deficits, as indicated by an increase in COP path length, resulting from slight perturbations inflicted on the participants.

Pilot testing of the system also highlighted that the non-dominant SL stance was too destabilising when coupled with the VR perturbations (Wilkinson, 2017). It is vital to ensure that the individuals are perturbed in order to assess deviations in COP, but not so destabilised that this induces a fall or step from the board. Participants must remain on the board in order for COP changes to be accurately measured. The SL stance was then removed from any further testing of the VR WBB system, due to its excessively destabilising nature. The use of the DL stance ensures the most reliable measures of COP are being utilised without being manipulated by horizontal forces (Pavan et al., 2015).

1.6.2 Optimisation of key parameters of the VR system

In laboratory testing of the VR WBB system, an Oculus Rift Developer Kit 2 headset was connected to a desktop computer and a WBB in order to assess standing balance. A visual scene was created through the computer programme Unity, whereby the words of the Stroop task appeared, an example is shown in Figure 4.

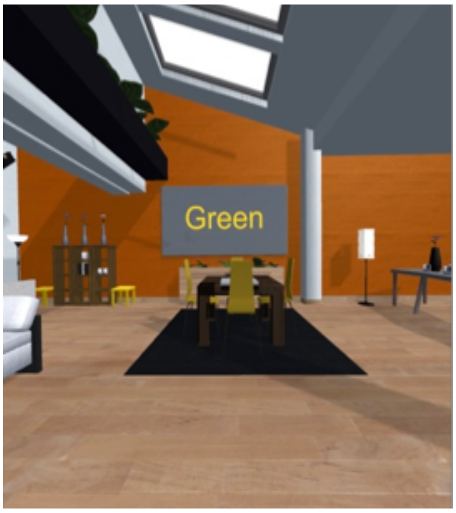

Figure 4. A screenshot of the visual scene created and implemented through the computer programme Unity. An example of the Stroop task which participants performed in the virtual environment is shown, in which the colour of the word is said out loud, rather than the word itself, i.e. in this example the participant was required to say the world 'yellow'.

Pilot testing of the VR WBB system also optimised the immersive measure of the Stroop task. The size and vibrancy of colour of each of the Stroop task words was optimised to ensure they were clear and visible for the participants, as shown in Figure 4. In each 20 second trial, 10 randomised Stroop words appeared reading either red, yellow, green or blue. A 2 second time interval between each of the words was deemed appropriate for the participants. The incorporation of the WBB, VR medium and a dual-task Stroop task was shown to provide a highly sensitive and objective balance assessment tool in a laboratory environment.

Key parameters within the VR system were also established during previous development testing. There is little documented evidence in the literature regarding the specific perturbation parameters within the VR system, such as the total perturbation tilt and the perturbation tilt speed. Slobounov et al. (2011) reported a total perturbation tilt angle of between 10-30° to be appropriate for destabilising balance. Initial pilot testing of the VR WBB system confirmed a total perturbation tilt of 22.5°, within the recommended 10-30° range, was found to be appropriate for destabilising balance. Perturbing the participants in the medio-lateral x-axis direction, the roll perturbation, was found to be more significantly destabilising to postural stability, specifically total COP path length, than the y-axis pitch condition. Therefore, only medio-lateral roll perturbations were adopted for the further development pitch-side VR WBB system.

A further 30 healthy participants from the student population at the University of Birmingham were recruited for additional laboratory testing of the VR WBB prototype. A total tilt angle of 22.5° was retained for the testing of the perturbation tilt speeds. 2 blocks of 16 trials including four different perturbation tilt speeds (4.5°/sec, 5.6°/sec, 7.5°/sec and 11.3°/sec) in the roll axis were randomly induced alongside unperturbed trials. The perturbation tilt speed was found to have a significant effect on COP sway length, with 4.5°/s evoking smaller COP deviations in comparison to the faster speeds. The COP response appears to saturate between 5.6°/s and 11.3°/s. The speed of the perturbation tilt was ultimately identified as a key parameter in the VR WBB system, which needs to be optimised and taken in to consideration in the assessment of standing balance.

Participants within the laboratory environment underwent 2 sets of 16 trials, completing a total of 16 randomly induced unperturbed trials and 16 randomly induced perturbation trials. This testing procedure lasted for approximately 40 minutes per participant, as 5 minute rests were taken between each set of 8 trials. The vast number of trials were performed in order to assess the effect of the axis and speed of perturbation tilt. In order to reduce the influence of a learning effect and make the test more appropriate for immediate assessment use in protocols such as the HIA, the VR trials were shortened from 2 sets of 16 trials, to 1 set of 8 in the current study. This also allowed for the removal of the 5 minute rest periods between trials, allowing for a total test duration of 5 minutes. In laboratory testing of the VR WBB system all trials were randomised within each set of 8 trials. However, in the current study, to allow them to settle in to the system and to assess baseline postural stability, the first two trials that they all received were unperturbed trials. It is important to consider that the appeal of the VR system lies in its ability to integrate a multitude of different assessments such as neurocognitive tests, not solely the assessment of balance in isolation.

1.7 Aims

1. To establish whether a novel VR WBB system is effectively able to assess balance, by evoking visual perturbations through a VR headset, and to record and assess subsequent changes in COP path length, as measured by a WBB, in a pitch-side environment.
2. To test the currently accepted standard mBESS assessment in a pitch-side environment, using both error scores and quantifying the effect of the mBESS stances on COP path length, as measured by a WBB.
3. To establish whether the mBESS error scores or mBESS COP path lengths correlate with changes in COP path length following the induction of a perturbation.

CHAPTER 2. METHODS

2.1 Participants

A total of 14 participants were recruited from the University of Birmingham women's hockey teams (mean age = 18.86 years, SD = 1.03; mean height = 164.79cm, SD = 5.66; mean body weight = 64.1kg, SD = 6.27). A well-established link between one of the researchers was utilised in the recruitment of athletes via email and telephone contact with team coaches. Awareness of the study and additional information was further promoted to the athletes via email. The study was given approval by the University of Birmingham Ethics Committee (ERN_17-0777) and conformed to the Declaration of Helsinki guidelines. Participants were asked to go about their normal daily routine during the study.

Exclusion criteria: History of epilepsy; suffering from any existing balance deficits or health problems relating to the inner ear; women who think they may be pregnant; concussion or a head-related injury in the past 3 months. Individuals with a history of epilepsy were excluded as seizure risks have been reported with respect to VR gaming, however, the VR system utilised in the current study has been specifically designed to omit this type of exposure. It does not feature any flashing lights or patterns, making the risk of seizures negligible for healthy individuals with no history of epilepsy.

2.2 Procedure

All testing took place in the pavilion next to the University of Birmingham sports pitches. Participants were asked to go about their normal daily routine, with testing taking place prior to a training session or match. On arrival, participants were asked to complete an informed consent form – see Appendix A, a demographics questionnaire - see Appendix B, and a suitability to participate checklist – see Appendix C. Participants were then given a full debrief by one of the researchers, detailing what their participation would involve prior to receiving a visual demonstration of both the mBESS and the VR WBB test. For the purpose of this study participants were randomly assigned to complete either the mBESS test then the VR WBB, or vice versa. Participants were reassured throughout the study that they were able to withdraw at any point.

2.2.1 mBESS

Participants were asked to perform the mBESS test, as published in the SCAT 5 (Echemendia et al., 2017). Individuals performed 3 trials lasting for 20 seconds each whilst performing three different stances. All trials were performed on a standard commercial WBB (Nintendo, Kyoto, Japan) to enable the collection of COP data for each of the individual's mBESS stances. COP data was sampled from the WBB at a frequency of 40Hz. The WBB was connected to a laptop computer (ASUS Strix Gaming Notebook PC GL702VS) via a Bluetooth connection. All stances were demonstrated by the investigators prior to the performing of any trials. Prior to the recording of any balance trials all participants consented to the use of video recording in the informed consent form and verbal confirmation of this was also given. Both investigators recorded all trials via a smart phone from both a frontal view and a side-on view. The number of errors made by individuals during their trials were assessed offline by seven independent markers, utilising the error classifications in table 3. Unlike the traditional mBESS assessment, participants performed the assessment with their footwear on, as pilot testing confirmed this made no difference to the performance of the individual and the acquired COP data. Each participant performed three 20 second trials, and the investigators only proceeded to begin timing when the individual was settled in the proposed stance with their eyes closed.

The first stance, known as the DL stance (*Figure* 2a), involved individuals standing with their feet together, hands on their iliac crests, and their eyes closed. The second stance, the SL (*Figure* 2b), was then completed by participants on their non-dominant foot. Individuals were told the dominant leg should be held at 30° of hip flexion and 45° degrees of knee flexion. The dominant foot was determined to be their preferred foot to kick a ball with. Participants were asked to aim to maintain their stability throughout the 20 second trials with their hands on their hips and eyes closed throughout. If they stumbled out of this position, they were asked to open their eyes and return to the original stance position. For the final stance, the TL stance (*Figure* 2c), participants were asked to stand heel-to-toe with their dominant foot at the back and their non-dominant at the front. Stability should be maintained for 20 seconds with hands on the iliac crests and eyes closed, with their weight distributed evenly across both feet. Similarly, as with the SL stance, if individuals stumbled out of the described position, they were instructed to open their eyes and return to the TL stance.

The video recordings of each participant's three trials were then assessed offline by seven independent investigators. Each of the trials were scored by counting the number of errors, or deviations the individuals made from the mBESS stance positions, in line with the error classification table (*table* 3). Scoring only began when the individual was settled in the proposed stance. The mBESS score was then calculated by adding one error point for each error accumulated during each of the three 20 second tests (*table* 3). 10 error points is the maximum that can be accumulated for any single condition. Individuals who were unable to maintain any of the stances for a minimum of 5 seconds at the start of the trials were given the maximum score of 10 for that individual condition. Individuals who performed multiple errors simultaneously were only given one error mark and marking continued after they had returned to the original stance.

<u>2.2.2 VR WBB test</u>

A standard commercial WBB (Nintendo, Kyoto, Japan) (W=228mm, L=433mm) was connected to a laptop computer (ASUS Strix Gaming Notebook PC GL702VS) via a Bluetooth connection. COP measurements were obtained via four load cells on the corner supports of the WBB. COP data was sampled from the board at a frequency of 40Hz. The HMD device utilised in the current study was the Oculus Rift Developer Kit 2 headset.

To ensure the wellbeing of all the participants undertaking the VR WBB assessments, all investigators were trained in manual handling. Manual handling involves the supporting of a load by hand or by bodily force including a variety of movements such as lifting, pushing or pulling (Carrivick et al., 2001). This ensured investigators were able to aid individuals if they were to fall of the board during a trial, therefore two investigators stood either side of the participants whilst they were undertaking the pre-trial familiarisation phase and all trials.

Prior to the beginning of each participant's trial block, the WBB was connected via a Bluetooth connection to a laptop. The programme Unity was then run to ensure the WBB was calibrated in alignment with the Oculus VR system. Participants were then guided through a pre-trial familiarisation whereby one of the investigators detailed what their participation would entail. Using a visual demonstration, investigators explained that the participants were to stand with their feet together on the WBB and their hands on their hips (*Figure* 5). The participants were asked to emulate this stance without the Oculus headset on, and then again with the headset on. This was performed in order for the participants to experience retaining the stance with the added weight of the headset on, and to further ensure the headset was comfortable and safely secured around the participant's head.

Figure 5. The experimental setup and DL stance. The participants were instructed to uphold this stance as best they could throughout all of the trials. Participants were instructed to keep their feet together in the centre of the board, hands on their iliac crests, and to freely adjust their head. During all trials two researchers trained in manual handling stood either side of the participant to ensure they did not fall from the board (not shown in image).

Figure 6. The visual calibration screen shown to the participants prior to each trial.
An example of the image participants viewed pre-trial through the Oculus Rift headset. The red dot represents the participants COP. The participants were required to keep their COP within the larger green circle, aiming for the central cross hair, prior to each trial to ensure they were stable. The calibration phase gave the individuals visual feedback regarding their balance to ensure they were maintaining their postural equilibrium prior to all the trials. The trial would not begin unless the individuals COP was held within the larger green circle for 3 seconds, for which the individuals viewed a visual countdown screen.

Participants then undertook a calibration stage to ensure that their COP stayed within their base of support (*Figure* 6). Henceforth, in order to start the subsequent trials, it is essential they retained their postural equilibrium. Participants stood on the WBB in the previously described stance and adjusted their balance in order for the smaller red circle to remain within the larger green calibration circle for three seconds (*Figure 6*). Participants are able to view this through their headset and adjust their balance accordingly, they are then required to remain in this position for a visual countdown of a further three seconds prior to the starting of the trial and the Stroop task. Any large deviances in COP after this calibration phase are more likely to be due to the ensuing perturbations in the visual field and not simply a loss of balance control.

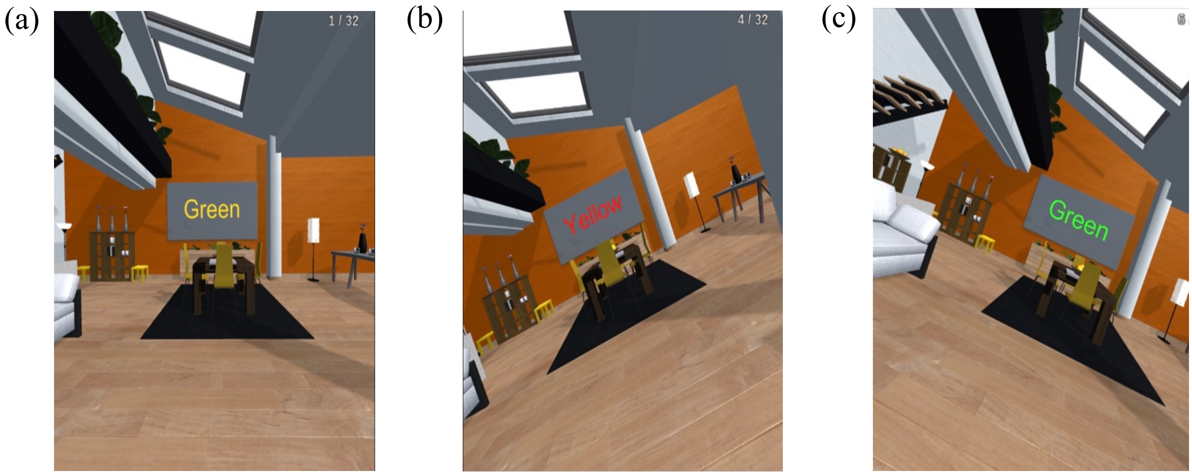

Figure 7. The panels illustrate the different trial conditions experienced by the participants during the VR WBB assessment. The examples include an unperturbed trial whereby the visual screen did not tilt (a), and anti-clockwise (b) and clockwise (c) perturbations in the x-roll axis. The cognitive Stroop task as shown in each of the panels, provides a dual-task element to the VR WBB assessment. This was merely used as an immersive measure to detract the participants from solely focusing on their postural stability, rather than for the assessment of cognition.

Participants then performed 8 balance trials consisting of perturbation trials and unperturbed trials. The first two trials every participant received were programmed to be unperturbed, in order to assess baseline stability and to ensure participants settled into the testing procedure.

The remaining six trials were randomly induced, consisting of further unperturbed and perturbation trials. In total, due to the randomised design of the study each individual experienced 4 unperturbed and perturbation trials. Each perturbation trial reached a total tilt angle of 22.5° at a speed of 7.5°/second, therefore, taking a total of 3 seconds to reach the desired total tilt angle. When the perturbation tilt has reached a total tilt angle of 22.5°, the visual screen remains at this tilt angle for the remaining duration of the trial. Each trial was 20 seconds long, with perturbations being randomly induced between 5-10 seconds following the onset of each trial. Each individual trial consisted of 10 words of the Stroop task that appeared within the virtual scene, and each word was separated by a 2 second interval. There was a 10 second rest between each of the 8 trials.

Following the completion of the block of 8 trials, participants were then instructed to remove the Oculus headset and step down from the balance board. The debrief involved ensuring the participants were not suffering from any dizziness or headaches. Participants were then administered an immersion questionnaire; in which they were informed they could give their feedback regarding their experience with the VR WBB system. The immersion questionnaire adapted from Gil-Gómez et al. (2013) evaluated how much the participants believed they were in the virtual environment, and included 12 questions such as ‘How much did you sense to be in the environment in the system?’ and questions regarding the post-VR effects such as ‘Did you feel disorientated during your experience with the system?’ (Appendix D). Participants were asked to provide a written response to the questions on a 5-point Likert scale. Questions concerning the effectiveness within the VR system were graded from 1 ‘not at all’ to 5 ‘very much’, and questions regarding the difficulty of the task from 1 ‘very easy’ to 5 ‘very difficult’. Finally, participants were asked to provide a yes or no response regarding their comfort during the test and were provided with space to include any additional comments.

2.3 Protocol

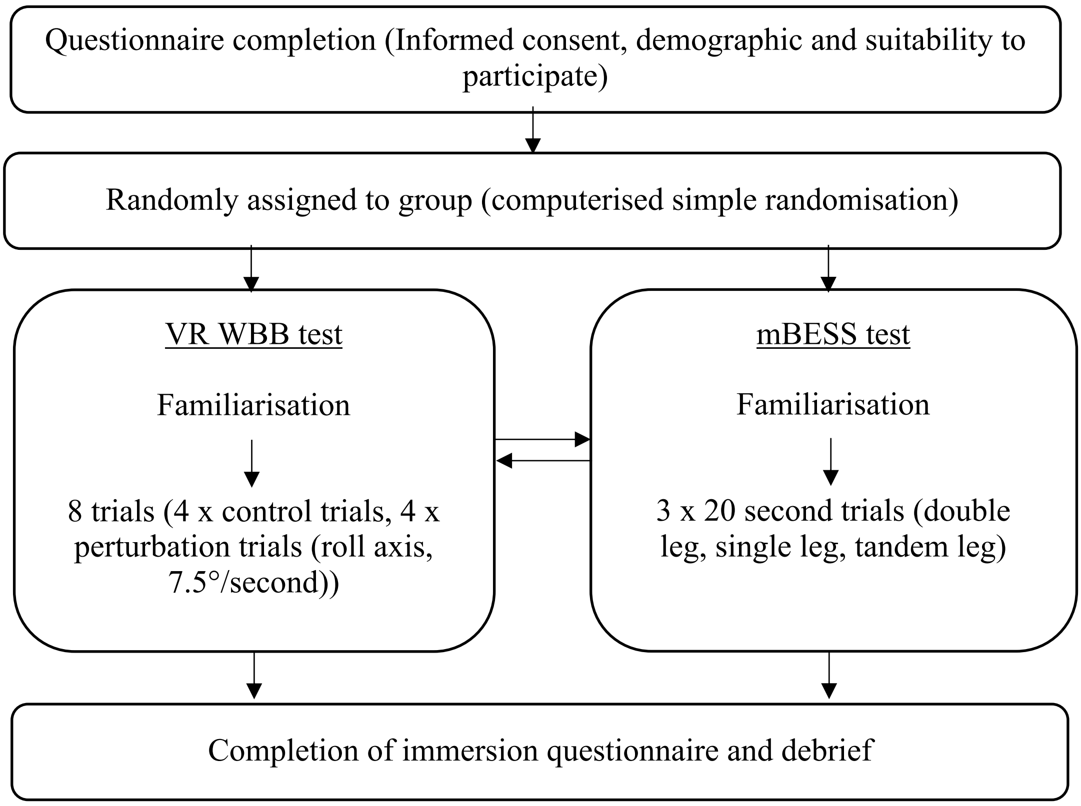

Figure 8. The study followed a within-subject experimental design. Prior to the completion of the VR and mBESS assessments, participants were required to fill out a number of questionnaires, ensuring they had all the appropriate information to deduce whether they were to fit to partake in the study, and had consented to do so. Participants were randomly assigned via simple randomisation to begin the study with either the mBESS or the VR WBB test. The mBESS was performed as published in the SCAT5 (Echemendia et al., 2017) whereby 3 different stances were performed, in order to obtain error scores. The mBESS stances were conducted on a WBB to obtain additional COP measures, alongside the traditional error scores. The VR assessment involved the performance 8 balance trials, whilst viewing a visual scene through an Oculus HMD device, whilst standing on a WBB to obtain COP measures. A short debrief followed the performance of both assessments, including an immersion questionnaire to assess any post-VR effects following the VR WBB test.

2.4 Data acquisition

MATLAB (MATLAB and Statistics Toolbox Release 2016b, The MathWorks, Inc., Natick, Massachusetts, United States) software was adopted to generate the code for the extraction of the data files (.txt) from the WBB and to plot the COP coordinates. The bespoke MATLAB

(MATLAB and Statistics Toolbox Release 2016b, The MathWorks, Inc., Natick, Massachusetts, United States) code was created at the University of Birmingham by Dr Michael Grey and Dr Sang-Hoon Yeo. This created a Graphical User Interface (GUI) of the COP path lengths for each trial. The code allowed for the obtainment of exact COP path lengths for the x and y axis, alongside the means and standard deviations. Each participant's COP path length was extracted from the WBB from 5 seconds prior to the perturbation onset, to the 5 seconds after the onset of the perturbation. This allowed for the assessment of baseline balance, and the direct comparison of the individual's balance response, the change in COP path length, following the onset of a perturbation.

2.5 Data analysis

MATLAB (MATLAB and Statistics Toolbox Release 2016b, The MathWorks, Inc., Natick, Massachusetts, United States) computer coding software was used to analyse and plot the COP data measurements in order to assess balance.

2.6 Statistical analysis

SPSS (IBM Corp. Released 2016. IBM SPSS Statistics for Mac, Version 24.0. Armonk, NY : IBM Corp.) was the statistical software utilised. Dependent samples t-tests were used to assess the effect of the perturbation tilt on COP path length, and the effect of unperturbed trials, pre-perturbation and post-perturbation on COPx and COPy. A repeated measures ANOVA was utilised to assess the habituation effect of pre and post-perturbation tilts on COP path length, and the COP path length percentage change from pre to post-perturbation. One-way repeated measure ANOVA's were further adopted to assess the effect of the mBESS stances on error scores and COP path length. Intra-class correlation (ICC) analysis was used to assess the inter-rater reliability of the mBESS error scores. Spearman rank order correlation analyses were used to compare the mBESS error scores and COP path lengths, and a Pearson correlation coefficient analyses between the COP path length percentage change from pre to post perturbation and SL mBESS error scores.

CHAPTER 3. RESULTS

All of the 14 participants performed both the VR balance test and the mBESS assessment. One participant was excluded from the data analysis due to an incomplete data set.

3.1 VR results

Table 3. Immersion questionnaire responses.

1 = Not at all 5 = Very much	Mean	SD
Q1. How much did you enjoy your experience with the system?	4.21	0.97
Q2. How much did you sense to be in the environment of the system?	4.43	0.51
Q3. How successful were you in the system?	3.86	0.86
Q4. How real is the virtual environment of the system?	3.93	0.83
Q5. Is the information in the system clear?	4.79	0.58
Q6. Did you feel discomfort during your experience with the system?	1.64	1.01
Q7. Did you experience any dizziness or nausea?	1.36	0.74
Q8. Did you experience any eye discomfort?	1.50	0.94
Q9. Did you feel disorientated during your experience with the system?	2.14	1.17
1 = Very easy 5 = Very difficult		
Q10. Did you find the Stroop task difficult?	2.43	0.85
Q11. Did you find it hard to maintain your balance throughout the test?	2.79	1.05

The sense of immersion within the VR system questions are highlighted in blue, post-VR effect questions highlighted in yellow, and task-specific questions highlighted in green.

Participants were asked to complete an immersion questionnaire (appendix D) following the VR task. Their responses are summarised in Table 3. The difficulty of the Stroop task was also assessed, whereby participants indicated they found it neither very easy or difficult. The aim of the Stroop task was to immerse the individuals within the VR system, detracting them from focusing on their balance. The responses from the immersion questionnaire indicated that participants did sense themselves to be within the VR environment. Participants experienced very little dizziness, nausea or eye discomfort during their experience within the system. Participants also responded in a yes or no manner to the statement ‘if you felt uncomfortable during the task, please indicate the reasons’. All participants responded ‘no’ to this statement, indicating they did not feel uncomfortable.

3.1.1. The effect of unperturbed and perturbation trials on COP path length

The bespoke MATLAB script (created by Dr Michael Grey and Dr Sang-Hoon Yeo at the University of Birmingham) allowed for the extraction of COP data in the x and y directions, standard deviations and mean COP values for each of the participants trials. The speed of the perturbation tilt was set at 7.5°/second; therefore, the participants spent a duration of 3 seconds reaching the total tilt angle of 22.5°. The incline of the purple perturbation trace line indicates the tilting phase of the trial, as shown in Figure 8a.

As shown by Figures 8a-d, there is a spike in COP path length in both the x and y directions directly following the onset of the perturbation. The COP path length spike is more apparent in the x-axis, as the perturbation tilt within the VR system was also evoked in the x-axis direction. Following the onset of the perturbation tilt, the participant aims to counteract the tilt within the VR environment. The participant must compensate for the tilt within the virtual environment by shifting their COP in the opposite direction, a sway response, in order to retain their postural stability. The greatest deviation in COP path length is during the 3 seconds whilst the VR scene is tilting. On average it took the participants 0.809 ± 0.18 seconds to evoke a balance response to the onset of the perturbation tilt. Once the VR scene has reached the 22.5° total tilt angle balance is still impaired in the following 10 seconds to the end of the trial, in comparison to the pre-perturbation COP path length.

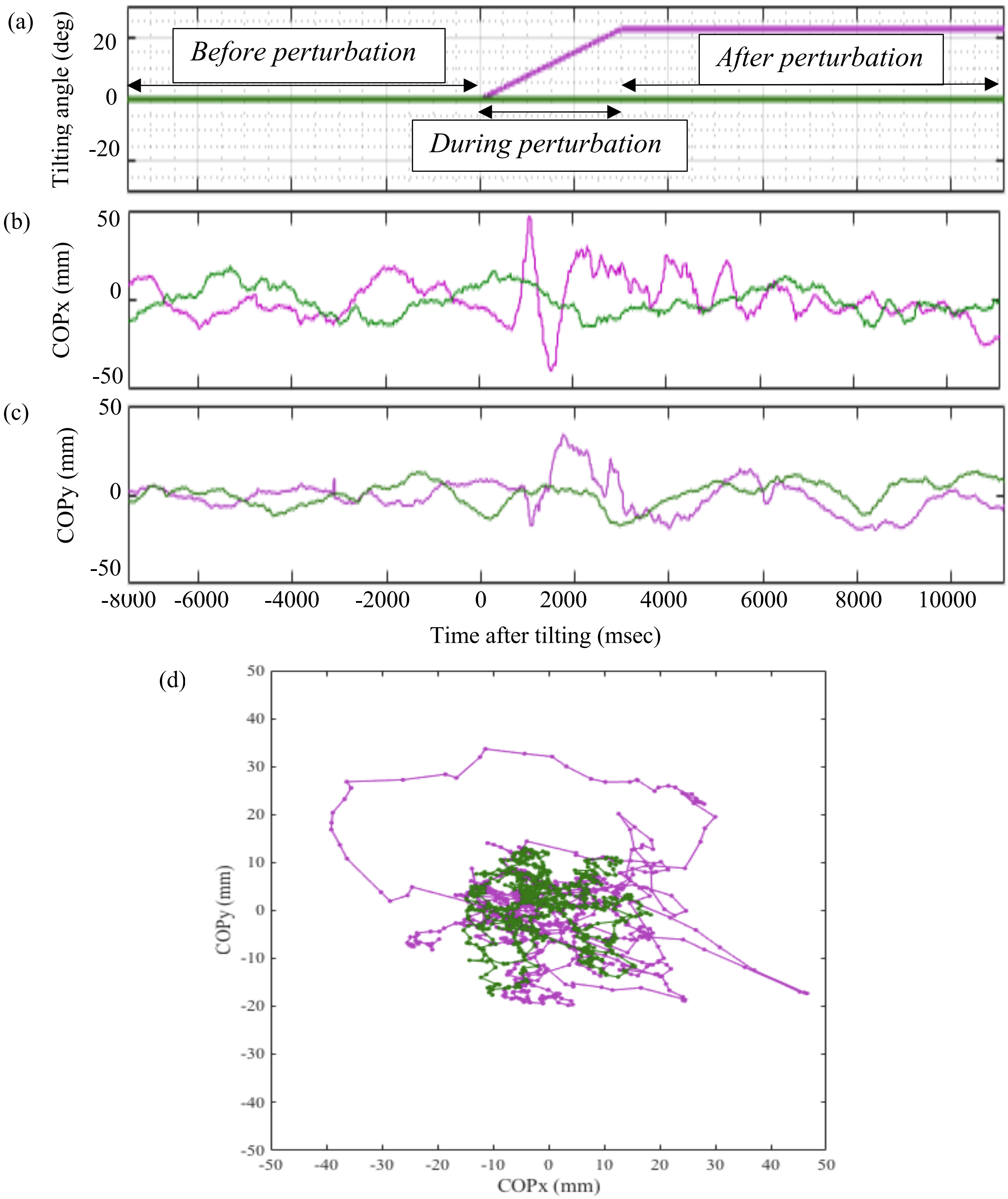

Figure 9. Representative data sample from one participant, showing one unperturbed trial and one perturbation trial. (a) One unperturbed trial (purple) and one perturbation (green) trial are highlighted. Time before perturbation onset is seen prior to 0 msec, tilting ceases when a total tilt angle of 22.5° is reached. (b) COP deviations are shown in the x-axis for both the unperturbed and perturbation trials. (c) COP deviations in the y-axis are shown for the unperturbed and perturbation trials. (d) The stabilogram outlines the COP path data traces of the unperturbed and perturbation trials, in the x and y directions.

3.1.2 The effect of repeat perturbation trials on COP path length

Due to the programming of the VR system, the first two trials were set as unperturbed trials to ensure the baseline stability was assessed prior to induction of randomised perturbation and unperturbed trials. Following this, all participants experienced 4 perturbation trials. The MATLAB software allowed for the extraction of data files from the WBB to plot COP coordinates, creating a GUI of the COP path lengths for each trial. The code allowed for the obtainment of exact COP path lengths for the x and y axis, total COP path length, alongside the means and standard deviations. Each trial lasted a duration of 20 seconds, with each perturbation being randomly induced between 5-10 seconds after the beginning of each trial. COP path length was extracted from the WBB from 5 seconds prior to the perturbation onset, to the 5 seconds after the onset of the perturbation. This allowed for the assessment of baseline balance, and the direct comparison of the individual's balance response, the change in COP path length, following the onset of a perturbation.

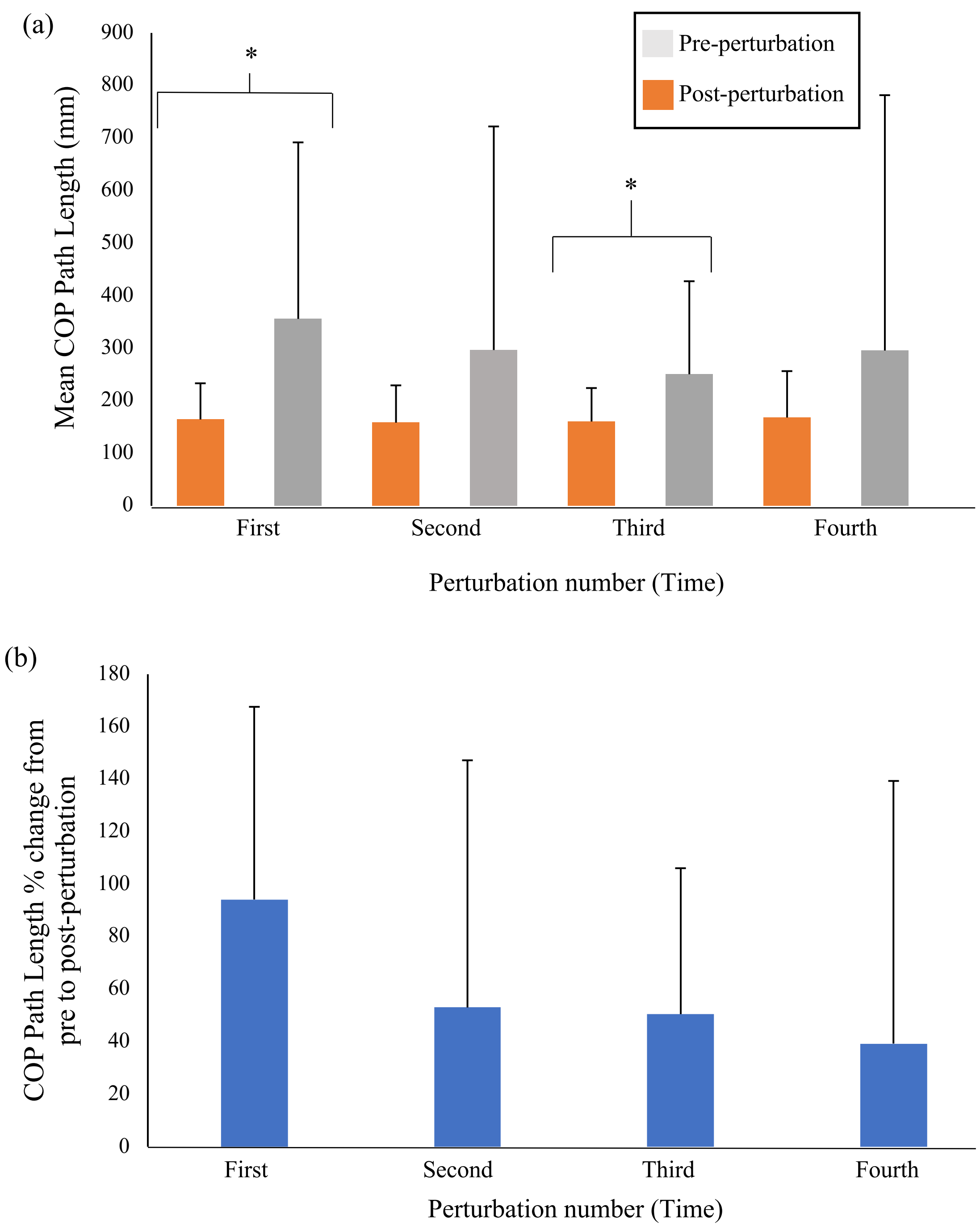

Figure 10. (a) Mean total COP path length and standard deviation before and after the perturbation tilt was induced. The significant effect of the perturbation tilt on balance is demonstrated in the first and third trials (* $p<0.05$) (b) The COP path length percentage change from pre to post-perturbation is shown, in order to assess the presence of habituation.

COP path length data for both pre and post-perturbation was obtained, as shown in Figure 10a. The extraction of the COP path length prior to the onset of a perturbation tilt provides data on baseline postural stability, which is specific to each individual. An increase in COP path length was observed in all trials post-perturbation, as shown in Figure 10a. Dependent samples t-tests revealed the mean COP sway length after the onset of the first perturbation tilt was significantly greater than the mean COP sway length before the onset of the first perturbation ($p = 0.025$). Furthermore, the mean COP sway length after the onset of the third perturbation tilt is significantly greater than the mean COP sway length prior to the onset of the third perturbation ($p = 0.025$). No significant differences were found between the mean COP path length before the second and fourth perturbation trials and following the onset of the second and fourth perturbation trials, respectively. A repeated measures ANOVA revealed there was not a significant effect of time on pre-perturbation COP path length, indicating no habituation or learning effect was present. Similarly, there was no significant main effect of time on post-perturbation COP path length, ($F_{3, 36} = 1.077$, $p > 0.05$, $n_p^2 = .08$), indicating that over time there was no significant learning effect of the balance response to a perturbation tilt.

The calculation of percentage changes is a useful way to present the results of the change in COP path length from pre to post-perturbation, as indicated in Figure 10b. The use of percentage changes controls for the individuals baseline postural stability. This allows the effect of the perturbation tilt to be seen more clearly, without being potentially confounded by the participants pre-existing balance ability. Following the onset of the first perturbation trial the total mean COP path length of the individuals was shown to increase by 94.9 ± 73.4 %. This highlights that the VR perturbation tilt has a profound destabilising effect on postural stability. The greatest percentage increase was found prior to the onset of the first perturbation tilt, and following the tilt, in comparison to the following perturbation trials. A repeated measures ANOVA revealed there was a significant effect of time on COP path length percentage change from pre to post-perturbation, ($F_{3, 36} = 3.35$, $p = 0.03$, $n_p^2 = .08$), indicating a habituation or learning effect was present.

3.1.3 The effect of unperturbed and perturbation trials on COPx and COPy path length

The data extracted from the WBB consists of COP path length values in both the x and y directions. Dependent samples t-tests were performed to assess the differences in x and y COP path lengths for the unperturbed trials, and both the pre-perturbation and post-perturbation sections of the perturbation trials. The COP path length induced by the unperturbed trials was significantly greater in the x-axis direction compared to the y-axis ($p = 0.05$). The COP path length induced pre-perturbation was also significantly greater in the x-axis direction, compared to the y-axis ($p < 0.05$). In addition, a significantly greater COPx path length compared to COPy was also reported post-perturbation ($p < 0.05$).

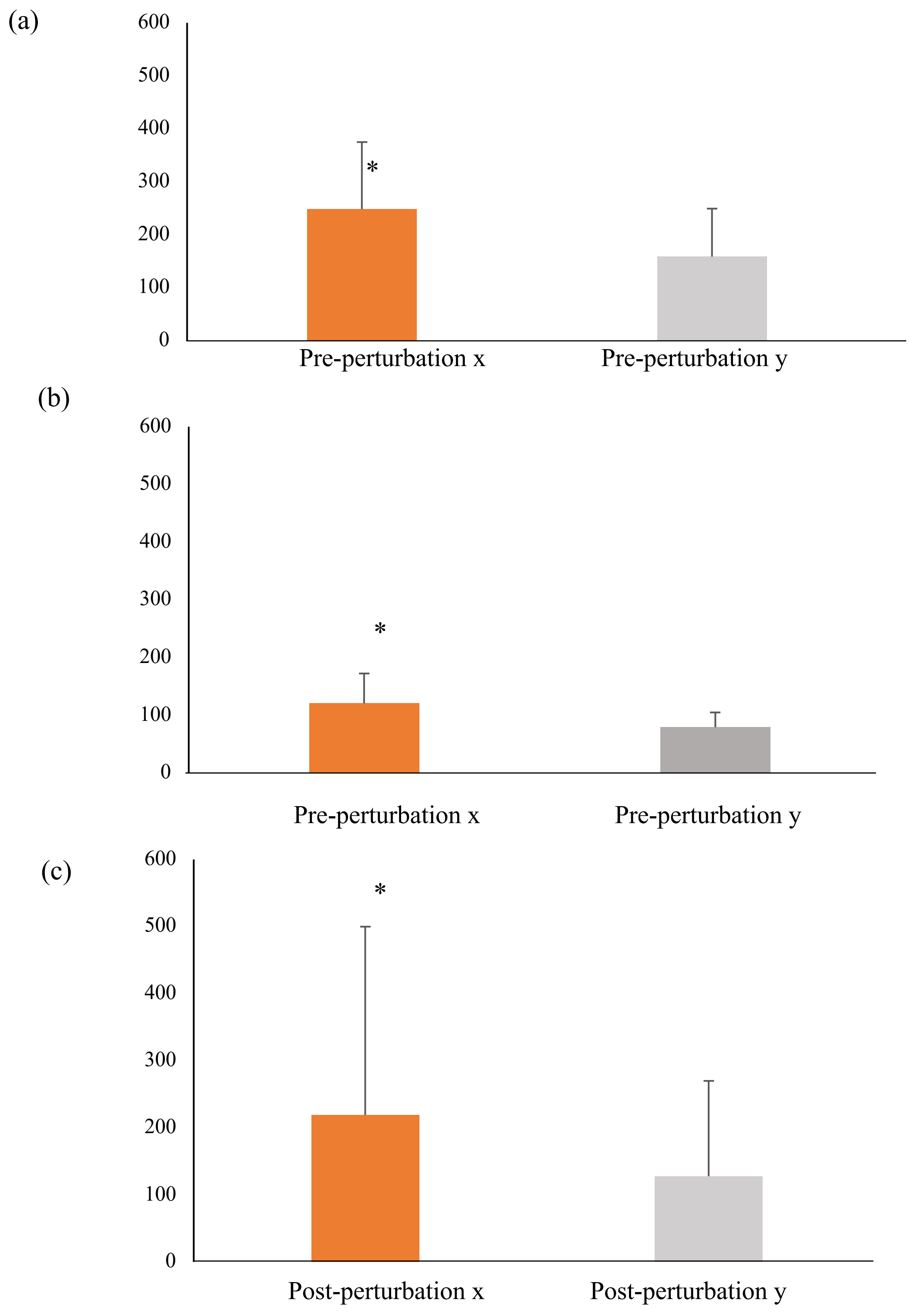

Figure 11. Mean COP path lengths of the unperturbed, pre and post-perturbation trials, separated into the x and y directions. (a) The mean COP path lengths in the x and y directions for the participants unperturbed trials (b) The mean COP path lengths in the x and y directions pre-perturbation (c) The mean COP path lengths in the x and y directions post-perturbation. (* indicates statistical significance, $p < 0.05$)

3.2 mBESS results

3.2.1 The effect of the mBESS stances on error scores

Table 4. Mean error scores and standard deviations, and the mean COP path length and standard deviations for each of the three mBESS stances.

	Error scores		COP path length (mm)	
	Mean	Standard deviation	Mean	Standard deviation
Double leg	0.08	0.07	339.05	138.08
Single leg	1	0.26	1692.37	1041.72
Tandem leg	0.23	0.15	1247.90	1152.31

A one-way repeated measures ANOVA revealed there was a significant effect of the mBESS stance on error scores, ($F_{2, 22}$ = 20.88, p = 0.002, n_p^2 = .635). The SL stance induced significantly higher error scores compared to the DL and TL stances. The DL stance induced a significantly lower mean number of error scores compared to the SL and TL stances. The TL stance induced a significantly greater number of mean error scores compared to the DL, but significantly fewer than the SL. Of the total mean number of mBESS error scores, the SL stance errors accounted for 67%, the TL 31%, and the DL stance 2% of the total errors scored.

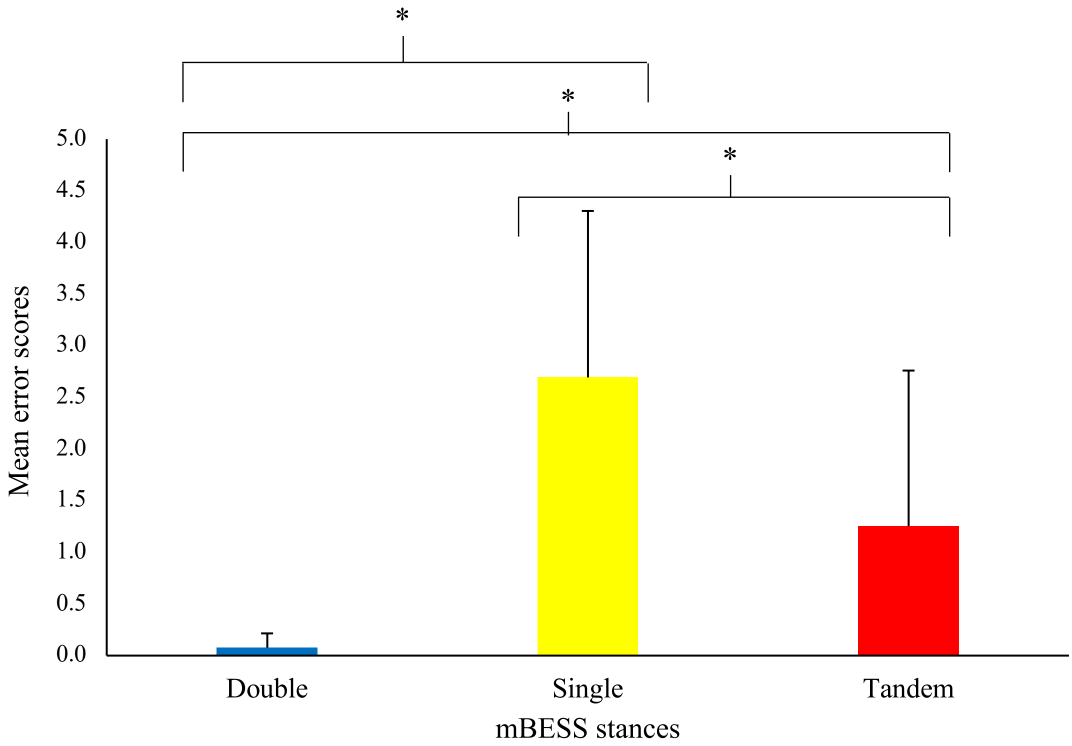

Figure 12. M ± SD for the error scores for each of the three mBESS stances. All trials were video recorded and assessed offline by seven independent assessors, (*p<0.05).

<u>3.2.2 Inter-rater reliability of the mBESS</u>

The Intraclass correlation coefficient (ICC) values for the SL, DL and total error scores were calculated to assess the inter-rater reliability of the mBESS assessment (Table 4). Both the SL and total error scores are shown to have fair inter-rater reliability, with the DL and TL stance having poor inter-rater reliability. The majority of error scores for the DL was 0, therefore the low ICC values can be attributed to the lack of variability between the error scores.

Table 5. Inter-rater Intraclass Correlation coefficient values.

	Intraclass correlation	95% Confidence Interval	
		Lower Bound	Upper Bound
Double leg	.043	-.058	.280
Single leg	.438	.225	.711
Tandem leg	.330	.134	.623
Total	.443	.229	.715

3.2.3 The effect of the mBESS stances on COP path length

Figure 12 highlights a representative data sample from one participant, showing COP deviations for each of the mBESS stances in both the x (*Figure 12a*) and y (*Figure 12b*) directions. The stabilogram in Figure 12c highlights the participant's DL trial, as represented by the blue trace line, is shown to remain centrally in both the COPx and COP y directions, with a small total COP path length indicating the individual was able to retain their postural stability. The red trace line indicates the participant's TL stance trial. Similarly, to the DL stance trial, the COP path in for the participant's TL stance trial remains fairly central, with a somewhat larger total COP path length. This is in contrast to the participant's SL stance trial as shown by the yellow trace line, which shows a larger total COP path length, indicating the individual was less able to retain their postural stability.

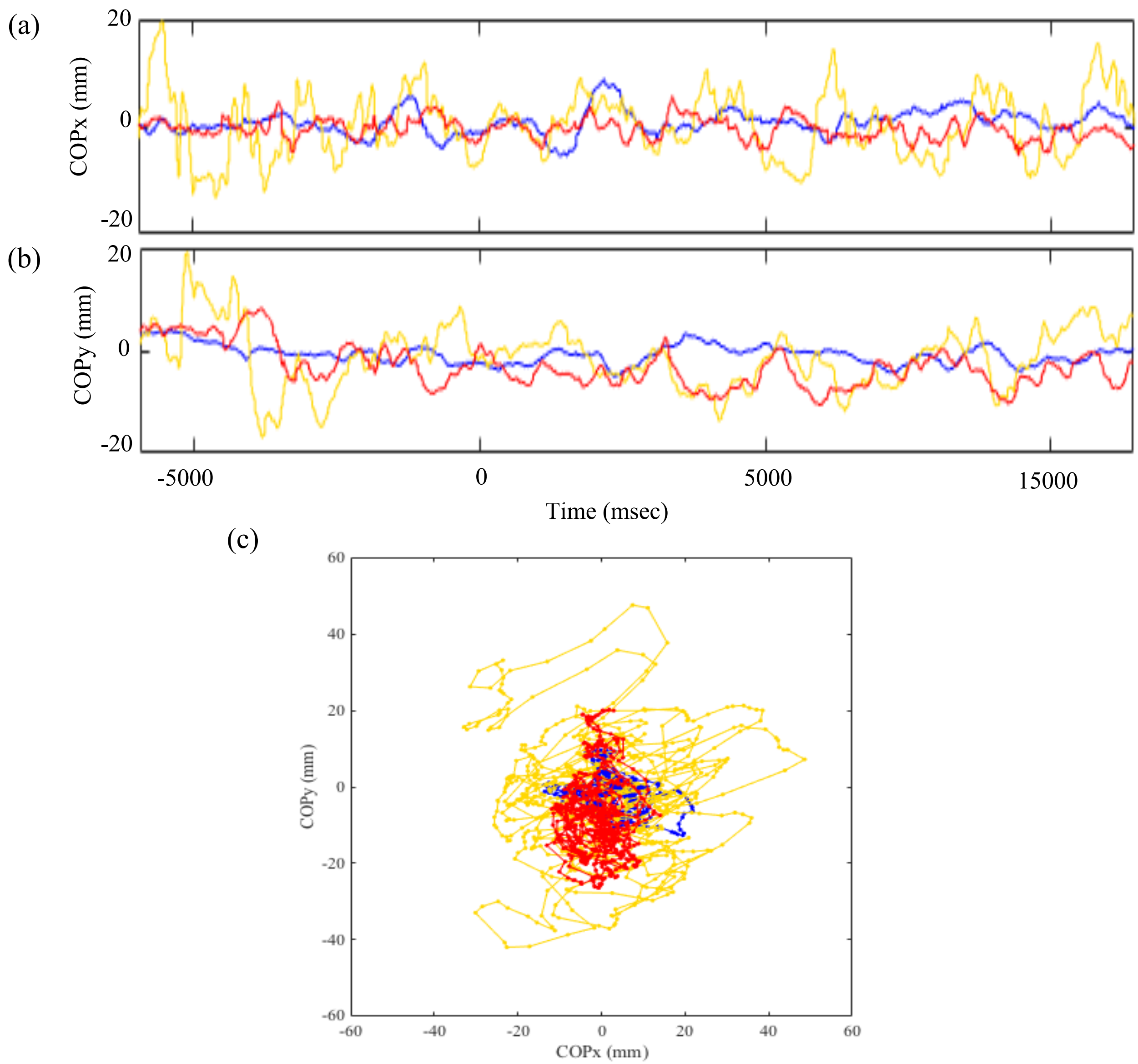

Figure 13. Representative data sample from a single participant highlighting the mBESS DL (blue), SL (yellow) and TL (red) stances. (a) COP deviations are shown in the x-axis for the participant's DL, SL and TL trials. (b) COP deviations in the y-axis are shown for the DL, SL and TL trials. (c) The stabilogram outlines the COP path data traces of the DL, SL and TL trials, in the x and y directions.

The effect of the mBESS stances on mean total COP path length was assessed using a one-way repeated measures ANOVA, revealing the mBESS stances had a significant effect on mean total COP path length, ($F_{2, 24} = 11.22$, $p = 0.000$, $n_p^2 = .48$). The DL stance induces a significantly lower mean total COP path length compared to both the SL and TL stances. There is no significant difference in mean total COP path length between the SL and TL stance. In terms of a total COP path length value, the DL stance accounted for 10.4%, the TL 38% and the SL 51.6%.

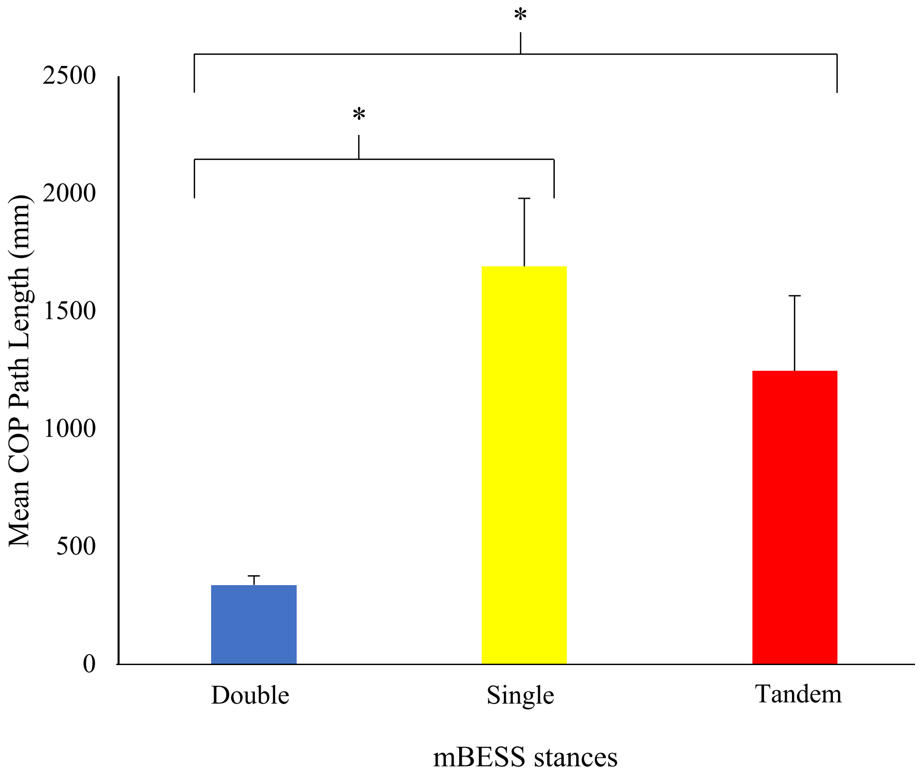

Figure 14. Mean total COP path length data collected from the WBB for the three mBESS stances, (*significance indicated at p <0.05).

The DL stance induced significantly fewer errors, via both the error scoring method, and significantly lower mean total COP path length measures, via the WBB, than the SL stance. Or vice versa, the SL stance induces significantly greater error scores and COP path length measures than the DL stance. Both assessment measures show that the DL and SL stances are significantly different. However, differences were observed between the objective COP measures and the subjective error scoring method for the TL stance. Using the error scoring method, the TL stance induced significantly more errors than the DL stance and significantly less than the SL stance. However, using COP measures, the TL stance induces significantly greater COP path length compared to the DL stance, however, it is not deemed significantly different to the SL stance. In addition, using the mBESS error scoring method the SL accounted for a larger proportion of the total mean number of errors scored (67%), in comparison to its contribution to the mean total COP path length value (52%). This may be due to the fact that for the mBESS error scoring method the DL stance accounted for only 2% of the overall total score.

3.2.4 Correlation between the mBESS error scores and mBESS COP path lengths

A Spearman rank order correlation analysis was conducted between the mBESS error scores and COP path lengths. The SL stance error scores significantly correlated with SL stance COP path length (r = .684, p = 0.01). However, TL stance error scores did not significantly correlate with TL stance COP path length. The lack of a significant correlation between the DL error scores and DL COP path length could be attributed to the lack of variability within the error scores, as many participants recorded 0 errors.

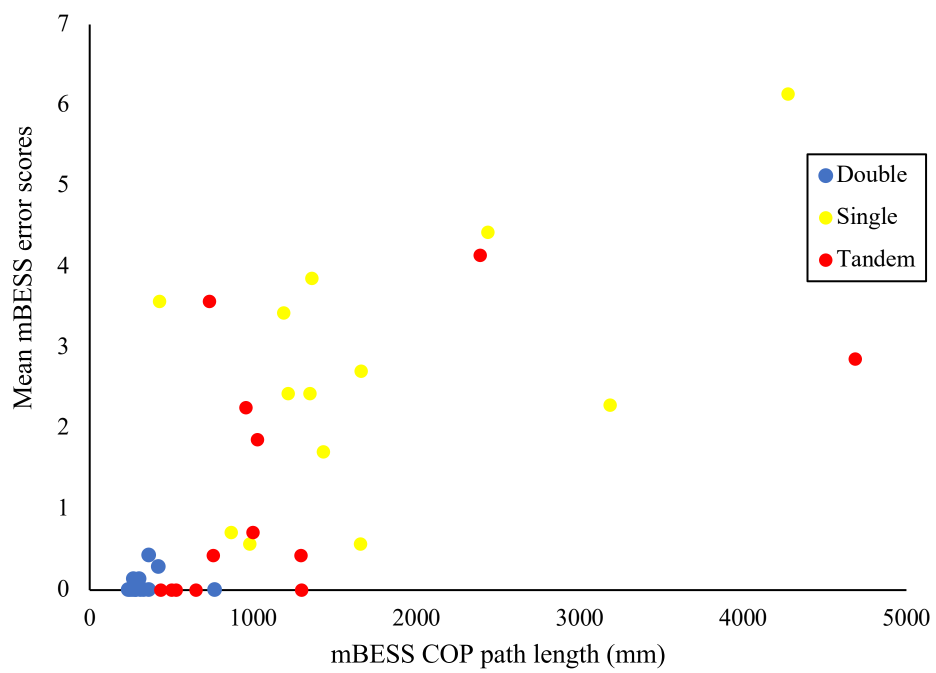

Figure 15. Correlation between COP path length and mean error scores for each of the mBESS stances. Each individual marker is representative of one participant's DL, SL or TL stance. The DL stance is represented by the blue open dots, the SL with the yellow, the TL with the red, respectively.

<u>3.3 Correlation between SL error scores and COP path length percentage change from pre to post-perturbation</u>

A Pearson correlation coefficient analysis identified that a significant correlation exists between COP path length percentage change from pre to post-perturbation, and SL error scores ($r = .692$, $p < 0.05$).

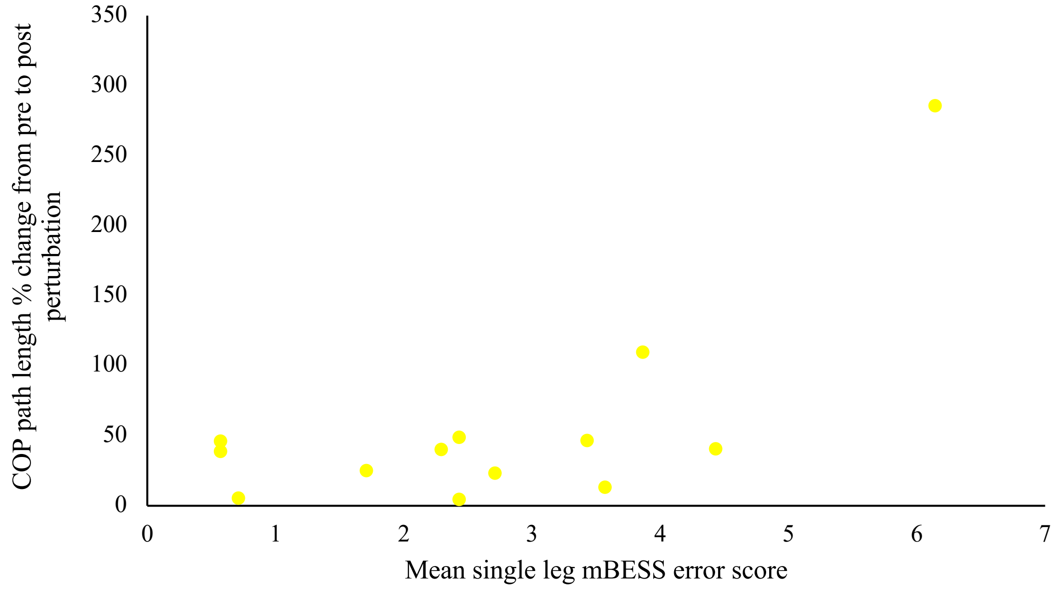

Figure 16. Correlation between COP path length percentage change from pre to post-perturbation and SL error scores.

CHAPTER 4. DISCUSSION

This thesis describes a novel VR based dual-task test designed as a pitch-side concussion assessment tool. The primary aim of this thesis was to test the ability of a novel VR WBB system to evoke perturbations within a visual scene to assess changes in COP path length, in a pitch-side environment. With the secondary aim to compare the novel VR WBB system against the currently accepted standard mBESS assessment. The primary objective of the current study was achieved as the test evoked visual perturbations and quantified the resulting balance response by assessing the changes in the COP of the body's centre of mass via a WBB. The COP path length following the onset of a perturbation tilt was significantly greater than pre-perturbation COP path length, indicating the tilt induced a measurable postural instability in healthy individuals. The use of a WBB and Oculus VR headset in the current study, overcomes many of the problems seen in much of the previous research, as laboratory limited force plates or large VR systems, are greatly plagued by their vast expense and portability issues (Slobounov et al., 2006; Wright et al., 2015). The portable nature of the VR system in a pitch-side environment is essential in the acute assessment of standing balance following a concussion sustained in a sporting setting. The effectiveness of the objective VR WBB system in the assessment of balance deviations, allowed for comparisons to be made between the novel VR test and the currently accepted standard mBESS, achieving the second aim of this thesis. A significant correlation was found between the SL error scores and the percentage change in COP path length from pre to post perturbation. The outcome measures of the mBESS and VR system significantly correlated, as those participants who performed more SL errors on the mBESS assessment, also evoked a greater COP path length percentage change from pre to post-perturbation. The ability of the VR system to produce objective COP measures which correlate with currently accepted standard mBESS error scores, heightens its appeal for use in the assessment of standing balance.

4.1 Novel pitch-side VR balance assessment

The VR WBB system was effective in evoking postural instability, as measured by significant increases in COP path length following the onset of a perturbation, compared to pre-perturbation, in a pitch-side environment (*Figure 10a*). In much of the previous research within the field, a gold-standard force plate has been adopted to objectively measure postural stability (Clark et al. 2010). The utilisation of a WBB in the present study overcame problems seen with the expensive and laboratory limited nature of the force plate. The portable nature allowed for ease of use at the pitch-side and the relative low cost of the VR WBB system allows the assessment to be reproduced and used on a large scale. The assessment of balance using a VR system cannot be considered in isolation, as the appeal of the VR technology lies in its flexibility to integrate different baseline and post-concussion measures, such as the assessment of neurocognition.

It has been suggested that the WBB is less sensitive in the detection of subtler balance deficits, however, this is largely overcome by the ability of the board to obtain reliable COP measures (Pavan et al., 2015), and by its portable nature. Pilot testing of the WBB outlined by Wilkinson (2017), ensured the WBB was a valid tool in the measurement of standing balance compared to a gold-standard force plate, corroborating the work of Clark et al. (2010) and Pavan et al. (2015). Performing the same stances on the force plate and WBB separately, Clark et al. (2010) identified that the WBB had good to excellent COP path length test-retest reliability, both within-device, and between-device for DL and SL stances. Our own piloting procedures ensured the WBB was able to detect deviations in COP in response to the induction of manual perturbations (Wilkinson, 2017). Comparing the same signals obtained simultaneously from a stacked WBB and force plate system was essential in eradicating any large differences that may arise from repetitive testing of standing balance. This procedure was similarly adopted by Pavan et al. (2015), who assessed the standing balance of 28 healthy individuals, adopting a DL stance with their eyes open and closed. Comparisons between the stabilograms obtained simultaneously by the WBB and force plate, showed a good superimposition of the COP measures (Pavan et al., 2015). The WBB has been shown to be a valid tool for the objective measurement of standing balance, with its relative low-cost and portability further heightening its appeal.

The use of the Oculus HMD device and laptop computer also allowed for easy use at the pitch-side. The portable nature of the current testing procedure is essential in the assessment of sporting concussion injuries, where it can be effectively used next to the field of play, for example in stage 2 of the HIA procedure, following initial tests of alertness on the pitch. The aspect of portability has plagued much of the previous research within the field, as large screen televisions (Wright et al., 2015), and harnessed projector systems (Slobounov et al., 2006) are unsuitable for use at the pitch-side. The use of large television screens or projectors as the medium of VR, also does not adaptively change to the user's head movements, preventing a sense of immersion within the system (Chiarovano et al., 2015). The Oculus HMD device contains micro-electrical-mechanical sensors, including a magnetometer, accelerometer, gyroscope, and a sensor which is able to track the position of the headset. Information from the sensors is combined, which determines the head motion of the user in the real world, in turn, synchronising the view of the user in real-time. This allows the visual display to move in the opposite direction to the head. This enables the participants to feel immersed within the system. This was confirmed by the results of the post-immersion questionnaire whereby participants indicated that they felt fully immersed within the VR system (*Table* 3).

Traditional paper and pencil, and computerised tests are widely used within the field of neuropsychological assessments. However, there is a need to develop neurocognitive tests that evaluate the individual in situations as close to real life as possible, not in a laboratory environment (Chaytor & Schmitter-Edgecombe, 2003). Teel et al. (2013) integrated the Stroop test into the SOT, enabling the simultaneous assessment of both balance and cognition. The integration of dual-task approach induced slower reaction times and moderate to high levels of reliability for cognitive balance tasks. In a sporting context athletes are required to simultaneously process motor, sensory and cognitive information (Broglio et al., 2005). The VR system is an excellent platform in which to integrate assessments of cognition and balance. The novel integration of a dual task Stroop test within the VR balance test has progressed and expanded beyond much of the previous research within the field (Slobounov et al., 2006; Parsons et al., 2011; Wright et al., 2015). The Stroop task was implemented within the current testing procedure to provide an aspect of immersion and to detract the individual's attention from focusing solely on their balance. This was shown to be an excellent immersive measure, with participants sensing themselves to be 'very much within the VR environment', as indicated in Table 3. In addition, the concurrent assessment of an individual's balance and cognition allows for the detection of more subtle deviations in COP measures and deficits in cognition (Guskiewicz and Broglio, 2011). In healthy individuals, there is an added cost to cognitive functioning via the integration of cognitive and balance assessment.

The current study did not assess cognition via the integration of the Stroop task, as it was simply used as a measure of immersion. However, if the Stroop or other cognitive measures were to be marked or assessed by an investigator whilst the individual conducts the balance assessment, a comprehensive assessment of cognition could also be established. It is not the integration of the specific Stroop task that is highly notable, but rather the capability of the VR system to integrate a multitude of other dual-task assessments. The symptoms presented following each concussion are unique to the individual, spanning a plethora of different categories (*Table* 1). The VR system not only has the ability to effectively assess deficits in standing balance within the physical symptom domain, but also a multitude of neurocognitive symptoms. The Stroop task concentrates on one area of cognition, whereas other tests can be integrated to assess aspects of cognition such as reaction time or concentration. Numerous assessments such as the Rivermead Behavioural Memory Test and the Test of Everyday Attention have already been integrated within a VR environment (Negu et al., 2016). VR based neurocognitive assessments have been shown to detect significant differences between healthy individuals and those with a brain injury, they are sensitive in detecting abnormal cognitive functioning (Negu et al., 2016).

The potential of the VR system to assess and provide objective data on two key areas of post-concussive symptoms is highly promising. The simultaneous nature of dual-task assessments also aids in a practical sense in the reduction of additional equipment and time needed for assessment. The dual-task paradigm adds to the heightened sensitivity in the detection of subtle and residual post-concussive balance deficits similarly seen in the VR system. The addition of a dual task alongside the assessment of COP measures through the use of a VR based approach heightens the novelty of the assessment.

4.2 The effect of VR unperturbed and perturbation trials on COP path length

The larger deviations, expressed as a percentage increase, in the participants mean total COP path length during the first perturbation trial are indicative of postural instability. It is vital that the perturbation trials are randomised and unexpected in nature. It is assumed that once a participant experiences the first perturbation trial, they will somewhat anticipate a further perturbation during the test. The first perturbation trial is perhaps the most important indicator of one's ability to remain postural stable.

The first two trials experienced by the participants were always unperturbed trials, in order to assess baseline stability. During the perturbation trials, prior to the onset of the random tilt, relatively small deviations in COP path length in both the x and y directions are observed, as shown in Figures 8b and 8c. An involuntary compensatory sway response movement in the opposite direction of the perturbation tilt in the x-axis direction is performed in order to maintain equilibrium, following the onset of the perturbation. Compensatory postural adjustments are triggered by sensory feedback signals, aiding in dealing with the effects of an unpredictable perturbation (Gago et al., 2016). The moving visual scene in a VR environment conflicts the somatosensory and vestibular system perceptions, as the body does not actually move. A postural reaction to the visual perturbation is shown by deviations in COP path length following the onset of the perturbation, compared to pre-perturbation.

Following the onset of an unexpected perturbation, there is a delay in the onset latencies of the postural muscles, therefore more time is required to stabilise COP (Woollacott and Shumway-Cook, 1990). Via mechanical moveable platform perturbations, it has been established that postural latency responses range from 70-180ms, and reaction times from180-250ms (Nashner, 1982). Visual stimuli are proposed to trigger slower postural compensations compared to mechanical perturbations (Nashner, 1982). In a combined VR and EEG study, Slobounov et al. (2013) found that the time needed to react to an unpredictable visual perturbation is 469 ± 39 ms. In the current study, the mean postural latency response to the virtual visual perturbation was 809 ± 18 milliseconds. Visual perturbations caused by moving visual images, may cause postural reactions in response to perceptions of instability as opposed to actual disequilibrium (Horak et al., 1997). Dual-task systems, whereby both tests balance and cognition and simultaneously conducted, have been shown to significantly increase postural reaction time, in comparison to a single task paradigm (Tsang et al., 2016). The integration of the dual task Stroop test within the VR system, alongside the use of virtual perturbation tilts may explain the larger postural latency responses identified in the current study.

The current study adopted a perturbation tilt speed of 7.5°/second. Previous unpublished laboratory work identified that the chosen speed was within a defined range of speeds (5.6°/second-11.3°/second) which elicited greater COP path lengths, compared to a slower speed of 4.5°/second. Henceforth, it took a total of 3 seconds from the onset of the perturbation tilt until it ceased.

The short duration of the perturbation tilt provides individuals with a small insufficient window in which to adjust their COP response, which may explain why it took participants a longer duration of 809 ± 18 milliseconds to respond, in comparison to values reported by Nashner (1982). The physical perturbation tilt speed of the movable platform used by Nashner (1982) was 20°/second, which was faster than the visual perturbation speed utilised in the current study. The slower visual perturbation tilt speed adopted in the current study and the different method of perturbation, may explain the longer postural latency response.

Furthermore, Nashner (1982) did not use a visual medium of VR to initiate a perturbation tilt, but rather physically perturbed the balance platform itself, which may also explain the discrepancies in the latency of the postural response.

Within the perturbation trials, the mean COP path length following the onset of the first perturbation tilt was greater than before the onset of the first perturbation tilt. The total COP path length increased by 94.9% ± 73.4, following the onset of the first perturbation, compared to before the perturbation onset. This was the largest percentage increase in COP path length observed between the onset of the five perturbation tilts. Essentially, it is the first perturbation that is unexpected to the participant, which has shown the greatest percentage increase in COP path length. Unexpected perturbations within a visual scene have been shown to evoke stronger modulation of the frontal-central EEG theta activity prior to the onset of the unpredictable postural perturbations, when compared to expected perturbation tilts (Slobounov et al., 2013). The additional demands placed on the brain by the unexpected perturbation tilt within the postural task is shown to be destabilising to postural stability, as individuals are unable to prepare an appropriate motor solution in order to retain their balance.

Analysis of the mean COP path length pre and post-perturbation onset for the four perturbation trials experienced by each participant was assessed to explore the presence of habituation. Habituation is described as "a behavioural response decrement that results from repeated stimulation and that doesn't involve sensory adaptation/sensory fatigue or motor fatigue" (Rankin et al., 2008). It is assumed that once a participant experiences the first perturbation trial, they will then become habituated to expect further perturbation trials and adjust their COP accordingly. No significant habituation effect was identified prior to the onset of the perturbation tilt, or post-perturbation, between the four perturbation trials.

Furthermore, a significant effect of time was also identified for the mean COP path length percentage change from pre to post-perturbation tilt for the four perturbation trials (*Figure* 10b). This indicates the presence of a habituation effect, whereby over time with repeated perturbations, the differences in the COP path length percentage change from pre to post perturbation is decreasing. The post-hoc analyses revealed that no significant differences in COP path length % change from pre to post-perturbation were identified between the four perturbations over time. However, a clear trend is evident, highlighting a reduction in the COP path length % change from pre to post-perturbation over time with each perturbation trial. It is essential that the perturbation tilts remain unexpected to the individual, so they cannot prepare an appropriate balance solution, which may mask the true effect of the perturbation tilt on standing balance.

It is essential that the VR system is refined to make it shorter and appropriate for the acute pitch-side assessment of standing balance in athletes. The greatest percentage change from pre to post-perturbation was evident in the first perturbation trial. Therefore, only one or two perturbations may be necessary to evoke a destabilising balance response, and subsequently assess standing balance. In the present study the individuals experienced numerous unperturbed trials, whereby the visual scene remains un-tilted for the duration of the 20 second trials. The two initial unperturbed trials at the start of the VR test were used to immerse and settle the participants within the system, and assess baseline postural stability, prior to experiencing any destabilising perturbation trials. The nature of the perturbation trials within the VR system inducing the perturbation tilt between 5-10 seconds from the trial onset, allow for the assessment of pre-perturbation COP path length, which acts in a similar manner to the unperturbed trials. In the further refining of the VR system, the need for the unperturbed trials in the acute pitch-side assessment of balance deficits may not be necessary. The presence of a habituation effect may be negated by the reduction in the number of trials experienced within the VR assessment. On the other hand, in the longer term assessment of balance deficits that may be evident with a concussion injury, the ability of an individual to habituate to a perturbation tilt may be cleverly utilised. Patients with Parkinson's disease have been shown to habituate slower to balance perturbations in comparison to a healthy control group (Nanhoe-Mahabier et al., 2012). Therefore, it could be postulated that a concussed individual may be less able, or even completely unable, to become habituated to the effect of a destabilising perturbation tilt. Whilst the reduction in the number of perturbation tilts may be necessary in the acute assessment of standing balance, investigating the how an individual responds to the effect of repeat perturbations may also be warranted.

All the participants were perturbed in the VR system within the x-axis roll condition. Previous research conducted by Slobounov et al. (2006), and development work of the VR system in a laboratory environment, confirmed that perturbations along the roll axis were more destabilising to postural stability than the y-axis pitch condition. The COP data extracted from the WBB not only provides an insight into the path length before and after a perturbation tilt, but also records the direction of COP path length sway. This can be seen clearly in the stabilogram (*Figure* 9d), whereby an ellipse is drawn identifying the direction of movement of the individual's COP path length. It is expected that perturbations along the roll axis, will produce greater COP deviation within the x-axis, medial-lateral direction. This is identified in Figure 11c, whereby, for post-perturbation the mean COP in the x direction was significantly greater than the mean COP path length in the y direction. The participants must produce a compensatory sway response in the opposite direction to the perturbation tilt in order to retain their postural stability.

This trend was similarly seen in the unperturbed trials and pre-onset of the perturbation tilt, whereby even with no tilt in the visual scene the mean COPx was also significantly greater than the COPy path length. The VR balance assessment adopted the DL stance position with the feet placed together in turn reducing base of support. By reducing the base of support, an increased balance response along the x-axis would be expected as the body will sway more in the mediolateral direction. Therefore, even without the induction of a perturbation tilt COP path length in the x-axis direction is significantly greater, which may be partly attributed to the reduction of one's base of support on the board.

The exact involvement of the sensory systems in postural control post-concussion is poorly understood, however, it is believed that it is a mismatch between these visual, vestibular and somatosensory systems that are responsible for postural deficits. Henceforth, perturbations within the visual field have been shown to exacerbate the destabilising postural response even in healthy individuals. The tilt about the x-axis can be confirmed as significantly destabilising to the postural stability of the healthy cohort. Following the perturbation tilt in the roll x-axis, the participants must compensate for this tilt within the VR environment by shifting their COP in the opposite direction. Previous research has identified that a VR system identifies long lasting residual balance deficits following a concussion (Slobounov et al., 2006; Wright et al., 2015).

4.3 Comparison of the mBESS error scoring method and COP path length

The mean number of mBESS total error scores recorded by the healthy participants in the current study was 4.02 ± 1.65 (expressed as M ± SD). In comparison to the current study, a higher mean number of total error scores (7.23 ± 4.65), was reported by Starling et al. (2015). Starling et al. (2015) recruited 82 collegiate football players aged between 18-22, who underwent the mBESS assessment marked in real-time by a team of neurologists. In the current study, the mBESS assessment was video recorded and marked offline by seven independent assessors. In terms of the marking of the mBESS assessments offline, no significant differences have been reported between the total error scores when marked in real-time or via video recording (Stern et al., 2014). The lower number of total error scores recorded in the current study may be due to the use of a relatively small cohort of healthy participants.

A key finding of the study completed by Starling et al. (2015), was the large degree of variability between the SL error scores of a group of non-concussed, elite athletes at baseline. This was similarly seen by the standard deviation of the SL error scores in a smaller cohort of non-concussed female athletes in the current study (2.69 ± 1.61). Furthermore, in terms of the contributions made by the different stances to the total error scores, Starling et al. (2015) similarly cohered with the current study, with the SL stance accounting for 71% of the total, 26% for the TL and less than 1 % for the DL. Further problems arise with the mBESS alongside the large variations seen in the SL stance, as it assumes that all the different stances contribute an equal weighting to the overall total scores. The current study identified that this is not the case with the SL stance accounting for 67% of the mean total errors scored, whereas the DL stance accounted for 2%. The total mBESS error score may not be an appropriate measure of standing balance post-concussion, specifically due to the large contribution of the errors performed during the SL stance. Starling et al. (2015) corroborates this notion, suggesting the SL stance could be eliminated from the mBESS protocol, as the DL and TL stances may be more effective in identifying balance abnormalities attributed to concussion, rather than large deviations and variations within the SL stance.

In the current study, the mBESS assessment was marked offline by seven independent assessors, in order to assess the inter-rater reliability of the mBESS assessment. The current study identified the ICC's for the DL (.043), SL (.428), TL (.330), and total (.443) error scores between the seven assessors. ICC inter-rater reliability measures of less than 0.40 are identified as poor, 0.40-0.59 as fair, 0.60-0.74 as good, and 0.75-1.00 as excellent (Cicchetti., 1994). Fair inter-reliability measures are shown in the current study for the SL and total error scores, and poor inter-rater reliability for the TL and DL stances. The poor inter-rater reliability reported for the DL stance error scores could be attributed to the lack of variability identified, as 9 out of the 13 participants recruited in the current study recorded no error scores for this stance.

Riemann et al. (1999) used three individuals to simultaneously mark the mBESS assessment, in order to assess intertester reliability. Excellent inter-tester reliability was identified between the error scores of 18 elite male varsity athletes, 0.93 for the SL, and 0.96 for the TL. The poor to fair inter-rater reliability identified for the mBESS error scores in the current study, may be due to the greater number of independent assessors utilised in the current study, and their experience in assessing the mBESS. Another potential explanation for the poor to fair inter-rater reliability reported in the current study, is the subjectivity present in the mBESS assessment itself. The detection of the error classifications is somewhat difficult to identify (*Table 3*), such as the visual identification of a subject's hip moving into more than 30° of abduction or flexion (Finnoff et al., 2009). Furthermore, if a participant performs many errors simultaneously or in rapid succession, this may be extremely hard to identify (Finnoff et al., 2009). The subjective nature of the mBESS assessment undoubtedly contributes to the poor to fair inter-rater reliability measures reported.

Differences in the error scores reported in the current study compared to those published by Starling et al. (2015), may also be due to a number of other factors. All the participants recruited in the current study were female, as opposed to Sterling et al. (2015) who recruited all male varsity athletes and reported higher mean error scores. Whilst this is important to note, Iverson and Koehle (2013) have reported no gender differences between mBESS error scores. From a sporting perspective, differences in ankle and knee proprioception between trained athletes and matched controls suggest that challenging the sensorimotor systems via participation in sport, may enhance postural stability (Bressell et al., 2011). The environmental demands and sport-specific skills are likely to pose different sensorimotor challenges that could potentially influence the balance abilities of athletes (Bressell et al., 2011). Bressel et al. (2011) reported higher BESS error scores of female basketballers when compared to gymnasts and soccer players, demonstrating inferior static balance. There is no evidence assessing the mBESS performance of hockey players, therefore, sport-specific balance abilities cannot be overlooked when exploring the variation in error scores between the current study and published literature within the field.

The current study corroborated that the mBESS error scores are proposed to increase in difficulty from the DL, to TL and the SL (Riemann et al., 1999). The SL was found to be the most difficult stance, as it induced a significantly greater number of error scores compared to the DL and TL stances. In terms of the error scoring method, the SL stance has been shown to induce greater postural instability than the DL and TL stances. This heightened postural instability is most likely the result of the essential reorganisation of centre of gravity over a narrow and sort base of support (Riemann et al., 2003). Although all participants in the current study were able to complete all the mBESS 20 second trials, including the SL stance, the reduction in one's base of support makes increased compensatory movements and falls frequent (Riemann et al., 2003).

The conduction of the mBESS assessment on the WBB allowed for objective COP measures to be obtained for each of the stances. The WBB approach can provide identical scoring regardless of the operator (Chang et al., 2014), whereas the mBESS error scores can vary greatly between raters (Bell et al., 2011). The mBESS stances had a significant effect on COP path length. The TL and SL stances induced significantly greater mean COP path lengths than the DL stance. No significant differences were found between COP measures between the SL and TL stances. This is to be expected as the DL stance provides a base of support twice as large as both the SL and TL stances, with the SL stance having the smallest base of support in both the anterior-posterior and medial-lateral directions (Palmieri et al., 2002).

Previous research within the field has been conducted to assess the mBESS error scoring method and sway velocity measures using of a portable force plate. Alsalaheen et al. (2015) identified that a significant relationship exists between BESS error scores and sway velocity for the SL ($r = 0.72$, $p < 0.001$) and TL ($r = 0.70$, $p < 0.001$) stances performed on a level surface. Correlational analyses were unable to be conducted between the DL stances and sway velocity due to the lack of variability due to the lack of errors scored for the condition. Similarly, low correlational analysis values were reported in the current study for the DL stance, as very few subjects recorded an error scores for the condition. Furthermore, the current study identified that only the mBESS error scores and COP measures for the SL stance were significantly highly correlated ($r = .684$, $p = 0.01$). This may be due to the relatively higher number of error scores recorded during the SL stance. No significant correlations were found between the mBESS error scores and COP measures for the DL and TL stances, respectively.

Differences between the two outcome measures of the mBESS assessment are evident. All stances of the mBESS error scoring method, were deemed statistically different. The SL stance induced a greater number of errors compared to the DL and TL. The DL stances induced significantly fewer errors than the SL and TL. Whereas, the TL stance induced a greater number of errors than the DL, but less than the SL. However, the mBESS COP measures identified there were no significant differences between the SL and TL stances. Like the SL stance the TL stance consists of a decrease in stance width, however it also consists of an increase in the length of the support base (Jonsson et al., 2005). In addition, the TL stance has a narrow medial-lateral support base resulting in increased unsteadiness in the medial-lateral direction, henceforth is not a stance for equal weight bearing (Jonsson et al., 2005). The rolling of the ankle joint along the medial-lateral direction was commonly seen as the participants performed the TL stance. This unsteadiness in the medial-lateral direction was highlighted by large deviations in COP path length as detected by the WBB. However, the mBESS error classifications as reported in Table 3, only state the 'lifting of the forefoot or heel' as an error score. There is no error classification for the rolling of the ankle seen with the unsteadiness in the medial-lateral direction in the TL stance. This may explain why the error scores for the TL stance were relatively low, as opposed to the greater COP path lengths.

4.4 Comparison between the VR system and mBESS

The mBESS is still regarded as the current gold-standard concussion balance assessment tool. The mBESS is easy to administer, inexpensive, and requires no additional equipment, which heightens its appeal over other assessments of standing balance. The total duration of the mBESS assessment in the current study took a maximum time of three minutes. In comparison, the VR system requires a 5 minute equipment set-up period prior to the arrival of the participant. This allows the researchers the set up the laptop and load the appropriate Unity visual scene, connect the Oculus headset, and connect the WBB via Bluetooth. An explanation of the stance is required, alongside a pre-trial familiarisation, followed by the conduction of the 8 VR trials, takes a further 5 minutes to complete. Arguably, the mBESS is far easier quicker and easier to administer than the VR assessment, and little expertise or experience is required to mark the test, providing an almost instantaneous score of standing balance.

In order to assess the current gold-standard mBESS assessment and VR system, a correlational analysis was conducted between the SL error scores and mean COP path length percentage change from pre to post-perturbation. A significant correlation was identified between the SL error scores and mean COP path length percentage change from pre-post perturbation (.692) (*Figure* 16).

As the VR system significantly correlates with SL mBESS error scores and COP measures, it highlights that both measures effectively identify deviations in standing balance, albeit using different methodological approaches. The mBESS is a measure of static postural control, whereas the VR balance system assesses the COP response and reset of postural stability following a perturbation. The VR is able to evoke postural instability through the incorporation of perturbation tilts within the DL stance, removing the extreme variation seen within the SL stance. The VR system allows meaningful objective COP data to be collected and compared with and without the evocation of a perturbation. Furthermore, the metric of the WBB COP measures is a continuous scale and therefore does not show the same ceiling limitation as seen with the error counting method (Alberts et al., 2015). The mBESS is a simple assessment measure of standing balance but fails to provide any further information other than an error score, deduced by a series of error classifications (*Table* 3). Alternatively, the VR system also provides a plethora of information regarding the effect of a perturbation on standing balance, such as reaction time to respond to the tilt, COP path lengths in the x and y directions, and total COP path length expressed visually as a stabilogram. The appeal of the VR system is further heightened by its ability to change parameters and integrate differing perturbation tilts, and neurocognitive assessments.

All participants recorded low (0.08 ± 0.14), or no error scores in the DL stance of the mBESS assessment. However, the same participants performing the objective VR or mBESS assessment on the WBB will always record a COP path length value. For example, participants will always record a COP path length value during the mBESS or VR assessments on the WBB, without necessarily making an observable error. This highlights the discrepancies seen with the assessment measures, as regardless of the absence of an error the WBB will always detect subtle deviations in postural stability.

The mBESS error scoring method may not truly be able to detect the subtle deficits in postural stability, in the same way that COP measures are able to. As previously noted, the weakness in the medial-lateral direction when aiming to retain postural stable in the TL stance, may not be comprehensively covered by the error scoring classification system. The subjective nature of the mBESS system is also problematic, as it is ultimately the opinion of an individual marker or group markers to deduce whether an error has been performed, which is highlighted by the poor to fair inter-rater reliability reported in the current study. The appeal of the VR based assessment is further heightened over the mBESS, as the system allows the manipulation of postural stability whilst maintaining a DL stance, where very few subjects recorded an error score. Deviations in COP path length are evident via the manipulation of perturbations within the visual scene in healthy individuals.

4.5 Limitations of the current study

Some of the limitations of the present study have previously been noted in Chapter 4 of this thesis. Ultimately the assessment was only performed on healthy individuals. This was to ensure the test is appropriate and safe for pitch-side use and was effective in its ability to evoke a postural response to a perturbation tilt. Undeniably, the test must be developed and tested on concussed individuals. The small sample size and lack of variation within the selected cohort presents problems within the current study. In addition, the small sample size within the study led to the recording of relatively low and lack of variability within the mBESS error scores. This could have been expected due to the cohort consisting of young, healthy female athletes. Previous developmental laboratory work on the VR system found no significant differences in the assessment of postural stability between males and females. This corroborated the work of Iverson and Koehle (2013), who also found no significant gender differences on the mBESS. However, further investigation is still warranted into the investigation of a wider range of age groups, and the inclusion of males, on the VR WBB system.

The within-subject design of the current study allowed for the participants to perform both the mBESS and VR WBB assessment. However, each assessment was only completed once. The repeat conduction of both the mBESS and VR assessments would have enhanced the validity of the study. This would have also allowed further analysis to be performed assessing the presence of any longer term learning effects of the balance assessments. A habituation effect was detected between the VR perturbation trials over the course of one assessment. However, it is unknown whether the repeat testing of the VR balance trials would identify a learning effect. This further testing is vital, as concussion assessments needs to involve multi-time point assessments, ranging from the acute phase immediately post-injury, to the period 48-72 hours, and to the longer-term recovery of balance deficits. No one concussion is alike in terms of the initial and developing symptomatology. Therefore, it is essential that the VR WBB assessment is able to be effective in the repeat testing of individuals.

The set programming of two control trials at the start of each participants assessment was warranted to ensure a period of relative postural stability could be maintained, and baseline stability assessed, prior to the induction of a randomised destabilising perturbation tilt. The induction of set perturbations within the system could have been maintained throughout all of the participants assessments, which would have allowed for more a straightforward analysis of the results. As this is only the developmental stage of the assessment, the VR WBB assessment was only completed once by each individual, this could have been easily implemented, as there is no danger of any long-term practice effects. Moreover, in the longer-term repeat testing, the ability to randomise trials within the VR system, may further prevent any habituation. Alternatively, in the repeat testing concussed individuals, the conduction of the same trial set over a period of weeks or months, allows for the assessment of both acute and long-term residual symptoms.

The development of this particular prototype of the VR WBB test enabling it to work pitch-side did not come without minor difficulties, in comparison to the relative ease in set-up and conduction of the mBESS. The mBESS requires no technology or complex data analysis techniques in order to obtain a measure of standing balance. The WBB VR system requires custom written software in order to extract data from the WBB, and analyse the collected data through a custom MATLAB script (MATLAB and Statistics Toolbox Release 2016b, The MathWorks, Inc., Natick, Massachusetts, United States). This may not be appropriate for widespread use of the system, and the subsequent interpretation of COP measures. Each individual WBB must also be calibrated prior to gaining accurate COP measures of standing balance. This requires time and technological expertise to perform this, enabling the collection and extraction of accurate COP data. Furthermore, the Bluetooth element of the WBB and the laptop computer did sometimes fail to connect. Pagnacco et al. (2011) notes that although the appeal of the WBB is heightened by its portability, it suffers from low resolution, low and inconsistent sample rates, low signal to noise ratio, and occasional glitches, usually a temporary malfunction of the electrical equipment. In the current study one participant had an incomplete data set and had to be excluded from the data analysis, which can be attributed to a temporary WBB malfunction. If the WBB is to be utilised in the assessment of acute balance deficits post-concussion it is essential that no technological malfunctions are evident.

Furthermore, it is important to remember that the WBB is essentially a video game controller (Clark et al., 2017). WBB's are made of plastic, as opposed to a force plate which consists of metal. The WBB is susceptible to elastic deformation if an excessive load is placed on it (Leach et al., 2014). Problems may arise with the acquisition of accurate COP data measures if the WBB surface is susceptible to deformation. The WBB must also be placed upon a level surface, which may not always be possible in a pitch-side environment. The WBB may also not be suitable for larger athletes, as the surface length in which to stand on the WBB measures only 228mm. If the front or back of the participants foot is overhanging the edges of the WBB, this may lead to the obtainment of inaccurate COP measures.

If the VR system is to be used in the acute assessment of concussion at the pitch-side, all aspects must be consistently working, and ready to use at any given moment. The sometimes technological problems arising from the system may seem minor, but the notion of a potentially concussed player having to wait for equipment problems to be solved prior to being tested is simply not adequate. Battery life of the laptop computer involved in the current study was also problematic. The Unity programme software used to run the virtual environment requires large amounts of power. The constant need for the laptop to be connected to a source of power was not ideal, as this may not be feasible when testing in somewhat remote pitch-side locations.

The use of an Oculus HMD device to immerse the participants does not come without limitations. Much like the WBB, the Oculus requires a period of time to set up the device, whereby it is connected to a laptop computer. Minor problems have arisen concerning the connectivity of the Oculus HMD, as it requires a sensor to be placed on top of the laptop and multiple connecting wires. Furthermore, in order for the system to successfully immerse the participant the visual scene must be both appealing and engaging. The time and technological expertise required to create such a scene must not be overlooked. Furthermore, in the past VR HMD's have been criticised for having lower low spatial resolution associated with decreased computing power, with small delays causing movement illusions and motion sickness (Nichols and Patel, 2002). The advancement in the current technology utilised in the design of the current study ensured that previous problems with post-VR effects were overcome. Steps were taken during the current study to minimise the risk of experiencing any post-VR effects. Participants were able to stand in each of the prescribed stances with the HMD on prior to the start of any trials to ensure the device was fitted comfortably and to accommodate its small additional weight. Additionally, participants were only wearing the HMD device for a maximum of 5 minutes. The post-immersion questionnaire confirmed that participants did not experience any post-VR effects, such as dizziness, headache or nausea.

If the test is to be developed within both a sporting and clinical environment, it is essential that the equipment components of test connect correctly to ensure all COP data is correctly collected. Although many of the limitations were minor connectivity issues, these must be eradicated to ensure no technological problems are apparent prevent the test from working in an efficient manner.

4.6 Future development of the VR WBB assessment

Following the success in showing the effectiveness of the VR WBB system in a pitch-side environment on healthy individuals, undoubtedly the future development of the assessment must involve the testing of concussed individuals. It is expected that concussed individuals would perform more poorly on a VR-based balance assessment, in comparison to a control cohort (Slobounov et al., 2006). Furthermore, the promising results within the current study warrant the assessment of the effectiveness of the repeat testing of the VR WBB system, perhaps over a season long period.

If the test were to be developed for use on a concussed cohort the use of pre-season baseline testing may be essential in the individualising of balance assessments post-concussion. The use of percentage changes or significant differences between an individual's baseline VR COP measures and post-concussion measures is essential in determining if an individual has experienced changes in postural stability. There are various ways in which a concussion diagnosis could be determined through the use of the measures obtained by the VR WBB system. Perhaps, a specific value of percentage change from pre-perturbation onset to post-perturbation, from baseline to post-concussion measures could be utilised to determine if an individual has experienced sufficient postural instability to indicate a concussive injury. Alternatively, the current study only used one specific perturbation tilt speed (7.5°/second), which was chosen between a range of destabilising speeds (4.5-11.25°/second). A range of speeds of differing destabilising abilities could be adopted to determine between those individuals who are or are not experiencing a concussion. The slower less destabilising speeds could be used initially to rule out any individuals with obvious concussions, instantly differentiating them from healthy individuals. The gradual increase in speed to create a more destabilising tilt speed could then be used to assess subtler post-concussion balance deficits. This may also useful in the charting of the recovery of balance symptoms post-concussion, as the repeat testing of individuals may allow them to experience progressively more destabilising speeds, indicating they are in a period of recovery.

Large standard deviations have been identified within the relatively small healthy sample used in the present study (*Figure 10*). It is assumed that large standard deviations would also be seen in a concussed cohort, as no two concussions sustained are identical in nature. With such large differences in postural stability contributing to the mean COP path length data, this may not be truly representative of a single individuals COP sway. Due to the nature of the current study only one single testing session of the VR system was conducted by each individual. However, the results of the current study warrant the repeat testing of the VR system over a period of days, weeks or months. The creation of an individualised postural stability profile for an athlete should be considered. Clear time points in the season can be cleverly utilised in the repeat assessment of athletes, such as the collection of baseline data during the pre-season. In the same way that no two concussions are the same, it could be assumed that no two individuals baseline postural stability will be the same. The use of differing difficulties of perturbation tilts and perturbation tilt speeds could aid in the individualising of the VR balance assessments. Outcome measures such as elliptical sway area, seen in the stabilograms in Figures 9d & 13c, would provide an excellent visual representation of deviations in postural stability. This would allow the creation of individualised thresholds or the calculation of percentage changes to determine if an athlete's postural stability has improved or declined from initial baseline values. In addition, the ability of the VR system to obtain COP measures pre-perturbation allows for individualised baseline postural stability data to be collected. Furthermore, an online database of stabilograms and data from athlete's balance assessments could be stored and effectively utilised by both researchers and clinicians.

COP measurements obtained from the WBB were the main outcome measure of the VR system, however, data can also be obtained from the Oculus HMD regarding the participants' head movements. Paloski et al. (2006) identified that when the head is tilted to ±30°, postural stability is decreased. Furthermore, in the roll axis, head movement may be as increasingly important, as poor eye movement is compensated for by superior head stability (Gresty & Bronstein, 1992). Reflex eye movements which are able to effectively stabilise the eyes during perturbations along the pitch axis, are deemed inadequate in the roll axis, in turn causing visual instability (Gresty & Bronstein, 1992). The collection of head movement data could be used to assess the supposed stabilising nature of the head movements in perturbations along the roll plane of movement. If both roll and pitch perturbations were used in future VR balance assessments in order aid in the differentiation of concussed and healthy individuals, the assessment of head movement data would be warranted.

The use of a dual-task approach is particularly relevant in a sporting context, as it requires the simultaneous processing of motor, sensory and cognitive information (Broglio et al., 2005). The integration of different neurocognitive assessments within the system will also be explored, in order to utilise the flexibility and novelty of dual-task nature of VR balance test. The novel use of a cognitive dual task Stroop test within the VR system has paved the way for the implementation of other cognitive tasks. Although in the current research the Stroop was merely used an immersive measure, the VR technology has the flexibility to integrate other cognitive assessments in to the system. Therefore, the test could not only be used as an assessment of balance, but also cognition.

If an alternative dual cognitive task were to be integrated within the system and tested on concussed individuals, the cognitive scores would be expected to decrease in comparison to healthy controls (Broglio and Puetz, 2008). Furthermore, if the current test were to be performed by concussed individuals, a greater number of incorrect Stroop answers would be expected (Guskiewicz and Broglio, 2011). The novel integration of a dual task assessment within the VR test, may not only provide immersive qualities, but also an assessment of cognition. The flexibility of the VR system lends itself to the integration of different cognitive assessments, and the repeat testing of athletes over a season long period. This precise nature of the assessment may aid in the prevention of a learning effect, whereby individuals can experience a multitude of different assessments within the VR system. The assessment of concussion must be multi-faceted, due to the range and development of signs and symptoms presented post-concussion. Hence, the inclusion of the assessment of various neurocognitive assessments would be invaluable, adding to the uniqueness and novelty of the assessment.

The VR technological aspect of the test provides an exciting, engaging and interactive way for individuals to experience concussion testing. This fast advancing field has provided many new opportunities to expand and develop the VR WBB system used in the current study. It is hoped that the test will be further refined, adopting the use of a Samsung VR headset, in which a mobile phone is integrated within the actual HMD device. This will mean the laptop computer will not being needed during the actual assessment phase of the test, as the VR visual scene along with the neurocognitive task will be viewed through the HMD via the mobile phone. This is also a wireless system, removing the need for connection wires between the HMD and mobile device. The use of an accelerometer system strapped to the body, would also remove the need for the WBB. This would also mean that a Bluetooth connection between the equipment would not be necessary, preventing any minor technological difficulties as seen in the present study. By reducing the number of separate components of the VR system, this will also aid in decreasing the set-up time required, enhancing its usability over current assessments.

4.7 Conclusion

This thesis identified that the novel pitch-side VR WBB system was effective in evoking a balance deviations through the use of perturbation tilts within a visual scene. This was indicated by significantly greater COP path length measures following the onset of the perturbation tilt in comparison to before the perturbation onset. The novelty of the study is further exemplified by the integration of a dual-task Stroop test, ensuring participants are immersed within the virtual environment, preventing attention focusing solely on their balance. Mean COP path length was significantly greater following the onset of a perturbation tilt, compared to prior to the onset. The perturbation tilts were destabilising to the participants, resulting in a compensatory sway response being employed in order to remain posturally stable. Outcome measures for the VR and mBESS assessments significantly correlated, as the mean COP path length percentage change from pre to post-perturbation significantly correlated with the mBESS SL stance error scores.

The rapid and relative ease of use of the mBESS contributes to its appeal. However, it is plagued by its subjective nature, and lack of information provided by its outcome measures. As seen with the DL stance error scores, none of the participants in the current study recorded an error score, deducing their postural stability to be error free. On the other hand, the VR WBB system has been shown to effectively evoke changes in COP path length through the use of perturbation tilts, always resulting in the recording of a value, highlighting subtle deviations in COP. The discrete mBESS error scores obtained via the observations of an assessor are much less sensitive than the continuous COP path length data extracted from the VR WBB system. The integration of alternative neurocognitive tests, and the further exploration of key parameters within the VR system in both concussed and healthy cohorts is highly warranted. This will aid in the refining of an effective, inexpensive, portable pitch-side concussion balance assessment tool, which can be individually tailored to allow comparisons between the baseline and post-concussive postural stability of individuals.

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APPENDICES

A. Informed consent form

INFORMED CONSENT FORM

UNIVERSITY OF BIRMINGHAM

Participant Identification for this Study:

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

Ethics code:

Name of researcher:

Please initial here:

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

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

B. Demographics questionnaire

Name …………………………………

Age ....

Height ....

Weight ....

Main Sport/Activity ....

Level of Participation: circle as appropriate

Recreational Club County Regional National International

Other Level (please specify) ....

C. <u>Suitability to participate</u>

Suitability to Participate Checklist

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

Please <u>initial</u> here:

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

Signed: ……………………………………

Date: ………………………………………

D. Immersion questionnaire (Adapted from (Gil-Gómez et al., 2013)

Participant Number: Immersion Questionnaire

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. How real is the virtual environment of the system?	1	2	3	4	5
Q5. Is the information in the system clear?	1	2	3	4	5
Q6. Did you feel discomfort during your experience with the system?	1	2	3	4	5
Q7. Did you experience any dizziness or nausea?	1	2	3	4	5
Q8. Did you experience eye discomfort?	1	2	3	4	5
Q9. Did you feel disorientated during your experience with the system?	1	2	3	4	5
	Very easy				***Very difficult***
Q10. Did you find the Stroop task difficult?	1	2	3	4	5
Q11. Did you find it hard to maintain your balance throughout the test?	1	2	3	4	5
Q12. If you felt uncomfortable during the task, please indicate the reasons.		(No)	or	(Yes + reasons)	
Q13. Any additional comments.					

E. Participant information sheet

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

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

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

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

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

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