Department of Engineering

University of Strathclyde

Design, Development, and Feasibility of a Stability-Based Training Package for People with Chronic Ankle Instability

By

Lauren Forsyth (MRes, BSc)

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Abstract

Chronic ankle instability (CAI) is associated with recurrent ankle sprains, mechanical laxity, and/or perceived instability. Stability-based rehabilitative training has been found to prevent further injury, however poor programme compliance can hinder the programme's effectiveness. Providing feedback on performance allows progress to be monitored and encourages motivation. For this reason, the stimulating and motivational environment created using virtual reality (VR) systems may be more conducive to adherence. Visualisation is the connection of biomechanical analysis and VR. Visualisation produces real-time feedback and uses VR to create a diverse, challenging, and controllable environment, representative of real-world situations. This study aimed to design, develop, and test the feasibility of a stability-based training package for people with CAI.

The package designed a stability-based programme and developed the visualisation to provide accurate feedback of movement in a virtual environment using motion capture to supplement that of the clinician in practice.

A feasibility randomised controlled trial was conducted for people with No-CAI and CAI to compare VIS and No-VIS groups across three sites in the UK and Australia. Outcomes at pre- and post-training included participant retention, adherence, adverse events, and objective and subjective stability performance.

Of the 28 randomised participants, 26 completed the feasibility study with two CAI participants withdrawing due to non-trial related matters. No adverse events occurred, and training was 100% adhered to.

The results of the stability-based training package were inconclusive for participants with no CAI. For people with CAI, training with visualisation did show significantly greater improvement for the Star Excursion Balance Test, but no conclusions can be drawn since the study was underpowered. All participants reported an enjoyable experience, and the visualisation did not elicit a greater change in results.

To conclude, this study supports the feasibility of the stability-based training package for people with CAI and provides evidence for further development.

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List of abbreviations

Abbreviation	**Definition**
AJC	Ankle joint centre
AP	Anterior-posterior
ASIS	Anterior superior iliac spine
CAI	Chronic ankle instability
CAIT	Chronic ankle instability tool
COM	Centre of mass
DLBT	Dynamic leap and balance test
HJC	Hip joint centre
KJC	Knee joint centre
MI	Mechanical instability (relative to the ankle)
ML	Medial-lateral (relative to direction)
ML Test	Multi-Leap Test
NHS	National Health Service
OA	Osteoarthritis
PACES	Physical activity enjoyment scale
PI	Perceived instability (relative to the ankle)
PM	Posterior-Medial
PL	Posterior-Lateral
PSIS	Posterior superior iliac spine
QOL	Quality of life
ROM	Range of motion
SD	Standard deviation
SEBT	Star excursion balance test
SLB	Single leg balance
USEQ	User Satisfaction Evaluation Questionnaire

Conference Proceedings

Forsyth, L., Roeles, S., Childs, C. (2018) World Congress of Biomechanics, Dublin.

Forsyth, L. & Childs, C. (2019) International Society of Biomechanics Congress, Calgary.

Forsyth, L., Bonacci, J., Childs, C. (2019) International Ankle Symposium, Amsterdam.

Forsyth, L., Bonacci, J., Childs, C. (2019) British Association of Sports Medicine Conference, Glasgow.

Chapter 1 – Introduction

1.1 Introduction

Chronic ankle instability (CAI) is a complicated multi-faceted clinical condition affecting one in five people who have experienced an ankle sprain. CAI is associated with recurrent ankle sprains, mechanical laxity and/or perceived instability, inhibiting daily activities and impacting quality of life (Hiller et al., 2012). If not managed it has been shown to lead to osteoarthritis (OA) of the ankle (Gribble et al., 2016). OA is the most common musculoskeletal disorder, and specifically ankle OA can be as debilitating as end stage hip OA, kidney disease, or congestive heart failure (Glazebrook et al., 2008; Saltzman et al., 2006). At the point of OA diagnosis, unlike hip OA, treatment options are limited thus prevention is important.

Stability-based rehabilitative training has been found to prevent further ankle injuries (Kosik et al., 2017). The literature has identified that poor programme compliance can hinder the programme’s effectiveness (Argent et al., 2018). Providing feedback on performance allows rehabilitative progress to be monitored. This can be used to encourage motivation by considering the basic psychological needs associated with self-determination theory (Carson and Polman, 2017). For this reason, the stimulating and motivational environment created using virtual reality (VR) systems may be more conducive to rehabilitation adherence (Lee, 2016).

Visualisation is the connection of biomechanical analysis and VR. It produces real-time feedback, by accurately monitoring movement and progress, using VR to create a diverse, challenging, and controllable environment, representative of real-world situations. To provide the feedback, visualisation uses motion capture for accurate analysis of movement and progression monitoring. In clinical practice motion capture is still underutilised due to the practicality of conducting this. This thesis aims to design and develop a stability-based package which uses visualisation for people with chronic ankle instability. If successful, such packages could be used in the future to enhance rehabilitation outcomes, experience and success for people with chronic ankle instability.

1.2 Research Aims

The main aim of this project is to design, develop and assess a stability-based training package for people with CAI suitable for clinical practice to improve rehabilitative outcomes.

This was evaluated in 2 ways. The first was to preserve or improve the ankle stability and postural balance of people with CAI. The second was to enhance the rehabilitative experience using augmented feedback in a virtual environment.

To determine these evaluations three subcategories needed addressed:

- Design of a stability-based training programme that was specific to ankle stability and postural balance
- Selection of a clinically appropriate motion analysis system
- Development of the visualisations for training to be objective, challenging, and enjoyable, yet conducted safely in clinical practice.

The requirements to achieve each of these are outlined in the subsequent chapters of this thesis (Section 1.5). These all work towards the solution that will use visualisation to provide accurate feedback of movement in a virtual environment using motion capture and game development approach. This will be a tool to supplement instruction and feedback from the clinician. This solution could be more successful and enjoyable than training without visualisation due to the design of the stability-based programme and incorporation of the virtual environment for objective, progressive and challenging training that is safe for clinical practice.

1.3 Research Questions

Can we develop a stability-based training package suitable for clinical use?

How does feedback influence rehabilitative outcomes after stability-based training?

1.4 Outline of investigation

- Present the clinical rationale for the investigation.
- Identify the importance of feedback for motor learning and rehabilitation success, and the use of virtual reality.
- Introduce visualisation as the combination of biomechanical analysis and feedback in a virtual space.
- Design a stability-based training programme for people with CAI.
- Review motion capture methods and current utilisation in clinical practice.

- Utilise a framework to choose the motion analysis equipment most appropriate for the stability-based training package.
- Discuss healthcare professional's opinions and experiences with biomechanics and the use of visualisation
- Develop a package for stability-based training using visualisation.
- Research the feasibility of the developed stability-based training package by conducting an RCT study.

1.5 Outline of thesis

The thesis has been outlined as follows:

Chapter 2: This chapter reviews the current literature about lateral ankle sprains, chronic ankle instability, and ankle osteoarthritis. The pathology of lateral ankle sprains is described before detailing the development and progression pathway to chronic ankle instability and ankle osteoarthritis. In this chapter it is highlighted that stability-based training is strongly recommended for people with chronic ankle instability, thus supporting the rationale of this investigation.

Chapter 3: In this chapter motor control and the stages of motor learning are introduced before discussing the implications for practice and how this can affect adherence in rehabilitation. It then discusses the role of feedback and motivation in rehabilitation and the implementation of virtual reality. The purpose of this chapter is to outline the importance of feedback and motivation in rehabilitation and introduce visualisation for rehabilitation providing feedback in a virtual space.

Chapter 4: A stability-based training programme is designed in this chapter. The principles of training are introduced as a guide for developing a programme for people with CAI before outlining a design framework for exercise prescription. The specific exercises chosen are then described in detail.

Chapter 5: Visualisation utilises biomechanical analysis, specifically motion analysis for this study, to provide feedback in a virtual environment. This chapter reviews motion analysis and the current utilisation of motion analysis in clinical practice. Following this a criteria of specific attributes for a clinically appropriate motion analysis system are described and the rationale for using 3D motion capture for the current investigation is detailed.

Chapter 6: In this chapter a focus group was conducted to explore the opinions of healthcare professionals regarding the use of biomechanical technology, specifically motion analysis, in clinical practice, and the development and future of visualisation.

Chapter 7: This chapter details the development of the stability-based training package. The stability-based training programme from chapter 4 is developed with visualisation for clinical use to create a hybrid tool to supplement the feedback provided by the clinician to improve and monitor stability, quality of movement and motivation in rehabilitation. A framework explicitly outlines the criteria for how the application was developed, followed by a detailed description of each exercise in the package.

Chapter 8: A feasibility randomised controlled trial was conducted to assess the stability-based training package. Chapter 8 outlines the trial and analyses of the objective data collected, presents the results, and discusses the findings. The data for the No-CAI and CAI groups are separately analysed to compare the VIS and No-VIS groups within each. It also discusses the strengths and limitations of the study protocol.

Chapter 9: In this chapter the subjective methodology and results from the feasibility study described in chapter 8 are presented and discussed.

Chapter 10: Following the feasibility study in chapter 8 a retrospective study was conducted to assess time efficiency of the stability-based training package during testing and training. Estimates of the preparation, calibration, and overall session length times were presented, to be discussed in chapter 11.

Chapter 11: Chapter 11 revisits the design and development of the stability-based training package, and discusses further the results of the feasibility study from chapters 8 and 9, and the results of the retrospective analysis in chapter 10, in relation to the initial design frameworks. This chapter also discusses the future development of the package regarding the clinically appropriate motion analysis system and the training application.

Chapter 12: The thesis concludes by returning to the research aims and questions to summarise the main conclusions of the project.

Chapter 2 – Clinical Background

2.1 Introduction

In this chapter we address the clinical rationale for this investigation. The chapter begins with a description of the ankle anatomy before detailing the evolution from lateral ankle sprain to CAI and osteoarthritis.

2.2 The Ankle Complex

2.2.1 Functional Anatomy

The ankle complex links the shank and the foot and comprises of two primary joints, ankle joint and subtalar joint (Figure 2.1). There is also a third articulation named the distal tibiofibular syndesmosis. Together these joints allow for coordinated movement of the rearfoot in all 3 cardinal planes of motion. However, movement does not strictly tend to be performed within these planes in isolation as the ankle complex acts as a unit along oblique axes thus performing more than one movement at a time. This is known as pronation – dorsiflexion, eversion, and external rotation (abduction) – and supination – plantarflexion, inversion and internal rotation (adduction) (Brockett and Chapman, 2016; Hertel, 2002).

Working in combination, the ankle complex is designed specifically to provide support for the body (Monk et al., 2016). Maintaining stability of the ankle is imperative to functioning in daily life when the joint is loaded. When static the congruity of the articular surfaces and ligamentous restraints are main contributors to stability, and during dynamic movement the musculotendinous units increase contribution for dynamic stabilization (Hertel, 2002). This is detailed further in the following sections.

2.2.1.1 Ankle joint

The ankle joint, or true ankle joint as shown in Figure 2.1, describes the tibiotalar joint. It is the primary joint in the ankle complex and is situated at the base of the distal end of the tibia and fibula and superior portion of the talus (Figure 2.1). There are articulations between the tibial mortice surface and talar trochlear surface and between the medial and lateral malleolar surfaces of the tibia/fibula and talus (Hertel, 2002). The design of these articulations allows torque to be transferred from the shank to the foot during pronation and supination movements, as well as primary stabilization when ankle joint is loaded. In isolation the joint acts as a synovial hinge joint, meaning plantar/dorsiflexion can be performed, as the joint acts in 1 degree of freedom (Dawe and Davis, 2011; Hertel, 2002). Here the tibia and fibula are considered as fixed allowing the talus to move, and movement is lubricated by the synovial fluid within the joint. The axis of rotation is situated at an oblique angle, in relation to the talar dome in the transverse plane, when passing through the medial and lateral malleoli (Figure 2.2) (Hertel, 2002).

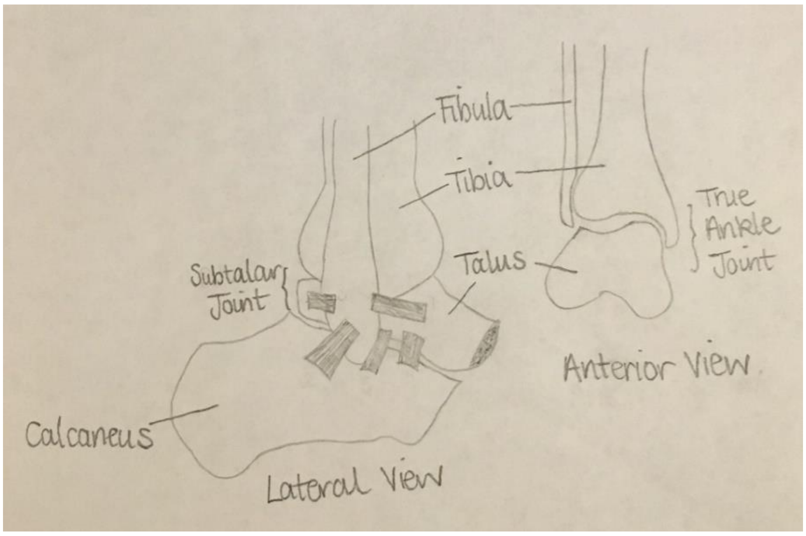


Figure 2.1 Anatomy of the ankle complex including the ankle and subtalar joint

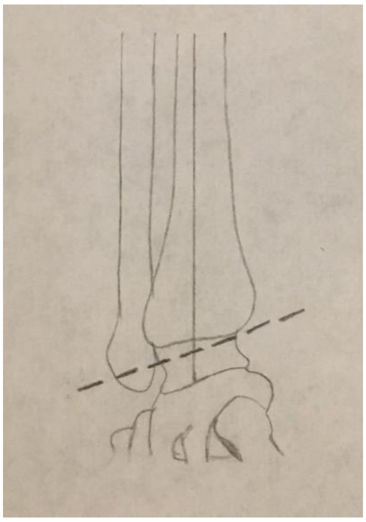


Figure 2.2 Oblique axis of the ankle joint

The ankle joint is subjected to entire bodyweight loading as the foot strikes the ground and it begins the loading response during any movement (Rahmati et al., 2016). Although it has a small surface area the joint has a larger weight-bearing area compared to the hip and knee to dissipate these large ground reaction forces. During gait the ankle complex is subjected to approximately five times body weight during loading, of which 83% has been shown to be transmitted through the ankle joint (Brockett and Chapman, 2016). For maximal stress reduction the joint must be optimally situated with high congruency and very little variation in anatomy. Monk and colleagues (2016) reported a talar shift of 1mm to cause an incongruence of the joint of ~40%. Hypothetically this would predispose the joint to degenerate quicker than healthy ankle joints.

2.2.1.2 Subtalar joint

The subtalar joint is located between the talus and calcaneus, articulating at two separate locations thus creating two joint cavities (Figure 2.1). The posterior subtalar joint articulates between the inferior posterior facet of the talus and the superior posterior facet of the calcaneus, while the anterior subtalar (talocalcaneonavicular) joint articulates between the anterior, superior facets of the talus, the sustentaculum tali of the calcaneus, and the concave proximal surface of the tarsal navicular. Individual variation of the anterior subtalar joint has been presented previously (Brockett and Chapman, 2016; Hertel, 2002).

As highlighted above, the two joint cavities of the subtalar joint act with the ankle joint to transfer torque from the shank to foot to produce pronation/supination, however in isolation the primary role of the subtalar joint is inversion and eversion (Dawe and Davis, 2011; Hertel, 2002). This is due to the two joints sharing a common axis of rotation, situated obliquely between the posterior, inferior, lateral aspect and anterior, superior, medial aspect of the calcaneus (Monk et al., 2016). Monk and colleagues (2016) further explained the importance of a neutral to slightly everted position of the calcaneus during the stance phase of gait to maintain flexibility of the foot through the stance phase. An inverted position was highlighted to diverge the oblique axes of the ankle and subtalar joints which therefore led to stiffening of the foot and a longer lever arm. This could subject the foot to greater forces, as well as placing the ankle complex in a position, which is harder to stabilise, thus increasing injury risk.

2.2.1.3 Ankle Ligaments

The ankle complex remains stabilized by the ligaments surrounding it and securely holding the bones in place, while allowing movement in all three planes of motion.

The ankle joint is supported from a joint capsule and four ligaments, three of which support the lateral aspect – anterior talofibular ligament (ATFL), posterior talofibular ligament (PTFL) and calcaneofibular ligament (CFL) – and the deltoid ligament which provides medial support (Figure 2.3). The ATFL origin is located at the medial-anterior portion of the lateral malleolus and runs flat to inserts into the talus. It is recorded as an average of 7.2mm wide and 24.8mm in length (Burks and Morgan, 1994), and acts to restrict the anterior displacement of the talus, as well as excessive inversion and internal rotation of the talus on the tibia. As the ankle complex moves from dorsiflexion to plantarflexion the ATFL becomes increasingly strained. Previously the ATFL has demonstrated decreased maximal loads and energy to failure compared to its lateral ligament counterparts, thus in the plantarflexed position this ligament is of increased risk of injury (Dawe and Davis, 2011; Hertel, 2002). The CFL extends posteriorly and inferiorly from the lateral malleolus to the lateral calcaneus. Spanning over both the primary joints the CFL restricts excessive supination of the ankle complex, specifically inversion and internal rotation of the rearfoot. Originating at the lateral malleolus, the PTFL extends posteriorly to the posterolateral aspect of the talus. As with the CFL this ligament provides support to both inversion and internal rotation, however the broad insertions on both the talus and fibula allow great restriction even when the tibiotalar joint is loaded (Hertel, 2002).

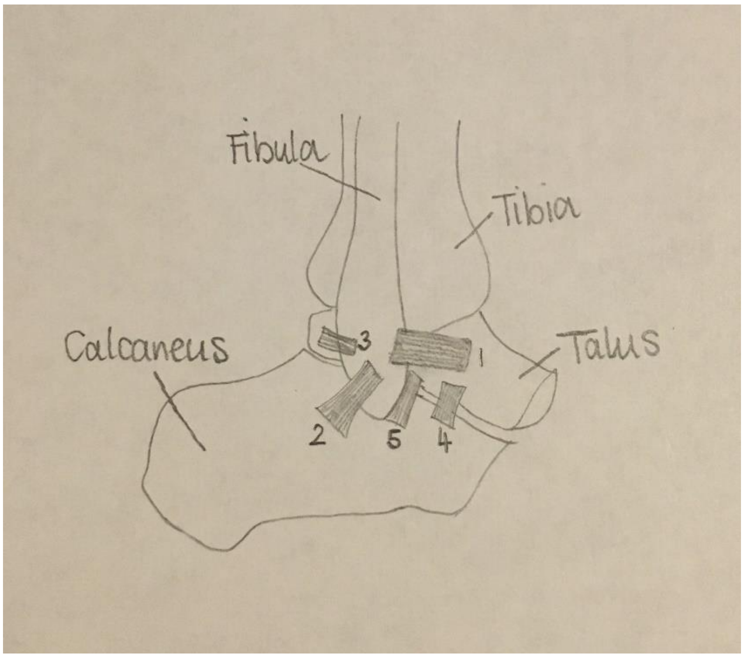


Figure 2.3 Ligaments of the lateral ankle - (1) anterior talofibular ligament, (2) calcaneofibular ligament, (3) posterior talofibular ligament, (4) cervical ligament, and (5) lateral talocalcaneal ligament

The subtalar joint is structured differently consisting of three groups of lateral ligaments: 1) interosseous ligament, 2) cervical ligament, and 3) deep fibres of extensor retinaculum (Figure 2.4) (Hertel et al., 2002). The deep ligaments are structured similarly to that of the cruciate ligaments of the knee, crossing through the canalis tarsi and stabilizing the anterior and posterior subtalar joints. The cervical ligament of the deep ligaments is the strongest of the deep ligaments and restricts supination. Aside from this one, the peripheral ligaments are the only additional ones to provide any stabilizing support to the subtalar joint and includes the CFL, which also spans the ankle joint, and the lateral talocalcaneal (LTCL) and fibulotalocalcaneal (FTCL) ligaments. The CFL is integral, while the LTCL and FTCL are much weaker ligaments playing more assistive roles (Hertel, 2002).

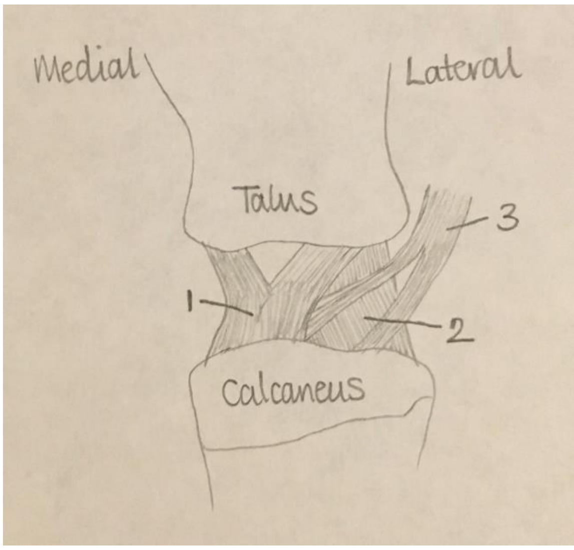


Figure 2.4 Ligaments of the subtalar joint - 1) interosseous ligament, 2) cervical ligament, and 3) deep fibres of extensor retinaculum

2.2.2 Joint Stability

Joint stability is a joint's ability to control forces to maintain posture, or return to a desired position, following a perturbation (Knudson, 2007). Overall stability of the body requires primarily stability of the joints and the ability for these to control the body segments in relation to one another (Clark et al., 2015).

During running and landing activities the ankle complex can be subjected to up to 13 times bodyweight and often these joint forces can exceed the physiological limits of the surrounding skin, muscles and ligaments which are statically securing the joint (Brockett and Chapman, 2016). This is when the ankle must be dynamically restrained (Wikstrom et al., 2006). Thus, Riemann and Lephart (2002) proposed the sensorimotor system – visual, vestibular, and somatosensory subsystems – to maintain joint stability, which was controlled by peripheral mechanoreceptors. Specifically, this relates to feedforward and feedback neuromotor control, which therefore affects the dynamic contributions to maintaining stability via afferent information and efferent motor response. The ability to maintain baseline neuromotor control is extremely important to protect the joint from extreme motion and ensure accuracy of afferent and efferent firing. If this ability declines and loses efficiency the reacting joint musculature during movement becomes less responsive. In relation to the ankle joint, this would allow for greater joint displacement before the mechanoreceptors would react to counteract a potentially dangerous movement. However, there is limited research experimentally isolating mechanoreceptor functions due to the difficultly in doing so (Riemann & Lephart, 2002).

2.3 Lateral Ankle Sprain

2.3.1 Pathology

Ultimately, a lateral ankle sprain (LAS) is a traumatic injury of the ankle ligaments (Calatayud et al., 2014). LASs have typically been reported to occur from an excessive supination of the rearfoot about an externally rotated lower leg soon after initial loading of the joint (Delahunt and Remus, 2019). The excessive inversion and internal rotation of the rearfoot, coupled with external rotation of the lower leg, results in overriding the static stability, as the body's centre of gravity rolls over the ankle which cannot be counteracted by the dynamic joint stability (Maffulli et al., 2012). If the strain exceeds the tensile strength of the ligaments, damage occurs. The rate of loading of the inversion, the load itself and the direction of said load, alongside the inverted position of the foot all influence the risk associated with experiencing a lateral ankle sprain (Calatayud et al., 2014).

The ATFL is the most commonly injured lateral ligament, affected in 90-95% of cases in previous research, with the CFL the second (Kofotolis et al., 2007; Malliaropoulous et al., 2009). Once the ATFL is damaged there is increased motion, occurring particularly in the sagittal and transverse planes. Anterior displacement of the talus within the ankle joint is greater, as well as the internal rotation of the rearfoot, as the talus is not as cemented in position. This increased movement not only shows a destabilized joint complex, but also increases the stress placed upon remaining intact ligaments within the ankle complex to maintain stability.

2.3.2 Prevalence of lateral ankle sprains

Despite the considerable research investigating lateral ankle sprains, the majority of research is carried out in young and competitive athletic populations (Brant et al., 2019; Calatayud et al., 2014; Kobayashi et al., 2016; Roos et al., 2017). This restricts the ability to generalise the results outside of this population.

Ankle injuries are among the most common injuries in recreational activities and competitive sports (Kobayashi et al., 2016), amounting to around 40% of all sporting injuries. Specifically, injury to the lateral aspect of the ankle complex accounting for 85% of all ankle injuries (Doherty et al., 2014; Maffulli et al., 2012). This has resulted in it being the second most common sporting injury, and first in young athletes and active duty military service members (Calatayud et al., 2014). A previous meta-analysis of athletic and military populations reported a prevalence of 11.55 per 1,000 exposures across 116 high-quality studies (Doherty et al., 2014), and a more recent study reported an increased risk rate of 49.5 per 1,000 exposures in US National Collegiate Athletic Association (NCAA) athletes across 25 sports (Roos et al., 2017). This translated to 1 in 28 collegiate athletes sustaining an ankle sprain each season (Roos et al., 2017). Compared to previous research on NCAA athletes was an increase from the 13.79 per 1,000 exposures across 15 sports over 16 years (Hootman et al., 2007). In youth athletes the prevalence of season-ending ankle sprains was 28 per 1,000 exposures over ten sport seasons from 2005-2016 (Brant et al., 2019). Compared to other lower extremity injuries this was 2.6 and 3.1 times more prevalent than the next most common injuries of the lower extremity – thigh sprain/strain and knee sprain/strain. However, it is expected that these numbers underestimate the prevalence in youth sports since only season-ending injuries were recorded. In a military population Waterman and colleagues (2010) conducted a study into all physically active cadets in the US military academy to assess prevalence of ankle sprains. Over a 2-year period from 2005-2007 78% of the 885 new ankle injuries were sprains. This gave an incidence rate of 58.4 per 1,000 person years in the 614 cadets with new injuries.

There is some evidence in the community that highlights the prevalence of ankle sprains (Hiller et al., 2012). A community-based population study from Hiller et al. (2012) found 61.1% of 751 New South Wales residents reported a history of ankle injury, of which the majority of cases were an ankle sprain (47.7%). Although the heterogeneity of the samples prevents absolute conclusions to be drawn, ankle injuries are clearly a common injury among many different populations.

2.3.3 Impact of lateral ankle sprains on health services and productivity

In order to evaluate the impact of ankle sprains on health services Bridgman and colleagues (2003) conducted a population-based investigation. This aimed to estimate the incidence of ankle sprains attending Accident and Emergency (A&E) units in the West Midlands, as well as the projection nationally across all units in the United Kingdom (Bridgman et al., 2003). The combined population across the 4 health districts – Dudley, Sandwell, Walsall, Wolverhampton – was approximately 1 million with each unit supplying data sets for diagnostic code ‘ankle sprain’. The data sets showed 5776 new ankle sprain cases were reported between April 2000 and March 2001. This equated to 52.7 per 10,000 cases, which approximated to 273,000 new ankle sprains per year (using the 1998 England and Wales population estimates as those were available at time of study) ((ONS), 2015). It is expected that some cases may have been missed since diagnosis was only completed in 88%, 100%, 89% and 68% in each of the areas. The work by Bridgman et al. (2003) has not been replicated. Since publication, the population of England and Wales has increased by 6,165,300, which would be assumed to have led to an increased number of cases at A&E units, and increased demands placed on the health services.

In more recent research ankle ligamentous injuries accounted for 40% of all cases reported in the National Injury Surveillance Study (LIS) and National Medical Registration (LMR) in a national retrospective study in the Netherlands (De Boer et al., 2014). This was the highest reported injury case out of those analysed from 1986-2010 and cost, on average, 823 euros per case. Importantly it should be noted that these results required A&E attendance at the point of initial injury. This leads these values to underestimate and under-represent all cases and costs since patients could have attended a local practice or sports injury clinic, or none at all.

Ankle sprains are not only associated with medical staff burden and costs but also productivity costs. Referring to Waterman and colleagues’ (2010) military-based study, military cadets on average lost 8.1 days of work each. This recovery time result was predominantly influenced by minor sprains as this was the dominant injury. Severe sprains had 3.5% of the cadets losing >21 days. Over the same time period 312 amateur footballers lost 975 sessions to ankle sprains which was on average 7 days, which supported the previous research in the military population (Kofotolis et al. 2007).

2.3.4 Recurrence Rates of lateral ankle sprains

After suffering an initial ankle sprain, the recurrence rates have been reported to reach 73% (Yeung et al., 1994). As a result, the biggest risk factor for an ankle sprain is a previous ankle sprain (Calatayud et al., 2014). In amateur footballers who suffered an injury during the season, Kofoltolis and colleagues (2007) reported 60.5% of the athletes had a previous ankle injury. This equated to the injured athletes having a 1.5 times chance of having had a previous history of ankle sprain. Waterman et al. (2010) supported this result in a military population stating that 75/641 cadets who suffered an ankle sprain were treated for multiple ankle sprains, which summed to 160 ankle sprains and an average of 2.13 ankle sprains per person. This has continued to be exposed in more recent literature of US National Collegiate Athletic Association athletes where 11.9% of lateral ankle sprains, or 1 in 8, were identified as recurrent injuries (Roos et al., 2017). This highlights the prevalence of ankle sprains as it is not just an increased number of people injuring the ankle, but the same people re-injuring. Since this remains an issue, as presented in more recent research, it can be inferred that treatment modalities remain suboptimal.

Recurrent ankle injuries have also been associated with 30-74% of people reporting continued pain, swelling and ankle instability 1.5 to 4 years post injury (Calatyud et al., 2014; Song et al., 2016; Yueng et al., 1994). As this becomes a chronic condition it impacts quality of life, as well as leaving some people unable to work, thus amounting further medical and time lost to productivity costs (Guillodo et al., 2013). This is discussed in detail in the chronic ankle instability chapter (Section 2.4).

2.3.5 Injury management following lateral ankle sprains

Lateral ankle sprains remain to be perceived as a benign injury as people disregard the potential risks for later life and do not seek professional care. De Boer et al. (2014) reported emergency attendance for ligamentous injuries approximately halved during the 25-year study period. This supported previous research which reported the majority of a 467 sample (31.5%) only visited a physician once (Braun, 1999), and alarmingly 35.5% of 459 participants never consulted a physician (Hiller et al., 2012). This is also apparent in youth athletes (Terrier et al., 2013). Terrier and colleagues (2013) found only 57% of 204 young athletes received rehabilitation from a professional when questioned. This could be related to the ‘minor injury’ attitude to lateral ankle sprains as well as the health service’s focus on the acute phase of injury using the PRICE Protocol – Protection, Rest, Ice, Compression and Elevation – leading people to undertake self-management as the primary source of care. In 2012 Hiller and colleagues reported 72.8% of a sample to opt for self-management, however this focuses directly on wound healing to relieve pain and prevent inflammation, and reduce it, as much and as fast as possible (Beynnon et al., 2006). These protocols do not address the changes to joint stability leading to the high re-injury rates.

Injury to the lateral ankle complex is almost always managed conservatively as surgery is no longer recommended following an acute ankle sprain. Research has concluded that surgical procedures fail to demonstrate beneficial evidence over conservative management, especially considering the medical costs, risk of complication and greater time lost at work (Al-Mohrej and Al-Kenani, 2016; Chaudry et al., 2015). For this reason, rehabilitation is the primary goal for successful return to activity and prevention of re-injury.

Currently there is limited structure to the treatment modalities within the health services (Calatayud et al., 2014), however research has shown strong evidence supporting balance training (D'Hooghe et al., 2018). The National Athletic Trainers' Association used the strength of recommendation taxonomy to create guidelines for the conservative management of ankle sprains in athletes. Balance training, particularly focusing on neuromuscular control, was recommended to be performed throughout rehabilitation and as a preventative strategy for re-injury according to consistent results across high-quality research. Although rehabilitation consisting of strength and flexibility exercises of the leg muscles were also recommended this was based on inconsistent findings or limited-quality research, for implementation during rehabilitation, and only usual practice, opinions or case studies for prevention (Kaminski et al., 2013). This is supported by a systematic review and meta-analysis by Schiftan and colleagues (2015) which found in a significantly homogenous population involving 1896 participants across 7 studies that isolated neuromuscular training significantly reduced ankle sprain incidence (RR = -0.65, 95% CI 0.55-0.77). These results were evident in participants regardless of whether an ankle injury had been sustained previously or not (Schiftan et al., 2015).

It is important to note that although there is a vast number of intervention studies following lateral ankle injuries there is a severe lack of high-quality empirical research. These studies highlight a heterogeneity of the interventions, including frequency and exercise characteristics, and large variability in sample sizes, which all pose difficulty for comparison in systematic reviews and meta-analyses (Schiftan et al., 2015; van Ochten et al., 2014). Furthermore, van Ochten and colleagues' (2014) systematic review published the effectiveness of treatments after ankle sprains and concluded that 18 of the 21 studies analysed had a high risk of bias.

Future research should combat this as opposed to reproducing studies of similar quality which are not validating due to lack of reliability.

In conclusion, the ‘minor injury’ attitude of the ankle sprain and educational barrier of the implications of the lateral ankle sprain need addressed. In addition to this it is currently unclear as to a direct pathway of rehabilitation and optimal care for patients, but the above sections have highlighted that research strongly suggests some form of rehabilitation is beneficial.

2.4 Chronic Ankle Instability

Chronic ankle instability (CAI) is often described as a ‘subjective phenomenon’ (Monaghan et al., 2006), however it is a complicated multi-faceted clinical condition. In this thesis the clinical definition used to define it is taken from the 2016 consensus statement from the International Ankle Consortium which states CAI diagnosis when recurrent episodes of the ankle joint ‘giving way’ and ‘repetitive bouts of lateral ankle instability result in numerous ankle sprains’ and symptoms recurring for one year (Gigi et al., 2015; Gribble et al., 2016; Hertel et al., 2019).

The progression from LAS to CAI is not well understood but CAI affects approximately 1 in 5 people of those who have experienced an acute ankle sprain, although many patients will remain undiagnosed and suffer silently (Hiller et al., 2012). A study in New South Wales reported an overall prevalence of chronic musculoskeletal ankle disorders in 19.6% of 751 residents interviewed. Of these cases 68% developed following an initial acute injury and 22% with history of sprain still reported ongoing problems. This had been an ongoing problem for at least ten years in 49.7% of participants (Hiller et al., 2012). A more recent study in 829,791 young adults reported a CAI prevalence of 1.1% and 0.7% for males and females, respectively (Hershkovich et al., 2015), and another in teenagers in rural North Carolina reported an incidence of 78.6% of 201 participants (Holland et al., 2019). Although the literature presented here samples a general population, the majority of studies analysing incidence rates of CAI are in specific populations, particularly military and athletic groups.

These chronic symptoms qualify CAI as a disability according to published work from the government as it is a physical impairment that has a ‘substantial and long-term negative effect on your ability to do normal activities’ which causes impairment to completing daily tasks over a period of more than 12-months (GOV.UK, 2010). The implications of living with a chronic disability are discussed in the next section.

2.4.1 Burden of chronic conditions

A chronic condition places a substantial burden upon the patient and those around them as the ability to work, perform simple daily tasks and partake in sporting activities become more difficult or impossible, and this severely affects Quality of Life (QoL) (Houston et al., 2014). QoL is multidimensional – socially, physically and psychologically encompassing – and research has begun to determine the impact of disability on every component to create a multidirectional profile opposed to focussing on just the physical impairment (Houston et al., 2014). QoL is assessed subjectively, which both benefits and limits investigations. The various patient-reported outcomes will be perceived differently from patient to patient, and answers do not always correlate with physical outcomes, however the results do give an insight as to the patient's feelings.

The subjective physical deficit in those with CAI decreases level of physical activity (Hertel et al., 2019). This was reported in two studies of people with CAI where 55% and 64.6% reported limited or modified physical activity, mainly sport, because of an ankle problem (Hiller et al., 2015; Hiller et al., 2012). This was supported more recently where significantly reduced scores in the self-reported function questionnaires for the Foot and Ankle Mobility measure in activities of daily living and sport, and the physical component of the Short Form-36 ($p<0.05$) were reported. This was even when there were no deficits across the various physical outcome measures including static and dynamic postural control tests (Terada et al., 2017). Previous research found that it was the injury specifically which incurred decreased physical activity and not a result of ageing or chronic inflammation (Gribble et al., 2016, Houston et al., 2015, Houston et al., 2014, Simon and Doherty, 2014). Animal-based studies also showed that ankle injury triggered CAI and a life-long decline in physical activity in mice 12- and 20-months post-injury (Hubbard-Turner et al., 2015; Wikstrom et al., 2015).

An increased sedentary lifestyle as a consequence of injury could result in greater disability and morbidity. Low levels of physical activity are currently estimated to contribute to 1 in 6 deaths in the UK (BHF, 2015). Primarily this is suggested to be mediated through weight gain, which is also a direct risk factor for osteoarthritis. This was found by Hershkovich et al. (2015) who analysed adolescents from 1998-2010 finding those who were obese or overweight were more likely to develop CAI according to odds ratio ($p<0.001$) compared to healthy controls.

It has been suggested that fear of re-injury may be preventing the participation in physical activity. Houston et al. (2014) reported a significantly increased fear of reinjury ($p<0.001$) in 25 people with CAI who were physically-active compared to a group of 25 healthy controls (Houston et al., 2014). This was found in both the Tampa Scale of Kinesiophobia-11 and Fear-

Avoidance Beliefs Questionnaire. Aside from fear of re-injury no other research has highlighted significantly decreased mental health in those with CAI (Hiller et al., 2012). Arnold et al. (2011) found the mental component of the Short Form-36 did not differ ($p=0.919$) compared to a healthy control group even though the physical component summary did ($p=0.005$). This result was unexpected since previous research has reported chronic conditions to be associated with poorer mental health, including anxiety and depression (Pruchno et al., 2016; Vancampfort et al., 2017). Scott and Docherty (2014) did not specify conditions (ie. Arthritis, diabetes) but for previous collegiate athletes who suffered major (67%) or chronic (50%) injuries, or daily (21%) or physical activity (45%) limitations, there was a significantly greater mean score of depression reported ($p<0.05$). In Pruchno et al.'s (2016) and Vancampfort et al.'s (2017) research the reporting of one chronic condition saw a rise by 4.4% and approximately 8% in the population depressed and anxious, respectively, compared to those with no conditions. Although previous research has been in relation to conditions such as low back pain, arthritis and diabetes, and no study has specifically assessed CAI, it remains a chronic condition and would be expected to show similar results to other chronic conditions.

There is limited evidence regarding the patient's mental health, however using specific measures to quantitatively monitor progress throughout treatment gives clinicians an important understanding as to the consequences of the treatment interventions, as well as the barriers present which may highlight a need to alter clinical care (Houston et al., 2014). Furthermore, this also allows the patient to realise the link between mental health and feelings of capability because this can often be overlooked or forgotten. Also objectively monitoring the physical rehabilitation process will give the patient a greater understanding, thus realising the positive steps being made (Houston et al., 2015). This is particularly important to note since reduced physical activity has been shown to negatively affect mental health, as well as increase risk of disease, as discussed throughout this section.

2.4.2 CAI Model

The development of CAI has been theorised as a cascade of events initiating from LAS (Wikstrom et al., 2013). However, this depicts CAI as a homogeneous condition, which may be a factor impacting further development of research in this field. Since those with CAI may only experience some but not all symptoms the condition must be treated as heterogeneous. Hertel initially proposed this using The Hertel Model of CAI (2002) (Figure 2.5), but a re-evaluation by Hiller and colleagues (2011) projected further breakdown of this model was needed for more accurate understanding (Figure 2.6). This not only leads to a greater understanding of the condition itself – more focused research on each homogeneous group, their relationships and effects on the disease breakdown – but will also aid the diagnosis and specific rehabilitation and prevention strategies for each subgroup.

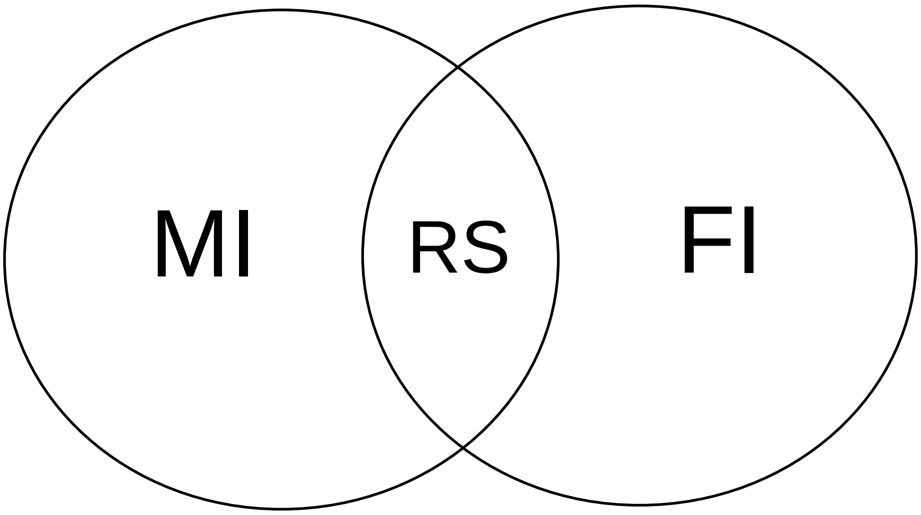


Figure 2.5 Original Hertel (2002) model for CAI. MI = mechanical instability, RS = recurrent sprain, FI = functional instability

The earliest discussions of CAI broke it down into 2 primary groups – mechanical instability (MI) and functional instability (FI). Patients with the former were physically impaired (Section 2.4.2.1), with evidence of ligament laxity about the ankle complex, whereas the latter reported only subjective feelings of symptoms about the ankle (Section 2.4.2.2). This ultimately left the ankle complex feeling less functional than before the injury occurred. Inconsistencies defining FI has led to discrepancies not only in diagnosis but also in inclusion criteria for research, which may explain the inconsistencies in findings among the CAI research (Hiller et al., 2011). Gribble et al. (2014) recently introduced a specific selection criterion in an attempt to combat this common limitation, which shall be used in the current investigation. In this initial model Hertel did appreciate and identify that patients did not necessarily fit into an isolated category, either MI or FI, but rather on a continuum, with recurrent sprains occurring when both conditions were present.

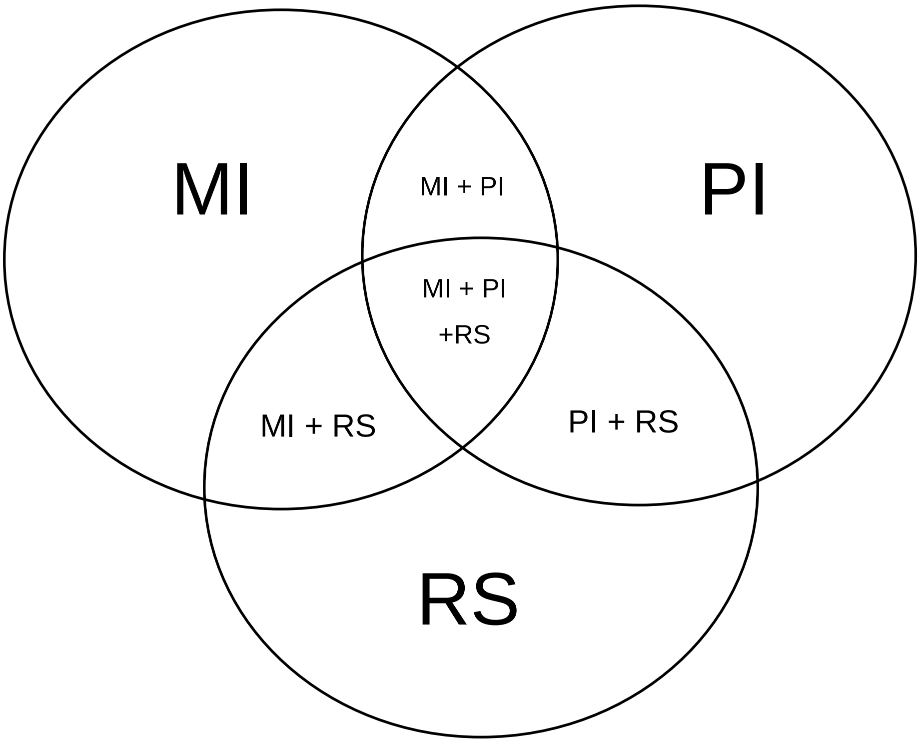


Figure 2.6 Model for CAI as proposed by Hiller et al. (2011)

The evolution of this model was instigated when Hiller and colleagues in 2011 disputed Hertel's model identifying 56.5% (47/108) of cases analysed to be 'non-fitting'. Consequently, a new model was proposed expanding Hertel's three category model to one with 7 sub-groups (Figure 2.6), theorizing that MI, FI and recurrent sprain could all exist either independently or together. The new model renames FI to perceived instability (PI). This was to combat the ambiguous use of the term FI since results are based upon the patient's perception of instability, opposed to an objective and quantitative measure. This is the term used for the remainder of this thesis. To assess the model, data from two recent studies from Hiller and colleagues were analysed resulting in 108 ankles from 81 adolescent dancers and adults with CAI (2007 and 2008). Compared to the Hertel (2002) model 100% (108/108) of ankles were accounted for in the re-evaluated model, with the majority of percentage fit lying in the PI subgroup (42.6%). This was followed by PI+RS (30.5%), PI+MI+RS (11.1%), PI+MI (9.3%), MI (2.8%), RS (2.8%), and MI+RS (0.9%). This highlighted that the model provided a better fit for a generalized population, accounting for all people with CAI in the study eliminating all non-fitters. The results also suggest a high prevalence of PI compared to other subgroups, which further analysis in the 2007 and 2008 studies confirmed PI to be the greatest influencer of stability performance both alone and when co-occurring with MI and/or RS. Although MI had some effect compared to the external control group, presence of MI alone appeared the least affected subgroup. The researchers stated that this study was only indicating that the subgroups exist and should not be perceived as an indication of prevalence and distribution of sub-groups (Hiller et al., 2011). Nevertheless, the study highlighted there are individual deficits for sub-group categorisation. Both MI and PI are discussed in greater detail in following sections.

2.4.2.1 Mechanical Instability

Mechanical instability is diagnosed where there is pathologic evidence of ligament laxity surrounding the ankle complex either from initial ankle injury or recurrent trauma (Hiller et al., 2011). A result of the ligament laxity is increased range of motion and incongruent bone interactions about the ankle joint complex (Bonnel et al., 2010). This does not only differ significantly to healthy controls and coper, but also those with only PI (Brown et al., 2015). Brown and colleagues (2015) reported the MI group to have an increased inversion laxity of 35.3±6.5° compared to 15.7±8.7°, 16.6±10°, 13.1±10.2° of PI sub-group, copers and control groups ($p<0.05$). To decipher the groups and identify specifically where MI was present, and where only PI was, the Ligmaster talar tilt cut off score of 29.4° was applied (LigMaster Version 1.26, Sport Tech, Inc., VA, USA). These results supported previous research which showed the CAI population not only had significantly increased inversion laxity (34.9±4.9° vs. 34.1±3.9°, $p=0.003$) but also anterior laxity (14.1±2.3mm vs. 11.9±1.9mm, p=0.05) compared to the control group. This was further highlighted by significantly greater asymmetry present in the CAI group for both anterior and inversion laxity ($p=0.03$ and $p=0.05$, respectively) (Hubbard et al., 2007).

Hubbard and colleagues (2007) reported both anterior and inversion laxity to be statistically significant in the predictive model for CAI. This accounted for 31.3% of the variance, which was greater than the other ROM, strength and functional balance measurements assessed in the study. These results suggest that mechanical factors are important predictors for CAI, suggesting that ligament healing post-ankle injury should not be overlooked during rehabilitation. However, as highlighted in Hiller and colleagues (2011) model re-evaluation there are many sub-groups of CAI and not all will have MI thus heterogeneous treatment pathways must be founded.

2.4.2.2 Perceived Instability

Pain and instability were the second most common symptoms, following ankle weakness, in a report where an initial sprain had led to a chronic condition (Hiller et al., 2012). Therefore, it is not surprising that in a study by Baldwin and colleagues (2017) PI was reported in 31.2%

of the population (276/884) aged from 8-101 years old. This was found to be persistent where 5-30% of patients across 9 high quality studies reported to still specifically perceive instability of the ankle 3 years post trauma (van Rijn et al., 2008).

Perceived instability is subjective and symptom-reported defined primarily by recurrent feelings of ankle instability due to neuromuscular deficits (Gribble et al., 2016). Initially a lateral ankle sprain affects a person’s ankle range of motion, muscle strength, postural stability and dynamic joint stability (Coudreuse and Parier, 2011). These short-term acute symptoms impact the sensory system, and as a consequence can cause reorganization in sensorimotor processing. This leads to long-term motor programming modification, affecting aspects of the person’s perceived stability as seen in CAI (Bastien et al., 2014). The feeling of instability has been related to inadequate balance and neuromuscular control, affected by deficits in dynamic joint stability, and has led to recurrent, or fears of recurrent, injuries, hence the notion of perceived instability. The literature surrounding neuromuscular control and perceived instability has been inconsistent and inconclusive. This is partly due to lack of sub-group division in the CAI literature but can also be explained by the differences in ankle stability classification between inclusion criteria in studies (Baldwin et al., 2017). For most research the CAI population assumes PI through self-reported inclusion criteria, however the presence of MI is often unknown as most studies do not conduct imaging/clinical assessment. Nevertheless, the research highlights that stability deficits are present in a CAI population.

A recent review by Thomson and colleagues (2018) reported reduced dynamic balance and strength to be strong contributors to CAI and reduced static stability a moderate contributor. During a double-leg stance with eyes open and closed a significantly higher velocity of the centre of pressure (COP) in both AP and ML directions was evident when comparing 16 adults with CAI and 16 healthy controls (p=0.03, p=0.05, p=0.01 & p=0.02, respectively) (Groters et al., 2013). These results supported those from previous work assessing single-limb stability in 22 participants with CAI (Ross et al., 2009). The results also showed significantly greater COP in both the AP and ML directions (p=0.02 for both). There was also increased excursion and standard deviation of the COP in the ML direction (p=0.01 & p=0.05, respectively) (Ross et al., 2009). When subject to an unstable surface by using the Biodex Balance System (Biodex Medical Systems, New York, USA) the antero-posterior, medio-lateral, and overall stability index scores were significantly worse in the 50 recreational athletes with CAI when the system was used (p<0.05) (Sierra-Guzman et al., 2018). Specifically the overall and medio-lateral stability index scores were both also reported to show negative correlation with PI by use of the Cumberland Ankle Instability Tool (Sierra-Guzman et al., 2018). This supported previous research reporting worse stability index scores in these directions only in 15 adults ($p<0.05$) (Rahnama et al., 2010). This difference between the CAI and matched-control group was not only apparent during this condition but also when a secondary task was included – postural control (primary task) + cognitive task (secondary task) ($p<0.05$). Furthermore, not only did the CAI group perform worse during the dual task but stability was also significantly more affected when the switch was made to the dual task ($p<0.05$). This was not evident in the control group suggesting that not only did the CAI population have a reduced ability to remain stable when there was only one focus, but also reduced control when there was a secondary task introduced (Rahnama et al., 2010). An increased reliance on attentional resources to maintain a stable posture indicates a lack of automaticity of postural control, particularly in the ML direction.

During a dynamic reaching task to test dynamic stability, previous research has also reported a significantly reduced performance (Doherty et al., 2016; Kosik et al., 2019; Sierra Guzman et al., 2018). To assess dynamic balance the International Ankle Consortium recommends using the Star Excursion Balance Test (SEBT), or a modified version of this (Gribble et al., 2016). When using the SEBT Sierra-Guzman et al. (2018) reported the greatest deficits in the posterior-medial (PM) and posterior-lateral (PL) directions, with large effect. This supported Doherty et al.’s (2016) findings for both the affected and unaffected limbs with significant effect ($p=0.01$). A more recent study also reported reduced reach distances in both the PM and PL directions, however this was not a significant deficit in the PL direction compared to the control group with no CAI ($p=0.09$) (Kosik et al., 2019). The PM and PL were also reported to have the highest correlation with self-reported PI using a recognised subjective scoring tool for CAI – Cumberland Ankle Instability Tool (CAIT) (both $r=0.5$, $p<0.001$) (Sierra-Guzman et al., 2018). Although these differences could be explained by reduced hip, knee and ankle flexion in the maximum reach position (Doherty et al., 2016), or the significant age main effect when the population was divided into younger and older-aged adults (Kosik et al., 2019), the literature concludes that CAI leads to reduced stability in both static and dynamic tasks.

Further to the simple static and dynamic tasks listed above it has been important to assess more complex and dynamic multi-joint tasks, particularly since the highest incidence of ankle injuries occur during indoor and court sports (Doherty et al., 2014). The research reports evidence of reduced overall stability in the CAI population (Groters et al., 2013; Ross et al., 2009). In a single limb jump landing task the time to stabilisation on landing was significantly increased in the CAI affected limb compared to the stable ankle in both the AP and ML directions ($p=0.01$ & $p=0.04$, respectively). As seen in the simple static and dynamic balance tasks above stabilisation in the ML took longer than in the AP direction (Ross et al., 2009). This is supported by a more recent study which assessed single limb landing during a multi-hop test. This was part of the same research referred to above by Groters and colleagues (2013), and the CAI group made significantly more balance errors (12±5.8 vs. 4.2±2.2, $p<0.01$) while completing the hopping course. Although the error score was coded to validate the method across participants this limits the research as this subjective measure will be interpreted differently between testers and research studies.

To summarise, despite the inconsistent clarification and classification of PI, those with perceived ankle instability appear to exhibit reduced stability with less efficiency to control and counteract balance perturbations. This is not only evident when maintaining stability is the primary task but is further reduced when there is a secondary task introduced or the task becomes more complex and multidimensional. For people with perceived instability this is of clinical importance as it may be a key risk factor for recurrent sprain. However, from the research it suggests that clinically CAI should be considered on an individual basis based on both physical and self-reported findings.

2.4.2.3 Conclusion

This section has highlighted the prevalence of CAI and discussed the debilitating impact of chronic conditions such as this on quality of life. The re-evaluated CAI model emphasizes the multi-faceted nature of CAI, of which its heterogeneity is supported by the current literature. However, there are neuromuscular deficits impacting postural stability in those with CAI which should be addressed to inform patient care, regarding both diagnosis and treatment.

2.4.3 Treatment interventions

As has been highlighted above people with CAI suffer ongoing symptoms for many years without seeking treatment. Taping and bracing are common interventions in clinical practice (Raymond et al., 2012). These are extremely successful in preventing further ankle sprains which importantly enables activity participation, but do not rehabilitate the MI and/or PI (Bellows and Wong, 2018; Raymond et al., 2012).

The stability deficits identified from reviewing the literature show that rehabilitation programmes must not only focus on improving postural control, but more importantly re-learning movement patterns in order to change the global motor programming. This supports the 2011 Cochrane review which concluded that balance training is effective, despite the high risk of bias between the research protocols (de Vries et al., 2011). The use of assistive devices and balance interventions are explored in the following sections.

2.4.3.1 Assistive devices (ie. Braces and taping)

An assistive device is usually one of the first forms a patient will be prescribed to use but due to the nature of support this hypothetically means that patients do not possess any more ability to control poor posture and stability. However current findings are inconclusive since the research lacks coherence methodologically and in participant population (Raymond et al., 2012). Raymond and colleagues (2012) pooled 8 studies finding no significant differences on sense of joint position of the ankle in the ankle brace group when it was no longer worn ($p>0.05$). This supported previous findings where single leg balance performance was not affected in a healthy population ($p>0.05$), despite significant heterogeneity between studies which may have limited the differences between groups (Ozer et al., 2009). The investigation also reported broad and vertical jump performances were reduced when the ankle was taped ($p<0.05$). This is suspected to be a consequence of the assistive device actively restricting range of motion of the ankle, and biomechanically altering the movement, to prevent re-injury. A number of studies have highlighted taping and bracing to significantly reduce the inversion ($p<0.001$) and maximum PF ($p<0.05$) angle, as well as the rate of inversion ($p<0.01$) observed pre- and post-initial contact and loading response during walking and/or drop landings ((Kuni et al., 2016, Zhang et al., 2012). However, contradictory findings were reported in a more recent study by Halim-Kertanegara and colleagues (2017) who found performance was not reduced in a series of functional tests. These included figure-8 hopping test, hopping obstacle course, mSEBT and single leg balance test ($p>0.05$). These opposing results researchers speculate may be related to the different braces investigated – ie. the use of a more encompassing and rigid brace.

Despite no rehabilitative or performance effects to be evident from using an assistive device research suggests it could be psychologically beneficial, which may have important consequences on quality of life (Sawkins et al., 2007). Halim-Kertanegara and colleagues (2017) explored this further assessing the effect of bracing an ankle during activity had on patient-reported self-efficacy, perceived stability, confidence and reassurance during functional activities. Results supported the researcher's hypotheses, showing a significant increase in all areas monitored for the 25 participants ($p<0.05$). Interestingly the functional tests where a difference was reported were the hopping tests and stair descent test which were the most challenging and dynamic tests completed. The increased perceived security and self-efficacy – belief in ability to succeed (Bandura, 1977) – experienced by the group of participants with CAI when the ankle was taped is extremely beneficial because it could encourage activity participation where it may have been avoided previously. Consequently this would increase physical activity and improve quality of life, which have reduced in people with CAI as discussed earlier in this chapter (Halim-Kertanegara et al., 2017). However, it should be acknowledged that this increased perceived stability may be present still when the brace is not worn but the ankle complex has not been rehabilitated. Therefore, it could be possible that if this increased self-efficacy is continued without the assistive device there could actually be an increased risk of injury as the person attempts the same tasks unbraced. Although this has yet to be investigated, the researchers believe this highlights the importance of fully rehabilitating the ankle alongside the use of an assistive device.

2.4.3.2 Balance interventions

Balance is the control of the body's COM within the base of support (BOS). Success is determined by stability of the joints and feedback and feed-forward corrective movements which act to ensure the body segments remain relative to one another over the BOS (Clark et al., 2015). There is a growing body of evidence to suggest that balance training is the most successful and recommended measure for rehabilitation for people with CAI (Guillodo et al., 2011; Kosik et al., 2017).

A systematic review by Kosik and colleagues (2017) assessed current therapeutic interventions and the effect of these on self-reported function. Balance training was the only type of intervention to be strongly recommended as deciphered by the Strength of Recommendation Taxonomy (SORT). This acknowledged consistent and good-quality patient-oriented evidence of the research despite the heterogeneity of the CAI population, and variability of the balance interventions in relation to exercises and length. The research reviewed included 6 balance training, 11 multimodal, three resistive, five joint mobilisation, one soft-tissue mobilisation, one stretching and one orthotic intervention. Balance training elicited greater and consistent findings than other interventions reporting moderate to strong effect sizes, with no 95% confidence intervals crossing zero, on activities of daily living and physical activity in support of the intervention (Kosik et al., 2017). The recommendations support previous research where self-reported perceived instability had significantly improved in ten males with PI following four weeks of balance training ($p<0.01$) (Clark and Burden, 2005). This was one of the only studies to clinically assess the participants for mechanical instability and exclude those, so although the sample size is small it presents a homogeneous sample. Training was conducted using a wobble board and led to a 28.4±13.8% improvement in patient-reported perception of instability, opposed to a 0.6±11.1% change in the control group (n=9 with PI). The exercise group did report an initial lower perceived instability score at pre-test, of which significance between groups was not reported, which could give reason for the better response to the training, however the researchers believe the degree of improvement exceeds this initial deficit.

Further to the subjective results, Lee and Lin (2008) published objective evidence supporting balance training. A main effect was found (F = 18.87, $p<0.05$) following a 12-week programme when the COP of the affected limb of 12 students was assessed using an ankle platform system (Lee and Lin, 2008). In a more recent study assessing the use of a progressive hop-to-stabilisation balance (PHSB) programme compared to the traditional single leg balance (SLB) programmes, Anguish and Sandrey (2018) recruited 18 participants with CAI to complete the programmes for four weeks. Both interventions successfully improved patient-reported outcomes and mSEBT performance with significant large effect sizes ($p<0.001$).

Despite the success of balance interventions in research, as evidenced by group means, the multidimensionality of CAI must be individually considered, and treatment plans should be relative to personal clinical cases. Burcal and colleagues (2019) highlighted this in a review of 6 studies which applied the same dynamic balance intervention for four weeks. The pooled population (n=73) reported significant improvements in mSEBT performance (Hedges' g effect sizes: A=0.65, PM=0.95, PL-1.16), however after individual analysis only 28/73 (38.4%) of the pooled population were considered to have had a successful treatment. Although the results suggest that participants with extreme performance improvement skew results, it does highlight the importance of individualised treatment plans (Burcal et al., 2019b). In a case study using an individualised programme which matched the functional demands of the athlete's sport, and the functionality and vulnerability of the athlete themselves, a multimodal rehabilitation programme was designed and adhered to for 6 weeks (O'Drscoll et al., 2011). The 19-year-old amateur rugby athlete was diagnosed with CAI following an initial lateral ankle sprain one year prior and reporting of ongoing symptoms. The programme was multi-modal including elements of postural stability, strength, plyometrics and speed/agility which made it a far more demanding protocol to those generally used in clinical practice, or research, for ankle rehabilitation. Post-intervention results showed further reach distances in every direction of the mSEBT, as well as a self-reported CAIT score improvement of 575%. The post-intervention score of 27 would no longer classify the athlete to have chronic ankle instability (O'Drscoll et al., 2011). Considering the individual success rate reported by Burcal and colleagues (2019), it could be suggested that the intervention completed in that study although repeatable and measurable may not have been functional or demanding enough to elicit the positive results seen in the case-study.

Despite the extensive range of the current literature the long-term effects of balance training remain unknown. One study showed the effects of the training are still maintained after no training when the same balance tests and subjective measures were repeated one-week later ($p>0.05$) (Burcal et al., 2019a). This was a short-term follow up one-week after finishing the training and completing the immediate post-intervention test. More research needed in this area to conclude the long-term effects of no training after following a rehabilitation programme.

2.4.3.3 Conclusion

As for lateral ankle sprains, CAI is most often self-managed and there is no clear management strategy. Perceived instability is a large contributor to the debilitating effects of CAI, leading to overall stability deficits. Therefore, rehabilitation is strongly recommended to focus on improving joint stability as a component of postural control using balance training as research has shown its effectiveness. Again, this is the same treatment recommended for lateral ankle sprain rehabilitation and should be prescribed on an individual basis due to the multifaceted nature and complexity of CAI.

2.5 Ankle Osteoarthritis

Osteoarthritis (OA) is the most common musculoskeletal (MSK) disorder in adults, with end stage ankle OA as debilitating as end stage hip OA or kidney disease, or congestive heart failure (Glazebrook et al., 2008; Saltzman et al., 2006). Affecting 8.75 million in the UK, with 20% of those seeking treatment for OA of the foot or ankle, this is fast becoming a more prevalent problem (UK, 2013). OA is a multifactorial process involving bone-related changes and cartilage degradation of synovial joints (Schmitt et al., 2015). Specifically at the ankle these changes are more commonly posttraumatic in nature (79.5% vs. 1.6% and 9.8% for hip and knee, respectively), resulting from an injury which has altered the joint habitat (Blalock et al., 2015; Brown et al., 2006; Valderrabano et al., 2008). This is opposed to primary OA where degeneration of the joint is an unavoidable cause of the ageing process. Previously, upon identifying supposed injuries leading to OA, ankle ligament lesion was the second listed accounting for 20% of the post-traumatic OA (PTOA) in ankles (65/318). This was in comparison to a series of fractures (malleolar (49%), tibial plafond (18%), tibial shaft (6%), talus and severe combined fractures (both 3%) (Valderrabano et al., 2009).

Approximately 25% of people with PTOA suffer from an ankle sprain initially, and recurrent ankle sprains, a common symptom of CAI, cause 61% of ankle lesions (Valderrabano et al., 2009). CAI also alters the joint contact stress and distribution of loading of the articular surface (Blalock et al., 2015; Kosik et al., 2020; Gribble et al., 2016). Thus the cascade of events for OA development is formed.

Golditz and colleagues (2014) provided evidence to support this theory by showing that physically active CAI participants had higher T2 relaxation times (ie. reduced cartilage health) relative to healthy comparatives. Not only was this evident in those seeking medical treatment for CAI, but also those not seeking treatment who were radiologically diagnosed with CAI but did not class themselves as symptomatic (Golditz et al., 2014). Despite the rapid degeneration of the joint within a five-year period from initial LAS in the young population (age=24.5 years old) the underlying progression remains speculative (Gribble et al., 2016). It has been hypothesized that the instability of the ankle joint in CAI leads to abnormal and suboptimal loading of the joint, thus leading to OA, however currently these remain only theories (Blalock et al., 2015,).

Due to the posttraumatic nature of ankle OA this has led to a younger population being affected at an average age of 51±14 years (Saltzman et al., 2005). This earlier symptomatic onset compared to OA of other joints means suffering is prolonged through life, and this must be endured while needing to stay physically active in order to lead fulfilling lives and capacity to work. These problems are not only heightened with the ever-increasing life span, but also the increased prevalence of obesity between the ages of 45-75 years (England, 2012). Obesity is another dominating risk factor for OA to be identified with ever increasing effect, with one quarter of both men and women obese, or morbidly obese, in the UK in 2012 (England, 2012). From this, those at risk of developing OA due to age are also increasing this risk by being overweight. This suggests an indirect pathway in which CAI could lead to OA, as discussed previously, since those with CAI display decreased levels of physical activity compared to healthy counterparts. This reduced physical activity can easily lead to weight gain, thus increasing the risk of OA.

As with any chronic condition, individuals experience substantial physical, social and economic effects (Section 2.4.2). Previous research from the Department of Work and Pensions estimated that 36 million workdays were lost because of OA in 2002, resulting in an economic production loss of £3.2 billion. Consequently £43 million was spent on community services and £215 million was spent on social services for OA, while £2.41 billion was paid out as Disability Living Allowance (Hamilton et al., 2009; Woo et al., 2003). Although revised statistics in 2013 reported workdays lost to have decreased to 30.6 million this clearly remains a prevalent and overwhelming problem ((ONS), 2015). However, the extent of the negative impact of chronic conditions on quality of life in ankle OA patients has been reported to be under appreciated (Witteveen et al., 2014). Witteveen and colleagues (2014) found foot and ankle surgeons and practitioners (n=40) significantly underestimated symptoms experienced by those with early-stage ankle OA (n=40) ($p<0.05$). This was apparent in the extent to which ankle stiffness hindered daily chores (77% vs. 42.5%), the stability of the ankle joint (80% vs. 32.5%), and the difficulty in standing (60% vs. 30%). Relative to CAI the different perspectives between clinician and patient could be preventing treatment interventions being administered, particularly if there is no pathologic evidence as would be the case in people with PI only. Acknowledging patient-reported feelings in practice, and not underestimating these, could be important for identifying treatment modalities to improve quality of life and ultimately prevent the development of OA.

As with CAI, there is currently no clear treatment pathway once ankle OA is diagnosed, aside from joint surgery a last resort in end stage OA. This section has highlighted how LAS and CAI may progress to PTOA, thus research should primarily focus on the rehabilitative modalities to treat or manage LAS and CAI in order to prevent this development.

2.6 Conclusion

This chapter introduced the high incidence of ankle sprains before discussing the debilitating consequences as this developed into a chronic condition. From reviewing the literature stability training is strongly recommended for people with CAI, however clinical pathways lack clarity and structure.

Chapter 3 – Motivation and feedback in rehabilitation

3.1 Introduction

Motor control refers to the ability to control and coordinate the body in a variety of contexts to achieve a desired outcome of movement (Utley and Astill, 2008). The process of how we learn and develop reliable and consistent skilled performance is known as motor learning. Motor learning encompasses the acquisition of new skills, or the relearning and improvement of motor skills acquired in the past, detailing the motor abilities which form the motor skill (ie. limb coordination, velocity of limb movement and accuracy in aiming) (Voelcker-Rehage, 2008).

This chapter introduces motor control and the stages of motor learning, the implications for practice and how this can affect adherence in rehabilitation. It then discusses the role of feedback and motivation in rehabilitation and the implementation of virtual reality. These come together for visualisation.

3.2 Stages of motor learning and rehabilitation

Motor learning is achieved through practice and/or experience to lead to a relatively permanent behaviour change (Utley and Astill, 2008). There are three stages of learning, as described by Fitts and Posner (1967), which outline three phases people go through when learning a new skill. The cognitive, associative, and autonomous stages describe the continuum of how the learner develops with practice (Magill and Anderson, 2017).

During the cognitive stage instructions and demonstrations are most effective where the learner is only just understanding the skill itself, and a trial-and-error approach is adopted. In the associative stage errors remain frequent and the learner must still focus attention on performing the skill itself however there is less reliance on a clinician or coach as the perception-action coupling is developed. During these initial stages of learning Bernstein (1967) described the strategy as freezing degrees of freedom to simplify the problem. Here the learner would hold or couple joints together to form rigid structures to attempt to coordinate the movement and allow the skill to be performed (Magill and Anderson, 2017). Reaching the autonomous stage the skill can be performed almost automatically, or habitually. By this point the learner would have unfrozen the joints as the movement becomes more coordinated through reorganisation and demonstrates functional synergy (Kerr and Rowe, 2019; Utley and Astill, 2008).

Although it is difficult to attain when individuals move from one stage to the next, Fitts and Posner’s (1967) stages of learning provide a framework for which rehabilitative programmes can be developed to ensure practice, feedback and attentional cues are appropriate for the specific stage of learning of the skill. The following sections detail this further.

3.3 Adherence in rehabilitation

During rehabilitation, this process can require high repetition practice. This is due to the cognitive and associative stages of learning which require repetitive practice to become familiar with the skill (Utley and Astill, 2008). However, the motivation for repeated practice can affect the adherence to rehabilitation programmes thus inhibiting their success (Argent et al., 2018).

The World Health Organisation (WHO) currently defines adherence as “the extent to which a person’s behaviour…corresponds with agreed recommendations from a health care provider” (WHO, 2003). This statement is relative to in-clinic sessions and home exercise programmes. Previous research has found that patient adherence to home exercises specifically can be as little as 50%, which could be the leading cause to programmes being ineffective (Argent et al., 2018). Further to this, Campbell and colleagues (2001) reported that not only did compliance to home exercises deteriorate from first to third follow up physiotherapy assessments in older adults with knee OA, but also that the patient’s and physiotherapist’s assessments of compliance were not always consistent. Here patients had reported full compliance but the physiotherapists had declared the same patients having at most only partial compliance (Campbell et al., 2001).

Previous research interviewing athletes identified that adherence appeared to be linked to low interest in exercises following lower limb and back injuries (Marshall et al., 2012). Further analysis showed this to be due to boredom or people seeing lack of value of the exercises to the outcome goals, which could be explained by a lack of education and understanding of importance in relation to their sport. Moreover, feelings of insufficiencies post-injury may create a barrier (Marshall et al., 2012; Teixeira et al., 2012). Following injury this is a time where the patient can suffer negative emotions such as anger, frustration and depression (Carson and Polman, 2017; Marshall et al., 2012), and so the quicker the patient becomes disengaged from these negative emotions the better as a more applied focus to the rehabilitation intervention can occur, leading to more effective recovery. For this reason, creating an environment to motivate and monitor and enable the patient’s behaviour to change, or be maintained, is of great importance. The principles from the self-determination theory (SDT) are discussed below which are utilised to attempt to satisfy the needs of the patients to elicit this change when using visualisation.

More recently virtual environments have become a popular way to provide feedback in rehabilitation to aid practice, adherence, and readiness to return to sport through increased motivation. This chapter reviews the impact of feedback and motivation in rehabilitation using virtual reality before introducing visualisation which could enhance these rehabilitation protocols in clinical practice.

3.4 Feedback in motor skill learning

Feedback of performance plays a central role in skill acquisition (Proctor and Johnson, 1995), and is the most important variable after practice affecting motor learning (Newell, 1991).

Upon movement initiation a person receives intrinsic feedback regarding the motor skill being performed. This represents the sensorimotor information which is perceived by the motor system during movement execution (Lauber and Keller, 2014). However, during the cognitive phase of (re)learning – for beginners or when neuromotor skills are impaired, as examples – this is often found to be compromised or unavailable. In these instances, research has shown augmented (extrinsic) feedback to be the most appropriate option (Williams and Hodges, 2004). This provides additional information externally to strengthen the internal perceptual trace as each practice is compared with a correct memory of the movement. Thus, as more correct movements are performed, the perceptual trace is solidified, and the recall is strengthened (Lauber and Keller, 2014). The learner develops the skill to recognise and evaluate skill performance – perception-action coupling (Utley and Astill, 2008). Hypothetically this decreases the reliance upon extrinsic feedback as the movement becomes more automatic, meaning movements can still be executed as before even when a certain aspect of feedback is compromised (ie. vision). When compared to no feedback at all, Moran and colleagues (2012) highlighted receiving quantifiable feedback on performance led to greater improvements and retention in a complex task – the tennis serve. Although this positively reflects extrinsic feedback, how and when this is presented can influence its effect. This is discussed below.

3.4.1 Augmented feedback

Knowledge of results and knowledge of performance are types of extrinsic feedback. The first feeds back the outcome of the movement (ie. Goal achievement), whereas the latter focuses on the technique of the movement to achieve this outcome (ie. Movement quality) (Lauber and Keller, 2014). Both knowledge of results and knowledge of performance can be presented using quantitative and/or qualitative information, as well as concurrently and/or terminally (ie. during or after the movement, respectively). In a recent study from Zhu and colleagues (2019) a discrete movement task was performed, tracking accuracy and reactivity. Participants received either knowledge of performance, knowledge of results or the combination of feedback following each trial. The results showed no difference between the three types of feedback regarding learned performance. This was not the case for the retention performance scores. In the retention tests the knowledge of results and combination groups missed significantly less targets ($F(2,32)=13.15$, $p<0.0001$), but knowledge of performance performed better for average hit time ($F(2,32)=30.82$, $p<0.0001$) and total movement time ($F(2,32)=42.19$, $p<0.0001$). These results partially supported the study’s hypotheses and the researchers suggested a speed-accuracy trade-off could explain why the reduced missed rate led to high movement times (Zhu et al., 2019).The results may have been different however if the goal of the task had been explained differently since knowledge of results feedback only gave information of a hit/miss and so participants were not aware of being timed. Nevertheless, the results suggest that either knowledge of results or knowledge of performance could be used, and the study did not recommend one over the other. This supported previous work by Cirstea and colleagues (2006) who found that in two stroke population samples movement reacquisition was enhanced equally by both terminal knowledge of results and concurrent knowledge of performance. However, regarding the movement as a whole, (a highly important aspect in rehabilitation), concurrent knowledge of performance feedback was superior. Knowledge of results led to more precise movements in the finger pointing task ($p<0.001$) and its retention at one month follow up (r=0.7). Knowledge of performance feedback led to faster ($p<0.05$), less segmented ($p<0.001$) and more consistent movements ($p<0.01$). At one-month retention follow up testing, this group had retained improved movement time (0.44), segmentation (r=0.43) and precision variability (r=0.58) (Cirstea et al., 2006). There is no definitive answer proposed by the researchers as to which is preferential since this is dependent on the learner’s needs, ability and the task in hand. The aim of rehabilitation is for patients to return to their daily lives using movements which closely resemble those of their non-disabled peers, to decrease chance of re-injury. To achieve this concurrent knowledge of performance feedback may be superior to provide information as to how the movement is being performed in real-time. This would be important when people with CAI are following a rehabilitation programme so that dynamic stability is improved, thus resulting in fewer recurrent ankle sprains. This does not mean knowledge of results should not be implemented here as this would provide quantitative data to record for future comparisons.

However, implementing concurrent feedback should also be carefully considered. Research has shown 100% concurrent feedback to be detrimental to performance (Goodwin and Goggin, 2018; Magill and Anderson, 2017). This is in relation to the guidance hypothesis (Lai and Shea, 1999) that suggests that although the feedback guides the learner to the desired response, the learning process may be neglected (Lauber and Keller, 2014). Further to this, it is well known that when a movement is repeated the movement pattern will be variable even if the same outcome is achieved (Latash, 2012). This creates the basis for the Uncontrolled Manifold Hypothesis (Scholz and Schoner, 1999), and thus presents the notion of whether movement should be guided specifically in this way throughout the duration of the movement. This has been acknowledged previously, however researchers suggested that when there is little to no perception of the body or the movement from which to correct against then this type of concurrent feedback could be useful (Gorman et al.,2019). In rehabilitation this could be important since patients must learn, or re-learn, techniques for successful treatment and prevention of re-injury.

Despite there being little research explicitly comparing knowledge of results and knowledge of performance both appear effective, and often used in rehabilitation. The decision to use one or the other, or a combination of both, should be dependent on the specific task, however the effectiveness could be influenced by the modality of the feedback. In rehabilitation both knowledge of results and knowledge of performance are often delivered via visual feedback or biofeedback.

3.4.2 Internal vs External focus of attention

Specifically related to knowledge of performance, another concept to consider is whether the feedback has an internal or external attentional focus. When the focus is internal the focus is on the bodily movements which result in the outcome. Opposing this, an external focus directs attention to an external factor during the movement (Schoenfeld et al., 2018). Using the single leg balance as an example task, an internal focus would be focussing on the foot interacting with the ground to remain stable, whereas an external focus would be focussing on a spot on the wall in front to remain stable.

In review studies the literature has reported enhanced performance, as defined by better motor performance and retention of movement technique, when an external focus is implemented (Benjaminse et al., 2015; Welling et al., 2016; Wulf, 2013). This has been shown across multiple sports and activities including golf, darts, and rowing, where an external focus led to enhanced movement variability and movement coordination, and technique that was retained and transferred (Welling et al., 2016; Wulf, 2013).

In relation to injury and rehabilitation use of an external focus of attention has again been supported (Rostami et al., 2018; Rotem-Lehrer and Laufer, 2019). Recently Rotem-Lehrer and Laufer (2019) conducted a short 3-day balance training intervention with male military outpatients following a lateral ankle sprain. The external focus of attention group were to focus on stabilising the platform, while the internal focus of attention group were to focus on stabilising their body. The results showed that use of an external focus of attention during training significantly improved postural control ($p<0.05$). In female volleyball athletes results showed a greater change in the kinetics compared to the control group following a 6-week ACL prevention programme (Rostami et al., 2018). The study stated that the control group received internally focussed verbal and visual instruction however the content and implementation of this was not reported. Although the study assessed the short-term effects only, the maximal ground reaction forces, rate of loading on landing, and the dynamic postural stability index, were significantly reduced in the external focus group from pre- to post-intervention ($p<0.05$) but not in the control group ($p>0.05$). This resulted in a small effect favouring the group who received instruction of external focus in the two types of common landing techniques assessed ($p<0.05$), although the study did indicate that the clinical relevance of this is not known (Rostami et al., 2018).

In summary, adopting an external focus of attention appears favourable to an internal focus of attention, particularly during the early stages of learning and during rehabilitation following an injury.

3.4.3 Visual Feedback

In review studies the literature has reported visual feedback enhances motor (re)learning outcomes (Rhoads et al., 2013; Rucci & Tomporowski, 2010; Sigrist et al., 2013; Walker et al., 2016). Previous research has used laser projections as visual cues to feedback to the participant during gait training in stroke survivors (Walker et al., 2016). Here a stationary target was positioned anterior to participants who were instructed to maintain the spot centrally from a head-mounted laser for the duration of 100 gait cycles. Results showed that the visual feedback positively influenced participants gait by reducing COM sway mediolaterally when walking ($p<0.05$). When assessing the execution of a specific weightlifting skill – the hang power clean – following six training sessions Rucci and Tomporowski (2010) found that for the visual feedback to be useful to the 16 female athletes it had to be supported by verbal information. This is likely due to the video not guiding the participant to the specific movement patterns to which they were being assessed. Regardless of technique the training led to a significant time effect for maximal strength and muscular power for all feedback groups – video only, verbal only, and combination ($p<0.05$) – with no differences between ($p>0.05$) (Rucci and Tomporowski, 2010). From the literature presented this suggests that visual feedback provides important information for motor (re)learning, however it may be important to supplement this with explanations although this will be individualised to the task and skill to be performed. For the reasons detailed above it can be understood as to why visual feedback is often used clinically, mainly in the form of mirrors or video recording (Proctor and Johnson, 1995). Nevertheless, although these are valuable methods, the information provided is neither in real-time nor an accurate representation of the movement to be processed while the action is being performed.

In the current study the final outcome aims to record, through knowledge of results, improved stability. However, knowledge of performance can be utilised to show the patients why these changes in results have happened and/or how these can be further improved, while making the patients feel more involved, as well as confident, in their rehabilitation treatment. Knowledge of performance can be delivered using visual feedback but supplemented with verbal feedback from the clinician for greater understanding during skill learning.

3.4.4 Verbal feedback

As highlighted in the above section, it is beneficial to supplement visual feedback with verbal feedback for interpretation (Rucci and Tomporowski, 2010). This knowledge of performance feedback gives further information to help the learner to address movement for improved performance of the skill (Magill and Anderson, 2017).

Verbal knowledge of performance feedback would be particularly important during the initial stages of learning where the understanding of the skill is still limited, and thus a learner would not yet have the ability to recognise their own errors in order to improve. At this point prescriptive, rather than descriptive, knowledge of performance feedback is thought to be more beneficial because it provides additional information on how to improve performance. Descriptive knowledge of performance feedback only describes what has happened. This is only useful to the learner if the requirements of the skill and performance are already intrinsically understood.

However, for verbal feedback to be effective the person’s ability and capacity to attend and process the information must be considered, as well as how the information is presented (Muratori et al., 2013; Magill and Anderson, 2017). To address this the quantity of instructions and use of cues are considered. When using prescriptive knowledge of performance feedback it has also been suggested that an active learning approach is adopted for the learner to be engaged with the learning process and can begin to solve the problem and prescribe the solution. However, the ability to do this will be dependent on the learner’s understanding of the skill (Muratori et al., 2013).

During the earlier stages of learning the skill requires conscious thought to perform the skill itself. This would suggest that the learner will have limited capacity to process information and respond to verbal instructions, thus a minimal amount of feedback should be provided so as not to overwhelm the learner (Zaton et al., 2018). Using cues is an effective method of ensuring the feedback is short and concise to direct learners’ attention and/or prompt action related to key movements (Magill and Anderson, 2017). As discussed in Section 3.4.2, using an explicit focus of attention for these is superior for performance and learning (Benjaminse et al., 2015).

3.4.5 Biofeedback

The use of biofeedback in rehabilitation by various health professionals is growing (Gheorghe et al., 2015). This type of feedback provides biological information to patients during movement as a guide, supplementing the intrinsic feedback (Gorman et al., 2019). It can be divided into biomechanical and physiological biofeedback – ie. physiologically includes neuromuscular, CV and respiratory, biomechanically includes measurements of movement, postural control and forces produced by the body. Visualisation immerses the person into a virtual environment where an avatar (real-time image of themselves) can provide biofeedback to the participant. This acts to guide the person through the movement in the desired way through specific and quantitative means to achieve the outcome goal.

In the rehabilitative environment previous research has provided knowledge of results using biomechanical biofeedback (Shepherd et al., 2016). All participants (n=22) watched an instructional video of how to perform the exercises but the biofeedback group (n=11) were the only ones to receive immediate feedback from inertial sensors to report movement success or failure. Information regarding the protocol, and specifically the criteria for errors, was not clearly stated in the publication however the results clearly showed that when feedback was provided this led to an approximately 80% reduction in errors from the first five repetitions to the last five repetitions of an exercise for one set of 10 repetitions in total, whereas there was no effect in the no feedback group. To understand this further the research compared two participants' trials for the one exercise where the errors were highest. This required the participant to hold the posture for the stated time. Results showed the feedback participant successfully held the posture for more than the threshold time for 10/10 attempts compared to the no feedback participant who had 0/10 successful attempts (Shepherd et al., 2016). The scope for interpretation of these results is limited, however, because the investigation was a case study. Furthermore, it was not reported how the participants presented were selected thus the study could have been subject to high bias. Considering this it is clear that using an inertial sensor to provide biofeedback as knowledge of results needs further investigation, however the concept has been shown to be feasible.

Alternatively, knowledge of performance can be provided using biomechanical biofeedback. When provided knowledge of performance feedback trained runners and novice rowers have effectively been shown to alter movement patterns (Eriksson et al., 2011; Gorman et al., 2019; Sigrist et al., 2013). The runners received concurrent feedback relative to the mechanical cost of running, and were able to modify their running as a result to reduce this cost (Eriksson et al., 2011). Research into novice rowers has found concurrent and terminal biofeedback of the oar movement pattern, and visual presentation of biofeedback for elbow flexion during the pull phase, were significantly more effective for enhancing technique at post-intervention and retention tests, respectively, compared to the control groups where no biofeedback was provided (Gorman et al., 2019; Sigrist et al., 2013). Sigrist and colleagues (2013) compared the terminal biofeedback to concurrent visual, auditory, haptic feedback finding it more effective for performance, however haptic feedback contributed more to learning. Previous research has only compared biofeedback to no feedback, however Sigrist et al. (2013) made a direct comparison to other types of feedback. Although this furthered previous research, this study was specific to rowing and the long-term effects on performance were not investigated thus future work is still necessary to greater understand the effects of biofeedback.

In motor learning rehabilitation for patients following stroke a study by Soares and colleagues (2019) compared performance and retention for each group after receiving either knowledge of performance or knowledge of results extrinsic feedback during training. Following a pointing task, the knowledge of results feedback showed the target ring and thus the number of points scored, and knowledge of performance feedback showed the movement trace of the index finger from the start to end position. Following 3 days of training both groups performed significantly better at post-test ($p<0.05$), however only the group who received feedback via knowledge of performance scored retained performance during both retention tests. Regarding the motor patterns both groups performed the movement with greater linearity from start to end position following training. Interestingly the knowledge of performance group achieved this making more corrections of movement during the pointing task compared to the knowledge of results group ($p=0.004$). This may suggest that this group had learned to perceive and control movement better that allowed for adaptations to be made in order to achieve better endpoint position, and thus a better score. The results here support the literature already discussed in this chapter that extrinsic feedback is effective, however this study suggests that knowledge of performance biofeedback elicits greater learning.

3.4.6 Conclusion

In conclusion, this section has reviewed 2 different types of feedback (knowledge of performance/results and attentional focus), as well as the delivery of the feedback (visual and biofeedback). These are important to consider prior to developing a training programme, particularly when using virtual reality which presents the opportunity for continual feedback when projected thus the researchers must know how to use this to optimise performance.

From the literature a mixture of knowledge of results and knowledge of performance, delivered not only be visual and biofeedback but also supplemented with verbal feedback from the clinician, should be implemented to engage the participant during training while eliciting maximal training effects, and should be individualised to the participant’s needs and stage of learning or level of skill acquisition.

3.5 Motivational components to rehabilitation

The influence of motivation on rehabilitation success has been alluded to at the beginning of this chapter. The Self-Determination Theory (SDT) was developed as an attempt to explain the motivation behind actions, and is dependent on the satisfaction of basic psychological needs (Ryan and Deci, 2000). The SDT is defined by the needs for competence (mastering skill), relatedness (creating/building meaningful connections) and autonomy (involvement and choice), and need satisfaction increases engagement and rehabilitative success (Carson and Polman, 2017, Cho et al., 2017). This influences the change of position on the self-determined continuum (Figure 3.1), which is explained in more detail below.

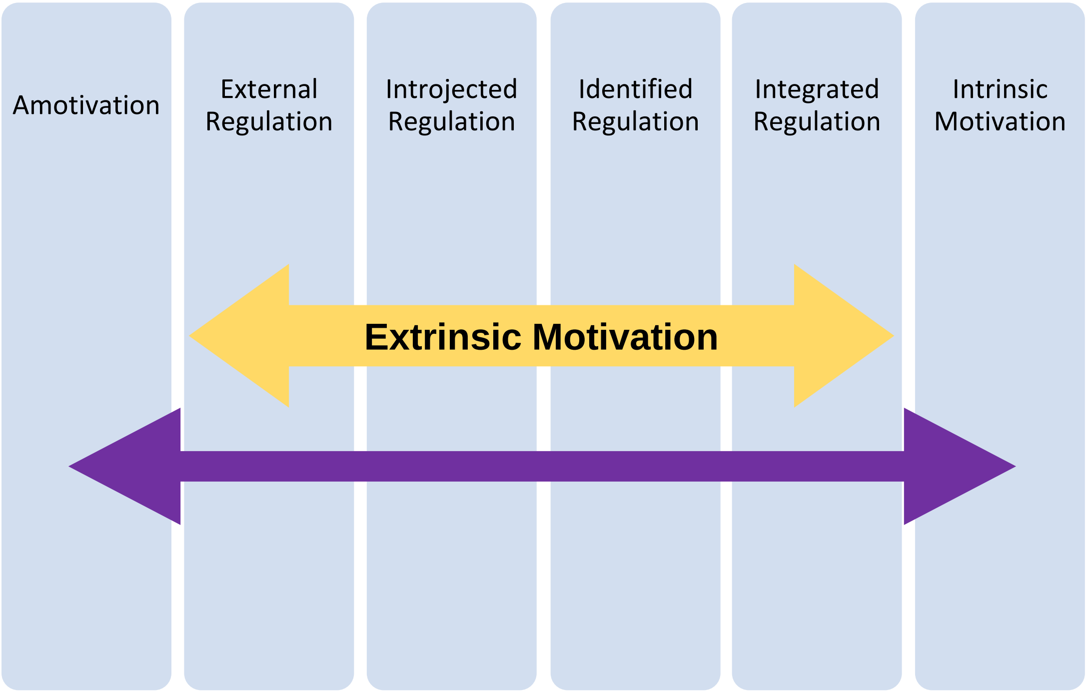


Figure 3.1 Self-determination theory continuum

Amotivation is the lowest degree of self-determination and leads to complete disengagement. This is negatively correlated with better exercise behaviour (p<0.05), thus the individual shows no interest in activities, no expectation of rewards, and no concern about punishment. Contrasting this, both extrinsic and intrinsic motivation indicated better exercise behaviour (p<0.01 and p<0.05, respectively) (Cho et al., 2017). External and introjected regulation lead to participation because the person wishes to avoid punishment or guilt, or gain reward. Identified regulation is the initialisation towards becoming intrinsically motivated, and the activity is deemed important but of no interest. The final regulatory of extrinsic motivation is integrated, where the person is not intrinsically motivated but performs the activity regardless. The results detailed above supported results from a previous systematic review, across a range of population samples both healthy and impaired. These showed the behaviours were maintained better in follow up data, analysed 24 and 36 months after initial data collection, when participants displayed higher levels of autonomous motivation (evident in identified or integrated regulated, or intrinsically motivated individuals) (Teixeira et al., 2012).

To understand how to influence motivational change along the SDT continuum previous research has been reviewed. Most recently Carson and Polman (2017) conducted semi-structured interviews during the rehabilitation of five professional rugby athletes post-ACL surgery. At the first data collection during the initial phase of rehabilitation the players identified the need to understand the rehabilitation process and become personally involved. This was important to satisfy autonomy and relatedness so as to not only trust the rehabilitative specialist, but also give some control over the process and understand for themselves as to what was being asked of them. It was suggested that this could be ensured through regular meetings with everyone involved in the rehabilitative process, which was important to the players. The results supported a previous qualitative study about the injury experience of 8 international athletes which stated a lack of support and direction from the rehabilitative specialists inhibited motivation to adhere to the programme (Marshall et al., 2012). This would ensure not only need satisfaction, but also give the opportunity to identify barriers which may prevent progress. Ball and colleagues (2017) found evidence in healthy adults relating to physical activity engagement to highlight the importance of recognising barriers. It was reported that despite not meeting the recommendations for physical activity each week this sample perceived themselves to have a higher need satisfaction than the sample of those who did meet the recommended amount of physical activity (p=0.001). This result was unexpected since those meeting physical activity recommendations would be expected to be more intrinsically motivated on the SDT continuum and thus have higher need satisfaction. The difference between the groups was accounted for by the increased barriers to exercise in the group who did not meet the recommendations (p=0.001) (Ball et al., 2017). These results do suggest that the sample not meeting recommendations may have an unrealistic perception as to their motivation, but it also highlights that barriers too need to be overcome for task engagement to be successful.

One reason it was important to outline the rehabilitative process from the beginning was so the athlete did not become distressed through not training (Carson and Polman, 2017). However, when there was not a clear direction of this process for the player, seeing improvements was a reassurance and did increase positivity (Marshall et al., 2012). This was particularly evident when goals were set. Although this does not reflect an internally motivating state it should be considered that rehabilitation may never be a self-motivating environment, thus using extrinsic motivators such as rewards may be needed to achieve success. One way to achieve this is by setting targets and providing feedback to set a clear benchmark of the requirements from the participant, thus the participant becomes accountable. Keller and colleagues (2015) conducted a study highlighting the effect of this, finding that providing the jump height as external feedback led to greater countermovement jump performances compared to when an external or internal attentive focus was utilised, providing internal feedback ($p<0.001$). The authors suggested that the provision of external feedback may have increased motivation as the participant had to maintain concentration and stay alert throughout the entire testing duration (Keller et al., 2015). In support of this, the external feedback condition reported a within-series positive effect on jump height performance compared to both the internal and external focus groups ($p<0.001$). This meant that the jump height performance did not diminish in the external feedback group as more jumps were performed and the final two jumps were compared as a percentage of the first 2 jumps. This may mean that when results were not projected motivation may have declined due to the lack of an objective goal, thus reducing performance (Keller et al., 2015; Yadava and Awasthi, 2016). This could be particularly important in the first phase of rehabilitation where the players could not be given as much autonomous control over the rehabilitative protocol and programmes often lack variety. Using external feedback could prevent the rugby players' feelings of boredom and helplessness as reported in the study (Carson and Polman, 2017).

In relation to the current research this highlights that if patients do not believe in the rehabilitative process and do not feel supported there will be little or no adherence. For this reason, rehabilitation must be interesting to aim to increase intrinsic motivation of the individuals (Cho et al., 2017). In this process by implementing need satisfaction through environmental manipulation, specifically from the use of reward, support and enjoyment, a novel method for rehabilitation could be successfully implemented. This should be achieved by providing varied, progressive, and challenging practices which clearly shows development and is related to the activity which cannot currently be performed.

3.6 Virtual Reality (VR) and Rehabilitation

The use of virtual reality is becoming increasingly popular within rehabilitation. The person is either immersed into a computer-simulated environment or, alternatively, a visualisation is created (an avatar) allowing the person to see themselves performing the exercise as it happens (non-immersive) (Howard, 2017). These differ from the methods historically employed within clinical practice where a mirror provides a reflective image, or a video recording can be reviewed post-performance.

Recent findings have shown that VR has shown improved performance in both healthy subjects and patient groups, however results have varied within balance-specific rehabilitation. A recent review by Vogt and colleagues (2019) found all studies in healthy adults and in people following MSK injury reported a positive effect favouring the VR interventions over traditional rehabilitation. In the healthy adults 8/11 studies reported a significant increase in at least one of the outcome measures for static/dynamic balance following training using VR. The evidence was not as strong in the injured groups (Vogt et al., 2019). These results supported previous systematic reviews from Howard (2017) and Tripette et al. (2017), which additionally included meta-analyses. Howard (2017) found the main effects of the meta-analysis showed that over all outcomes – motor control, balance, strength, and gait – physical abilities were improved 0.397 SD above comparison groups ($p<0.01$). However, across nine rehabilitation programmes for balance specifically, only a small positive effect 0.25 SD beyond comparison groups was evident ($p>0.10$). This review was not as comprehensive as Vogt and colleague's (2019) as no information regarding the sample of impaired individuals was provided, thus the reader does not know the variation upon sample populations. This may have skewed the results due to sample heterogeneity as currently the generalisation of the effectiveness of VR results across populations is unknown. In contrast to this, Tripette and colleagues (2017) clearly stated the exclusion criteria and specified the inclusion criteria for each outcome measure used in the meta-analysis which compared the WiiFit traditional training (n=25). In the patient group, the pooled between-group differences for the Borg Balance Scale (BBS) significantly favoured the WiiFit intervention group ($p=0.04$). For healthy adults the results were non-significant which was likely because only two studies had been included in the analysis, although it could be that an impairment is necessary for the VR to take effect. Kalron and colleagues (2016) assessed a sample with multiple sclerosis and Corbetta and colleagues (2015) conducted a systematic review of stroke survivors of which both reported VR to enhance balance performance in the respective populations. The prior investigation's results showed significant improvements ($p<0.05$) in 3 of the 4 clinical balance tests in the study after following a VR training programme, compared to those of the standardized exercise group in a small sample (n=15) (Kalron et al., 2016). In the VR group, participants were semi-immersed into a road scene on the Computer Assisted Rehabilitation ENvironment (CAREN) (Motek Forcelink, Amsterdam, The Netherlands) where balance was to be maintained, and targets collected, while the platform moved according to the visual stimuli. This supported the results of the latter study where various VR rehabilitation training was partially, or fully, integrated into the programmes (ie. virtual outdoor walking and Wii Fit balance board games) significantly improved balance with a pooled mean increase of 2.1 points on the Berg Balance Scale (95% CI 1.8-2.5, n=130) (Corbetta et al., 2015).

Within rehabilitation the aim is to return the patient to desired activities as quickly as possible, while minimising risk of reoccurrence. Regarding this Mortimer et al., (2015) found using VR as part of a 'Multimodal balance rehabilitation training device' during the initial stages of rehabilitation to be particularly promising. Despite no mention as to the specific training activities used, the authors suggested that VR facilitates a more rapid progression compared to conventional therapy. Once 'caught up' the final outcome was reported to be similar in a group of geriatric patients (n=12) (Mortimer et al., 2015). Although a significant improvement by week 2/8 was reported this study lacked any detail or result of this. However, it presents the potentiality that VR facilitates the physiological activation of the brain's areas devoted to motor learning, leading to quicker development (van der Meer et al., 2014). A quicker development, alongside statistically similar retention compared to conventional practice, of the motor skill through VR is promising for clinical practices as patients could hypothetically be discharged quicker.

When incorporating VR into rehabilitation it is important to consider the user perspective (Salamin et al., 2010). There are 2 visual perspectives available – first person and third person. A first-person perspective has the camera positioned through the avatar's eye, as if the participant was fully immersed in the environment. The third-person perspective has the camera looking onto the avatar from a distance, allowing for a full view of the body and its movements. This can be adjusted and moved to view the avatar from different angles (Salamin et al., 2010; Trabucco et al.,2019). Research comparing these has reported that user perspective alone does not appear to influence task success or engagement in activity (Covaci et al., 2014; Salamin et al., 2010). However it was seen that the third-person perspective led to better performance for movement tasks, including more similar performances to real world performances, and did influence depth perception and target performance in training when there was a higher cognitive load (Covaci et al., 2014; Salamin et al., 2006; Salamin et al., 2010; Trabucco et al., 2019). This may be due to the improved space awareness and unrestricted field of view that the third-person perspective offers, thus allowing for concurrent knowledge of performance feedback and enabling movement corrections (Gorisse et al., 2017). Trabucco and colleagues (2019) concluded that third-person perspective would be preferred when high cognitive load is required, and movement requirements are unfamiliar. Although these studies have mainly tested user perspective in an immersive environment, opposed to non-immersive, this does suggest that third-person perspective may be the more suitable approach during the initial stages of learning and rehabilitation. The research discussed above highlights the possible clinical benefit of VR, however this is not conclusive. One reason for this has to be the discrepancy between the modality in which the VR training is implemented. One study specifically highlighted this indicating within each population group reviewed the number and duration of sessions greatly fluctuated by 28 sessions and 70 minutes in stroke, 10 sessions and 30 minutes in Parkinson's disease, and 27 sessions and 20 minutes in cerebral palsy (Juras et al., 2019). Furthermore, the various VR environments created, and how they are perceived and interacted with, may be influencing the results as there could be latency and a difficultly with depth perception (Morel et al., 2015). The technology is discussed in a later Chapter 5.5.

3.6.1 Virtual Reality and motivation in rehabilitation

As mentioned, the motivation to complete rehabilitation and adhere to programmes is an important determinant to a successful outcome, but typical rehabilitation programmes are often described as boring and repetitive (Howard, 2017; Vogt et al., 2019).

Training with VR can provide adequate stimulation to engage participants for the duration of learning, which has been associated with training satisfaction and high levels of enjoyment (Kim et al., 2013; Lee et al., 2016; Llorens et al., 2015). Kim and colleagues (2013) found that when VR was integrated into the unsupervised strength and balance exercise programme in older adults there was 100% completion rate (n=18). This was compared to an 11% drop out due to loss of interest in the programme in the control group (n=17). Findings from more recent literature highlighted training satisfaction in regard to improving daily activities, which was reflected in the significantly better outcome of the Berg Balance Scale results for the VR group compared to the control group following training (5.36, p=0.012 vs. 0.77, p=0.917). Here 91% of patients were satisfied, and 77% would like to continue using it (Lee et al., 2016). The researchers also reported that 85% of caregivers felt that the Wii games benefited the patients as well.

It is important to note that use of VR should be used as an additional method for rehabilitation alongside the clinician, and should not be a replacement (Meekes & Stanmore, 2017). To compliment the need for relatedness in relation to SDT the patient must feel adequate support from the clinician. Meekes and Stanmore (2017) highlighted this reporting that although feedback was provided by the game the patients found additional feedback from the physiotherapist important (Meekes and Stanmore, 2017). This was also reported by Carson and Polman (2017) where a high order theme during the early and late limited participation phases and return to play phase of rehabilitation identified the physiotherapist as an essential source of social support. This was alongside the coach in order to maintain a positive team interaction regardless of current playing ability. This could also explain the results of Gustafsson and colleagues (2017) who reported that physiotherapist-supervised rehabilitation was superior to written instructions alone. Following an acute ankle sprain, the group receiving physiotherapist supervision (n=33) reported significantly better outcomes compared to the written instructions alone group (n=39) in quality of life (p=0.01), activities of daily living (p=0.016) and sport/ recreation function (p<0.001), and this was retained 3 months following the study also (p=0.015, p=0.001, p=0.005, respectively). Further to this after both 6 weeks and 3 months the physiotherapy group reported greater satisfaction of rehabilitation (p=0.023 and p=0.023, respectively) and physical activity ability (p=0.006 and p=0.004, respectively) (Gustafsson et al., 2017). Despite no record of baseline scores the outcome suggests that written instructions, as an additional source of information following the initial consultation where the physiotherapist had explained the rehabilitative exercises, was insufficient at improving patient-reported outcomes compared to receiving regular supervised rehabilitation sessions. With the advancing technology, and increasing popularity of using VR in rehabilitation, there is the potential for the clinician-patient interaction to be reduced, however the research here highlights that supervised rehabilitation remains superior.

Specifically, regarding game design in virtual environments Lohse and colleagues (2013) published a study which reported six key principles for effective game design for rehabilitation relative to engagement and motivation. These include:

- Reward
- Difficulty/challenge
- Feedback
- Choice/interactivity
- Clear goals and instructions
- Socialisation

The study concluded that these were neither exhaustive or mutually exclusive, and the needs, desires and ability of the players will require these principles to change. The review gave an example of this, indicating that at the beginning of a game players desire a low level of challenge as they become more familiar with the game. This has been supported more recently irrespective of age group (19-39, 40-59, 60+ years old, p>0.001) that games should be easy to learn, play and hop in and out of, but challenging and include lots of variety (Salmon et al., 2017). Very easy to play games discouraged players (Cota et al., 2015).

Clear goals were particularly important for patients to understand. Here, patient-therapist communication was highlighted as an important contributing factor to maintaining high motivation as clear and consistent instructions reassured the patient. This reiterates the importance of satisfying the needs of the patient as per the SDT as discussed above. Contrary to this, the study reported that poor instruction led to frustration and confusion and ultimately motivation deteriorated (Lohse et al., 2013).

Socialisation in rehabilitation is not always possible, and in certain populations discouraged, however it has been reported competing against time could satisfy the competitive desire (Ravyse et al., 2017). Other methods incorporated as competition with yourself have included the inclusion of scores and operant conditioning in the form of rewards as competitive elements in game design for rehabilitation, which also satisfies the reward component of effective game development (Shah et al., 2014). Considering the section on motivation previously in this chapter this is unsurprising. Previous research showed the addition of operant conditioning and/or scoring parameters significantly enhanced scores for enjoyment/interest, competence, and effort/importance ($p<0.05$). This was in comparison to a basic version of the game which included neither. The study assigned 37 healthy volunteers to play a basic version of a VR rehabilitative game and one other version of the game, in a random order, which either informed the participant of a score, included operant conditioning, or included both. Using this experimental set up the study was limited as it is unknown how the participants would have perceived the scoring, operant conditioning, and version including both compared to one another, however, a competitive and rewarding element was positively received by the healthy participants. Further to this, evidence of competitive practice during gaming in rehabilitation has been found to be successful in not only motivating participants, but also increasing the exercise intensity (Gorsic et al., 2017). Competitive practice was reported as the favourite game in 12 of the 29 participants, followed by the two cooperative practices and lastly single player. Compared to single player, the preference of competitive practice was significantly greater (p=0.013) and players also reported putting in significantly more effort (p=0.046) (Gorsic et al., 2017). This supports the literature highlighted previously to encourage extrinsic motivation during rehabilitation for adherence when intrinsic motivation is absent. Thus, use of competition within rehabilitation could lead to positive engagement and increased motivation for participation.

In addition to these principles the type of game is also important to consider. In Salmon and colleagues (2017) study all participants reported playing puzzle/strategy games most frequently and most played alone, regardless of the age of the participants. These are important results to consider as it suggests that if these aspects are included in the development of a new game for rehabilitation it could be widely accepted and enjoyed. The scope of generalisation of these results is however limited because despite the study being open to all US and Canadian residents the responding participants resigned from Canada (96%), specifically from Nova Scotia (82%) (Salmon et al., 2017). Furthermore, although Salmon and colleagues (2017) compared the different age groups there has been no research noted on the gamification of rehab across different injury populations. Thus, although future game development could consider these aspects to motivate all ages, it would be specific to the population tested only and the results could not be generalised.

3.6.2 Virtual Reality and translation to the real world

Often within rehabilitation patients perform tasks and activities which do not relate to the tasks to be achieved in the real world, even though they may target the desired motor skill. This rehabilitative technique has, however, been questioned regarding the transferability of these skills as development and ability to synergise movement needed for the desired activities may not be sufficiently learned (Howard, 2017). For these reasons it is suggested that rehabilitation programmes should involve imitation of the desired motor skills for the daily activities desired in order for optimal outcomes. VR presents the opportunity for simulation and to perform many different tasks in a safe and controlled manner, while allowing patients to relate their rehabilitation to functional activities they perform in everyday life (Keller et al., 2015, Novak et al., 2014).

Despite VR presenting a platform to achieve this there has been little research regarding the translational effects of VR training (Howard, 2017). Published work from Sloot and colleagues (2014) did find self-paced walking with VR on a treadmill better resembled normal overground walking than walking without VR (6.8m/s vs 6m/s, $p>0.05$), although this was not to significant effect (Sloot et al., 2014). Incorporating VR in balance training specifically has resulted in mixed translational results. Bonney and colleagues (2017) found that both children with developmental coordination disorder and those typically developing had significantly improved after training using VR in all functional skills including stair climbing, lifting a box, sprint slalom ($p<0.05$) (Bonney et al., 2017). Contrasting this, Mombarg and colleagues (2013) reported that although significant improvements in balance were found in children with poor motor development this was not transferred to the running, agility or hopping (*p*>0.02) in the BOT-2: running speed and agility (Bruininks and Bruininks, 2005) section scores. The result was not significant however and so further research would be needed for a definitive no transfer-effect (Mombarg et al., 2013). Howard (2017) reported similar findings but also reported that participants were able to better respond to unexpected stimuli and dual-tasking post-VR training. This is beneficial as many injuries and falls in the real-world occur due to the inability to react to external stimuli, thus VR can provide training to stimulate a positive change in the ability to cope in these occurrences.

3.6.2.1 Virtual reality and psychological readiness to return to activity

Before being discharged from rehabilitation or returning to activity and sport the person must be both physically and psychologically ready to return. Having the confidence to cope with different circumstances and unexpected situations outside of a rehabilitative environment is important for success of the task, and imitation through VR could increase the participant's readiness to do so. In previous research this has been mainly focussed on return to play following an injury in a sporting context (Podlog et al., 2011), but this could also be referred to clinical rehabilitation and returning to daily life activities. On returning to sport following injury athletes identified anxieties for fear of re-injury and performance inabilities compared to pre-injury standards. The reduced feelings of competence at this stage could inhibit the rehabilitative outcome and successful return to activity as motivation is affected as per the SDT (Podlog et al., 2011). More recent research also highlighted having confidence as a key theme following an online survey in 21 participants post-ACL reconstructive surgery (Kunnen et al., 2019). This was expressed as self-confidence in physical ability and no fear of re-injury. To achieve these outcomes participants reported being able to train, including cut and turn movements, and perform high level skills under pressure helped identify psychological readiness to return to play. Incorporating VR into a programme prior to return to sport presents an opportunity to closely simulate these situations under the control of the rehabilitative specialist, and potentially earlier on in the rehabilitative process than standard due to the increased amount of control that can be had over the VR environment, which could in turn reduce anxieties and increase confidence not only in ability but also the rehabilitative process. Furthermore, the deficit when returning to play for other aspects of the individual's skilled performance due to lack of match and training practice may be reduced as the VR training could potentially have maintained this. This is however purely hypothetical, and research is yet to be conducted regarding this.

3.7 Visualisation using Optoelectronic Motion Capture in clinical practice

As discussed above, all type of feedback is important when considering the various ways people perceive the information and use it as a motivator during rehabilitation. Visualisation combines knowledge of performance and knowledge of results, using both visual feedback and biofeedback, and biomechanical techniques to theoretically provide a new and enhanced approach to rehabilitation.

Introducing new rehabilitation techniques into clinical practice can be difficult, however Ballinger and colleagues (2016) found a sample of rehabilitation specialists from southern-central Scotland to be enthusiastic about the proposed application of visualisation technology after years of the same practice and equipment. In their study 16 stroke rehabilitation specialists participated in semi-structured interviews from across a range of disciplines (two orthotists, five physiotherapists, nine occupational therapists. There was a large range of 2-26 years of experience, but the majority had been practicing in the NHS for at least ten years. All were from southern-central Scotland and chosen for convenience rather than being purposefully recruited. Although this was a small and specific sample it included a variety of specialists with various experience which is beneficial during qualitative research where the results are subjective, and opinion based. The specialists proposed the main impact of visualisation on rehabilitation would be communication, which was suggested for three reasons:

1. easier understanding of complex tasks,
2. promotes ownership to satisfy autonomy, and
3. allows easy and objective progress monitoring.

Many discussed the current challenges of relaying concepts of tasks to patients who misunderstand and thought using visualisation would positively influence this problem. For example, patients are often unaware how their body moves and the compensatory movements which occur as the result of another (Ballinger et al., 2016). Real-time images and feedback alongside specialist explanations could combat this (Byl et al., 2015). Secondly, incorporating visualisation would allow enhanced communication between the specialist and patient, opposed to from one to the other, as the patient would have a greater understanding of their own rehabilitation and be more involved within the process. This would also promote intrinsic motivation tendencies as the need for autonomy is satisfied, according to the SDT. In relation to the third point, progress could be easily monitored as results are projected on the screen to be saved. Hypothetically this could benefit practices particularly where specialists are newly qualified with less experience as the desired information is output accurately from the application. Aside from communication, specialists were enthused by the motivational aspects of rehabilitation with visualisation. The importance of motivation during rehabilitation has already been discussed in this chapter, and the results from the rehabilitation specialists supported the identification that motivation is a key difficulty within practices. Visualisation could positively impact this problem, as the results of Loudon and colleagues (2012) would suggest. The investigation tested the use of visualisation with public and patient involvement (PPI) and received positive feedback from setting objective goals during treatment and having the ability to 'compete with yourself' (Loudon et al., 2012). Despite these favourable results, follow up work has yet to be published on use of visualisation within clinical practice.

3.8 Conclusion

Visualisation presents an opportunity to provide augmented feedback in a virtual environment to supplement that of the clinician which could potentially enhance rehabilitation for the stability-based training programme. This chapter has highlighted the importance of feedback and motivation when developing a rehabilitation programme for clinical practice, and the considerations necessary to achieve this in a virtual environment.

Chapter 4 – Design of a Stability-based training programme for rehabilitation

Stability-based training is strongly recommended for people with CAI. This chapter outlines the design of the stability-based training programme.

The aim of the programme was to improve ankle joint stability and overall postural control through constant challenge and by incorporating elements relative to the activities of daily living, such as single leg standing, change of support, transfer of weight, and coordination.

The following sections discuss the principles of training for programme design, and detail the exercise selection and progression framework for a stability-based training programme for people with CAI.

4.1 Stability-based training for people with CAI

For a training programme to be successful at improving performance there are key components to consider:

- Specificity
- Progressive overload
- Varied practice (ACSM, 2018).

Specificity ensures the exercises chosen are representative of the movements and muscles involved in achieving the desired outcome. This may be in terms of the skill as a whole, or aspects of the skill (Haff and Triplett, 2016).

Progressive overload refers to the continual challenge of the programme to ensure there is a stimulus for change and improvement. This increase in training intensity can be achieved by increasing training frequency (ie. Number of sessions per week), increasing session intensity (ie. Number of sets, reps, or exercises), or altering the requirements of the exercise (ie. Reaching further or adding cognitive tasks). However, the most important aspect of progressive overload is that progression is gradually introduced and is dependent on the individual’s ability (Haff and Triplett, 2016).

Varied practice refers to practice being performed in a variety of movement contexts (Utley and Astill, 2008). This will enable stability to be achieved and maintained across a number of different activities, tasks and conditions, and is optimal for learning (Magill and Anderson, 2017). It promotes the contextual interference effect, where the memory and performance disruption that is thought to be caused from performing a more random practice that requires multiple skill performance, leads to better learning (Magill and Anderson, 2017; Takazono et al., 2020).

These principles of training were applied to inform the design of the training programme in the current investigation. The programme produced addresses ankle stability and overall balance ability, while providing a challenging overload at appropriate intensity and regularity to stimulate change across a variety of movements and conditions (Conradsson et al., 2012).

The following section outlines the specific criteria and framework for the design of the training programme prescribed in this study.

4.2 Exercise prescription for stability-based training

Consistent with the principles of training, the stability-based programme in this investigation is specific for developing ankle stability and postural control across four movements. In order to select the exercises a framework was designed based on the principles of training and literature, functionality, and safety of the desired programme. The criteria and rationale for the stability-based training programme and detailed in Table 4.1.

There is minimal consistency between the protocols of previous research for CAI and current clinical practice. Therefore, the development of a comparable programme would not be possible regarding reliability and validity (Hegedus et al., 2015). The inconsistency across rehabilitation programmes in research extended beyond just exercise selection but also included the length of time to which the rehabilitation programme was implemented. Due to these methodological differences there has been no agreement in optimum exercise frequency (ACSM, 2018; Zouita et al., 2013).

Table 4.1 Criteria for stability-based training programme

Criteria	**Rationale**	**Evidence**
Previously used in lower limb and/or ankle rehabilitative research	To ensure that the exercises selected are representative of previous research on ankle stability-based rehabilitation Safety for performance in clinical practice.	Anguish and Sandrey, 2018; Clark et al.,2015; Cruz-Diaz et al., 2015; Hupperets et al., 2009; Comfort et al., 2015; Jaffri et al., 2017
Specific stability-based exercise	To remain specific to the goal of the programme	Magill and Anderson, 2017; Clark et al 2015; Jaffri et al., 2017
Single leg component	To challenge stability with a smaller base of support	Haff and Triplett, 2016
Dynamic exercise	Dynamic exercises can be more challenging than static exercises, and closer resemble functional activities.	Klatt et al., 2015; Utley and Astill, 2008; Gentile, 2000
Closed-kinetic chain exercise	Require minimal equipment. Greater coordination and postural control required as multi-joint exercises.	Haff and Triplett, 2016; Lee et al. 2013; Kim and Yoo, 2017
Skill level	Exercises should not be too difficult to understand or learn	Utley and Astill, 2008; Kerr and Rowe, 2019
Easy to progress	To ensure the programme can be progressive	Haff and Triplett, 2016
Modifiable	Can be modified as per individuals ability, and could be easily modified to suit differing abilities, as highlighted by the exercise progressions detailed for each exercise.	Haff and Triplett, 2016

The final exercises selected were seen to fit all criteria for the stability-based programme, as shown in Table 4.2 below. In the following sections these are discussed in greater detail.

Table 4.2 Guidelines for stability-based training programme. *Partially closed kinetic during take-off and landing.

	Single Leg Balance with leg lift	Star Excursion Balance Exercise	Lunge	Dynamic Leap and Balance Exercise
Previously used in ankle rehabilitative research	✓	✓	✓	✓
Stability-based exercise	✓	✓	✓	✓
Single leg component	✓	✓	✓	✓
Multi-joint exercise	✓	✓	✓	✓
Dynamic exercise	✓	✓	✓	✓
Closed-Kinetic	✓	✓	✓	✓ *
Skill Level	Low	Low	Moderate	Low
Safe	✓	✓	✓	✓
Easy to progress	✓	✓	✓	✓
Modifiable	✓	✓	✓	✓

The training programme is outlined below in Table 4.3. Each exercise was performed at every training session. The intensity of the exercises were considered from previous research and guidelines from the ACSM guidelines. This was to ensure that the programme remained specific to the goal of the programme which is to become more stable, and fatigue did not affect performance or safety (Guler et al., 2020; Lacey and Donne, 2019; Wilkins et al., 2004). Each exercise was performed for 2-3 sets with adequate rest between. A Rate of Perceived Exertion (RPE) from Borg (1990) of 10-12 was expected, signifying light-moderate exercise (Hupperets et al., 2009; Hale et al., 2007).

To ensure the rehabilitation programme is progressive the exercises must be challenging and directly respond to the increasing level of ability. Using the FITT principles this programme achieved this by increasing the frequency, intensity, time and/or type of the exercises (ACSM, 2018). According to the American College of Sports Medicine increasing the difficulty of balance exercises is achieved by adapting the programme to challenge the sensorimotor system more, such as:

- Reducing base of support
- Performing dynamic movements, disturbing centre of gravity
- Reduce sensory input
- Cognitive manipulation (Chodzko et al., 2009; Dault et al., 2001; Klatt et al.,2015).

Considering the above, the progression method is outlined in the table below (Table 4.3). All of these progressions were easy to introduce to progress or digress the exercises when necessary according to the clinician. The specific progressions for each exercise are then detailed in the respective sections below.

Table 4.3 Exercise frequency, intensity, and progression method

	Single Leg Balance with leg lift	**Star Excursion Balance Exercise**	**Lunge**	**Dynamic Leap and Balance Exercise**
Frequency	2 x per week	2 x per week	2 x per week	2 x per week
Intensity	2-3 sets x 10 reps 10-12 RPE	2-3 sets x 8 reps 10-12 RPE	2-3 sets x 12 reps 10-12 RPE	2-3 sets x 10 reps 10-12 RPE
Progression method	Increase intensity: perform 3 sets	Increase intensity: perform 3 sets	Increase intensity: perform 3 sets	Increase intensity: perform 3 sets
	Sensory manipulation: Vision occluded Wobble board added	Sensory manipulation: Vision occluded Wobble board added	Sensory manipulation: Wobble board added	Sensory manipulation: Vision occluded Wobble board added
		Cognitive manipulation: reactivity added	Cognitive manipulation: Dual task added	Cognitive manipulation: reactivity added
				Increase target distance

For the current investigation, a wobble board would be the only specific piece of equipment introduced as a progressive element to the training to create an unstable surface on which the participant has to control stability in a more unpredictable and challenging environment. Figure 4.1 shows an example of this being used. Previous research has shown an unstable surface to increase the number of inversion/eversion direction changes and peak velocity of ankle joint movement during a single leg balance compared to a firm surface (p<0.001) (Strom et al., 2016). For the healthy participants, these kinematic perturbations on the unstable surfaces were at least 4 times greater than performing the test on the floor. In a CAI population a greater difference would be expected due to the decreased ability to control the ankle. Further to this, studies including training on unstable surfaces as part of the balance programme have reported better outcomes in people with CAI and/or recurrent ankle injuries (Clark et al., 2015; Hupperets et al., 2009). These studies did not directly compare the specific use of an unstable surface in the programme, but rather the overall programme, however the logical progressions onto an unstable surface are justified by the need to progress training for continual performance and learning especially relative to controlling the ankle if the ankle was to give way.

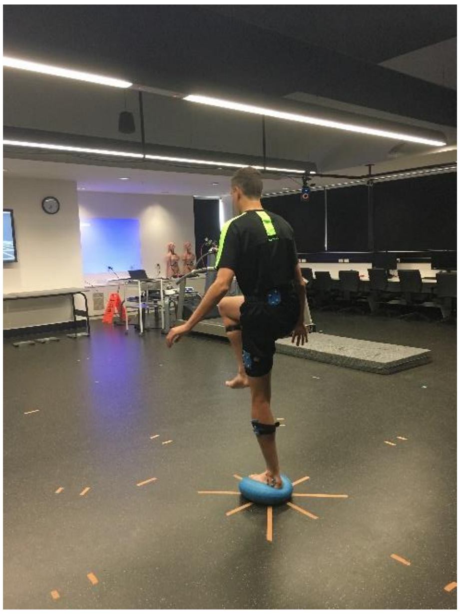


Figure 4.1 Participant performing SLB progression using wobble board

The following section explains in greater detail the exercises selected for the stability-based training in this investigation, and the levels of progression.

4.2.1 Single Leg Balance and Leg Lift (SLB)

Walking requires unilateral balance every time a step is taken but when balance and stability are affected, specifically at the ankle in those with CAI, the ability to maintain control on one leg is reduced. For this reason, the single leg balance remains an integral part of any balance programme (Clark et al., 2015; Hertel et al., 2019). Furthermore, this task is easily simplified and adjusted for all abilities, easily advanced as postural control and stability improves, and requires minimal equipment or physical exertion. However, despite the simplicity of this exercise it remains non-functional since during everyday activities the human body does not balance unilaterally without the movement of at least one other limb. For this reason, we incorporated a contralateral knee lift, as a closer imitation to everyday activities, such as the stance leg and swing leg when walking. This has been called achieving the runner’s pose (Hupperets et al., 2009).

4.2.1.1 Exercise Progressions

In order to ensure continual development throughout the training programme the SLB was progressed based on the principles above and previous research (Clark et al., 2015; Cug et al., 2016; Donovan et al., 2016; Hupperets et al., 2009). The exercise progressed when the current level was able to be performed for 3 sets of 10 reps with good technique and control. Progressions are detailed in Table 4.4 and an example of progression 2 is displayed in Figure 4.2.

Table 4.4 Exercise progressions for the SLB

SLB EXERCISE PROGRESSIONS	EQUIPMENT	DESCRIPTION
1	None	Leg lift only. Progress from 2 – 3 sets.
2	None	Leg lift with 90-180° head turns.
3	None	Leg lift with eyes closed.
4	Wobble Board	Leg Lift only.
5	Wobble Board	Forward hinge + leg lift.
6	Wobble Board	Leg lift with eyes closed.

Figure 4.2 Participant performing SLB during training

4.2.1.2 Technical considerations

Movement technique is fundamental in order to achieve full rehabilitation and functionality, where the likelihood of re-injury is reduced. When performing the SLB the body should remain still from the pelvis down, apart from the hip and knee of the non-supporting limb which are flexed to approximately 90°. The supporting limb should remain straight, with the hips level, and the moving limb should move vertically straight upwards. However, research has shown that often hip hiking can occur (Lee and Powers, 2014). This is when the hip is displaced vertically when the hip and knee are flexed. This occurs when the hip flexors and abductors are weak, thus requiring an elevation of the pelvis to elevate the foot. Aside from the sub-optimal position the spine is subjected to (Figure 4.3), this leads to a mediolateral shift of the centre of pressure which increases the difficulty of maintaining stability (Figure 4.4), which then increases the risk of ankle re-injury. Furthermore, the force acting on the body will be increased as the moment arm from the COM to the line of force is increased. This, in addition to the line of force being closer to the outer boundary of the base of support, creates a greater torque to control, thus requiring greater muscle strength to maintain postural control.

Lee and Powers (2014) reported in static standing and a dynamic step down this resulted in significantly increased peak ankle invertor and evertor moments ($p<0.05$). The primary aim of this programme is not to strengthen muscles, specifically, but addressing quality of movement will help improve body awareness which is important for control and coordination as more complex tasks are performed.

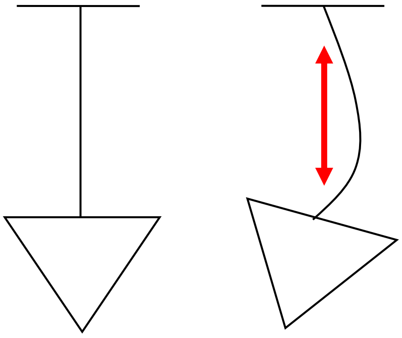


Figure 4.3 Shoulder, spine and pelvic position without (left) and with (right) hip hiking. Arrow indicates the squished spinal position

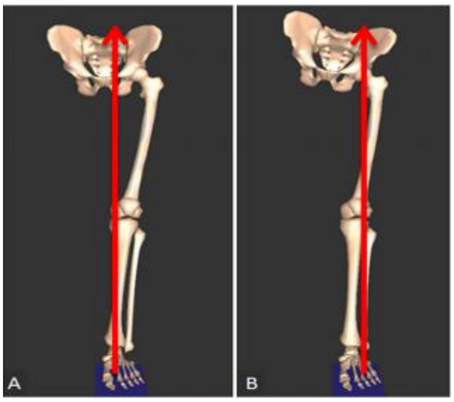


Figure 4.4 a). SLB with no hip hiking, b). SLB with hip hiking. Red arrow indicates the centre of pressure (Lee and Powers, 2014)

4.2.2 Star Excursion Balance Exercise

For the stability-based training programme to be functional it must challenge dynamic balance. The Star Excursion Balance Test (SEBT) is an accepted and reliable method adopted in clinical practice to assess dynamic postural control, and positively identify people with CAI (Gribble et al., 2012; Gray, 1995; Ness et al., 2016; Pozzi et al., 2015). The SEBT was adapted to be an exercise in the training programme.

The SEBT testing protocol requires the individual to reach in eight pre-determined directions as far from the stance leg as possible, while maintaining unilateral stance and without shifting the weight from the stance limb (Figure 4.5). In the current investigation the SEBT was adapted to form an exercise where the directions reached were not necessarily completed in the pre-determined order.

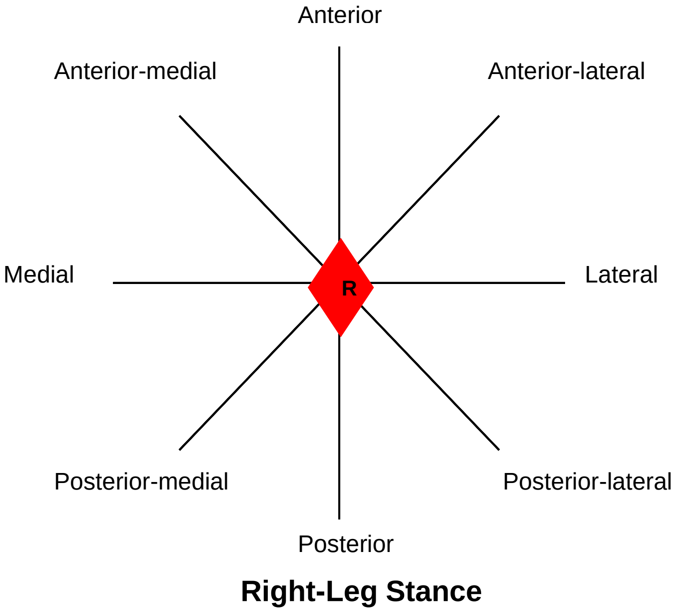


Figure 4.5 SEBT testing set up. Each black line represents the line which is to be touched as far from the stance foot (red diamond) as possible.

4.2.2.1 Exercise Progressions

These progressions are detailed in Table 4.5 and examples are shown in Figure 4.6.

Table 4.5 Exercise progressions for the SEB exercise

SEB EXERCISE PROGRESSIONS	EQUIPMENT	DESCRIPTION
1	None	Reach 8 directions in order. Progress from 2 – 3 sets.
2	None	Reach 8 directions in a random order.
3	None	Exercise performed with eyes closed. Reach directions ordered.
4	None	Exercise performed with eyes closed. Reach directions random.
5	Wobble Board	Progressions 1-4 repeated on WB.

Figure 4.6 Participant performing SEB exercise during training without (left) and with (right) wobble board

4.2.3 Lunge with distractive techniques (dual-tasking)

Within rehabilitation, exercises with greater functionality may be advantageous over traditional clinical measures since integration and coordination of multiple body components is required. Considering this, the lunge has become a common exercise within rehabilitation as a closed kinetic chain exercise since the foot remains planted on the ground and requires sequential and multi-joint movement (Kim and Yoo, 2017; Singh et al., 2015). Despite this, there is little research assessing the use of the lunge exercise for rehabilitative practice for people with chronic ankle instability.

In reality, when we move, we rarely concentrate on the primary movement being performed as the focus is either on the goal of the movement or, more often, on a completely different activity. Examples of this include talking to another person while walking, rather than focussing on the act of walking itself, or deciding where to pass the ball on a netball court, rather than landing on the ground after receiving the previous pass. It is while focusing on these other activities that the risk of destabilization is increased, thus increasing risk of injury. Rehabilitation should ensure progressive cognitive overload to increase motor skills and automatic information processing in preparation for return to sport or daily activities (Tavakoli et al., 2016). This is known as dual-tasking and is designed to re-direct attention to a secondary task while performing the primary task (Ghai et al., 2017).

Recent evidence has shown that the secondary task is prioritised to the detriment of the primary task in both healthy and CAI populations (Madehkhaksar et al., 2016; Springer and Gottlieb, 2017; Tavakoli et al., 2016). Previous research in healthy populations reported an additional cognitive task increased the mediolateral range of motion of the centre of mass, and in a CAI population this resulted in reduced variability of gait (Madehkhaksar et al., 2016; Springer and Gottlieb, 2017). The authors suggested this to reflect the inhibited ability to adapt to new environments (Springer and Gottlieb, 2017). Incorporating dual-tasking into training has been reported to successfully enhance postural stability. Ghia and colleagues (2017) reported results showing large effect sizes in the positive domain for healthy and stroke-affected elderly populations (Hedge's g: 1.63 and 0.32, respectively). To date this has not been investigated in a CAI population using a lunge.

A reverse lunge was adopted due to the significantly reduced vertical GRF and relative peak eccentric and concentric forces and joint moments compared to the forward lunge ($p<0.05$) (Comfort et al., 2015). This meant that the stresses upon the joints were controlled since the training was primarily to target and progress stability and not strength.

For the lunge exercise reverse lunges were performed continuously, alternating between legs with hands placed on iliac crests or relaxed by side for six reps on each side. Starting in a standing position facing forward the exercise was performed by stepping posteriorly to the body with one foot so that the front foot is flat on the ground with toes pointing straight forward, and the foot stepping posteriorly is in contact with the ground by the toes. The body was lowered through anterior limb hip and knee flexion, and posterior limb knee flexion. Once the anterior thigh and posterior leg were parallel with the ground, approximately 90° knee flexion in both limbs in the sagittal plane, the starting position was returned to. The trunk maintained a neutral and upright position (Nadzalan et al., 2017; Kritz et al., 2009). The aim was to perform this exercise with the anterior hip, knee and foot staying aligned to one another (avoiding knee valgus/varus), the trunk to remain upright and central to the 2 limbs in the split leg position, and for the trunk and/or knee to not shift anteriorly during the downward phase (Darragh et al., 2016). These objectives aimed to not overstress joints from reduced quality of movement and position the centre of mass between the limbs to distribute force more equally and ensure that the anterior limb was not favoured due to the more stable position of the foot, and consequently that loading of the posterior limb was not avoided due to its more unstable position (Kritz et al., 2009).

4.2.3.1 Exercise progressions

The exercise was progressed at the researcher’s discretion to challenge the participant cognitively and physically (Table 4.6). This occurred once the lunge at the current level was able to be performed for 3 sets with good technique and control, and the cognitive task could be performed with ease.

Once the lunge could be performed under various constraints a wobble board was added, for reasons discussed previously in this chapter. At this point the participant returned to level 1 again, but with the added difficulty of the wobble board under one foot. Following dual-tasking on the wobble board a leg drive could be added so the participant finished the lunge task balancing on one leg for a few seconds before placing the raised foot on the ground, rather than bringing it straight back to its start position (Figure 4.7).

Table 4.6 Exercise progressions for the lunge

LUNGE PROGRESSIONS	EQUIPMENT	DESCRIPTION
1	None	Reverse Lunge. Progress from 2 – 3 sets.
2	None	Tester points in a direction and participant must say the direction pointed to.
3	None	Exercise performed with cognitive task. Example: count down from 50 in 2s.
4	Wobble Board	Progressions 1-3 repeated on WB.

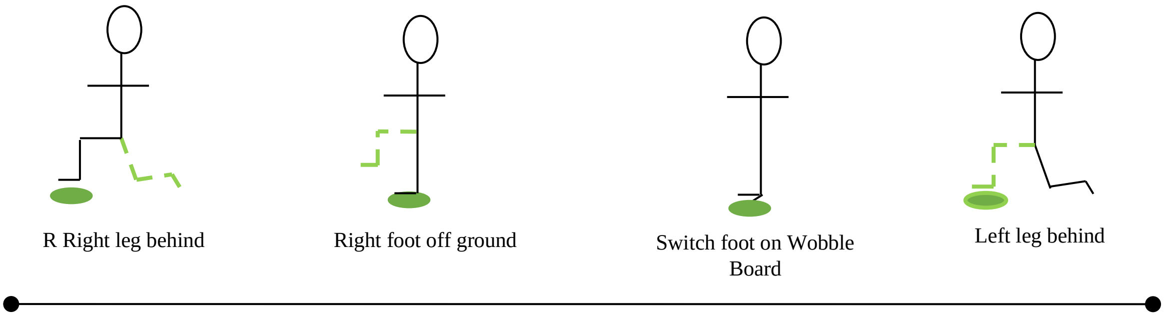


Figure 4.7 Lunge exercise performed using wobble board. Green dashed line = right leg

4.2.4 Dynamic leap and balance exercise

Currently in rehabilitation, lateral hopping exercises and tests are used to challenge the ability to control the centre of mass in the frontal plane within the narrow base of support of the foot, and the lateral aspect of the ankle complex (Caffrey et al., 2009). However, activities of daily living require postural control during multiple changes to the base of support and alternating supporting stance limb. Jaffri and colleagues (2017) created the Dynamic Leap and Balance

Test (DLBT) as a more functional measure for rehabilitation, which showed excellent test-retest reliability (ICC – 0.93). The original DLBT was a timed test in which leaps were made to each point in the predetermined order, incorporating multiple directional leaps. The targets for the DLBT were 100% and 150% leg length distance for the participant from the central target which totalled 20 leaps for the test (Figure 4.8). For the exercise in the stability-based training programme, participants were instructed to leap to either the 100% or 150% targets, depending on ability, thus performing a total of 10 leaps per set. Examples of participants performing the exercise are shown in Figure 4.9.

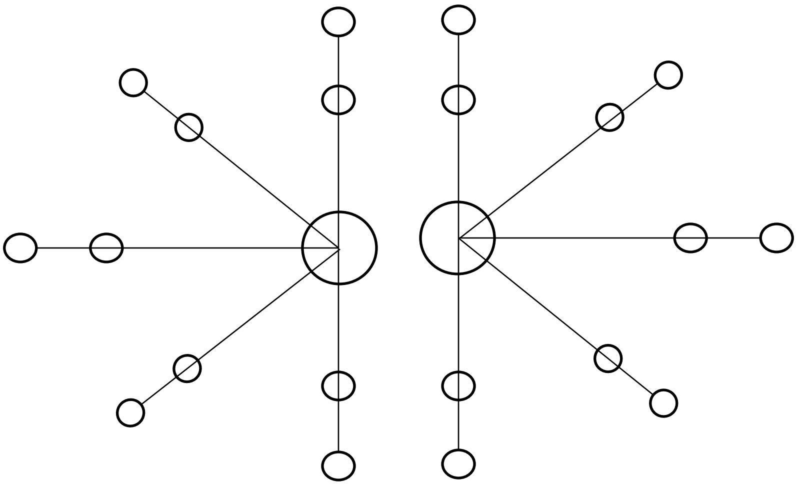


Figure 4.8 DLBT pattern for right limb (left image) and DLBT pattern for left limb (right image). Inner targets at 100% leg length distance and outer targets at 150% leg length distance from centre target

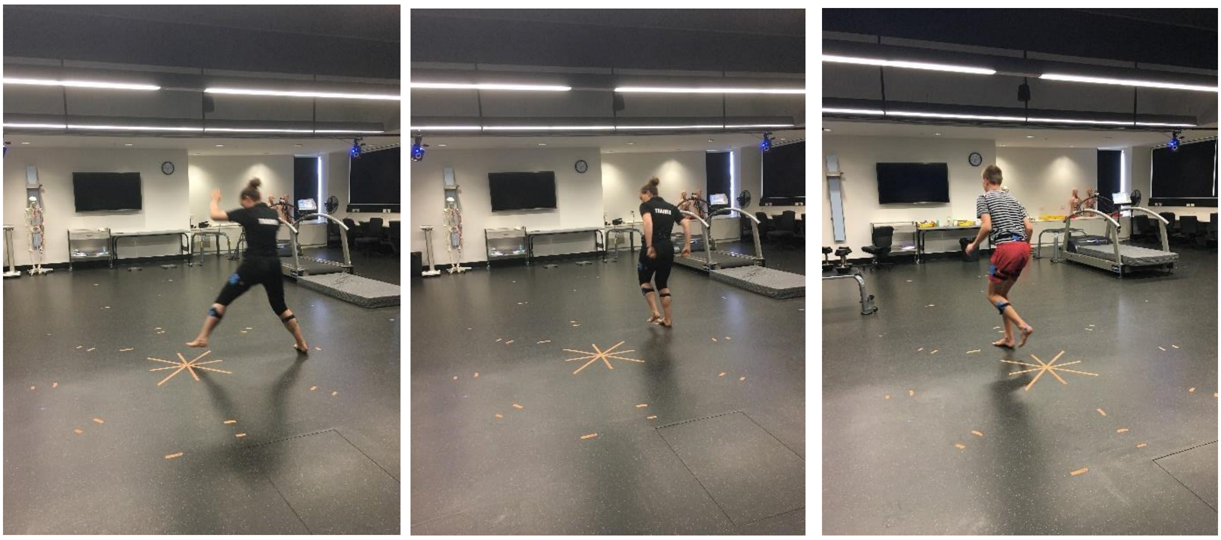


Figure 4.9 Participants performing dynamic leap and balance exercise during training. The small dots using brown tape was used to guide the direction and distance to be leapt

4.2.4.1 Exercise progressions

To ensure continual development the participants used the progressions outlined in Table 4.7. In addition to this SL squats and calf raises were added as an additional stability challenge. These exercises were chosen because they would require the participant to remain balanced unilaterally for a longer period of time while the exercise was performed.

Table 4.7 Exercise progressions for the dynamic leap and balance exercise

DLB EXERCISE PROGRESSIONS	EQUIPMENT	DESCRIPTION
1	None	Leap 5 directions in order each side. Progress from 2 – 3 sets.
2	None	Leap 5 directions in a random order each side.
3	None	Exercise performed with eyes closed. Leap directions ordered.
4	None	Exercise performed with eyes closed. Leap directions random.
5	None	Progressions 1-4 repeated leaping to distance of 150% leg length.

4.3 Conclusions

This chapter presents a stability-based training programme for people with CAI designed by applying the components of training to be specific for ankle joint stability and overall postural control and functional by incorporating elements relative to the activities of daily living. Using a progressive approach this programme aims to provide constant challenge and creates the foundation for which we add motion capture and feedback to enhance rehabilitative success.

Chapter 5 – Human movement analysis

5.1 Introduction

The analysis and interpretation of human movement is important in relation to how feedback is provided during the stability-based training programme with visualisation.

This chapter explores human movement analysis and current utilisation in clinical practice. Considering these aspects, the design criteria used to select the most appropriate technology are discussed.

5.2 Kinematics

Kinematics describes movement (Knudson, 2007). It is the study of motion where the linear and angular positions are quantified and analysed without regard of the forces acting to cause this motion (Robertson et al., 2014). In human motion, this includes identifying the position, velocity and acceleration of the movement necessary for said action, as well as calculation of the linear and angular movements of individual joints. Kinematic evaluation can be carried out in both 2-dimensions (2D) and 3-dimensions (3D), however the latter is more common nowadays with technological advancement, thus allowing for an in-depth analysis of how a body is moving (Robertson et al., 2014).

Kinematic analysis can be an end in itself, as well as supporting kinetic and/or electromyography data to give added value as to how the results have come about. Regardless of this it is important the kinematics are quantified accurately.

5.2.1 Kinematic Analysis

Historically, cinematography was used to quantify movement (Lu and Chang, 2012, Robertson et al., 2014). The cameras were of high quality and operated at a variety of frequencies, however the process was time-consuming and subject to error. Since computer technology had not been developed yet the data processing required manual digitization which introduced human error and the process was laborious as it had to be completed on a frame-by-frame basis. Furthermore, the film could not be viewed during data collection thus the quality of the data was unknown until the participant was no longer present. For these reasons the clinical applicability of motion analysis at this time was limited (Lu and Chang, 2012).

Advancements in technology progressed this to video, digital video, and optoelectronic cameras, and from 2D to 3D motion analysis. For planar motion only one camera is required perpendicular to the axis of motion desired, and 3D motion requires at least two cameras. For the analysis of movement relevant to clinical practice video cameras are popular since they provide an inexpensive tool for data collection which can be completed quickly, without extensive biomechanical expertise, and can also permit real-time participant viewing. However, the current gold-standard for reliable 3D motion capture utilises multiple optoelectronic cameras (Robertson et al., 2014). The system numerically tracks markers attached to the body using cameras which emit infra-red light. The mean error of tracked markers has been reported to range from 0.1-6mm depending on the chosen hardware, specification and number of cameras. This is explored in relation to other hardware equipment later in the chapter.

Despite just two cameras required for 3D kinematic analysis using more than this is advantageous. Creating a multi-camera system will not only reduce measurement error, but also there will be a decreased risk of marker drop out (Robertson et al., 2014). In this situation the marker is not seen by at least two cameras and thus no information from the marker at that point is detected or recorded, leading to gaps in the data.

When using optoelectronic cameras, the system must be calibrated before using for kinematic analysis. Firstly, the cameras are masked to ensure each camera view is not affected by the infrared light from another camera. This will avoid the illuminations to be mistaken for markers during assessments. Next within the field of view the software accurately reconstructs the markers on a precision-engineered calibration wand (Figure 5.1) before reconstructing the capture volume, so the cameras are all correctly defined relative to one another, and defining the volume origin.

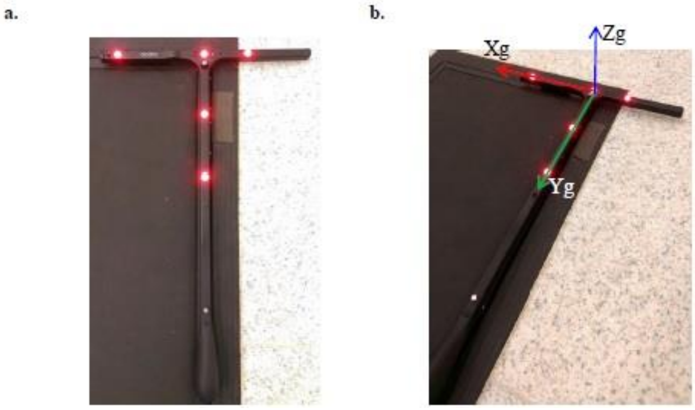


Figure 5.1 a) Calibration wand for global reference frame definition, and b) global reference frame axes (Millar, 2016)

The cameras are calibrated to minimise the residual value of each camera as this determines the accuracy of the 3D reconstruction of the markers. This residual value is required in modern motion capture to identify the marker centre where more than two cameras are used, thus meaning camera rays cannot be assumed to intersect (Figure 5.2). A mean camera residual of 0.5mm is usually deemed a successful calibration (Millar, 2016). Once this is complete the system can now be used.

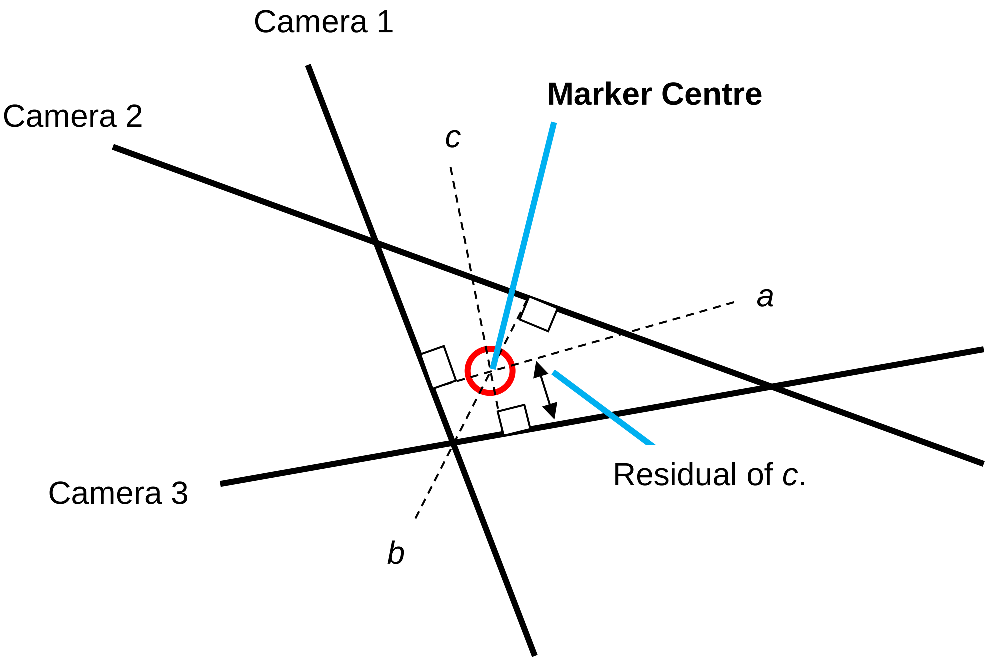


Figure 5.2 Example of determination of the marker centre using the 'least-squares' method when 3 cameras are used

5.2.1.1 Marker Models

For kinematic output during motion analysis a biomechanical model must be applied, and this requires model specific marker placement and processing for the required simulation. Markers are either individually placed on the body or attached to rigid plates (clusters) which are then attached to the body. The application of individual markers can be a time-consuming procedure as each marker is individually placed on the skin to track the movement of the underlying bone. Not only is this a timely procedure but since the markers are placed on the skin the motion between the marker on the skin and the underlying bone (soft tissue artefact) can incur inaccurate quantification of movement of the marker positions. Soft tissue artefact is well documented in the literature to be a principal error (Leardini et al., 2005; Manal et al., 2000; Peters et al., 2010). Peters and colleagues (2010) conducted a systematic review of the current literature reviewing 20 studies regarding soft tissue artefact. Despite these being high-quality studies, a pooled analysis could not be performed due to the heterogenic instrumentation and protocols of the included research. Nevertheless, results stated soft tissue artefact at anatomical landmarks to be highly variable under the various test conditions (greater trochanter: 4-20mm; lateral epicondyle: 5-30mm; lateral malleolus: 6-10mm). This in turn then affects the translational and rotational differences between methods reported for knee kinematics. Whilst this provides evidence of soft tissue artefact, results have been evaluated with caution due to the heterogeneity of the literature sample reviewed.

As well as application being a timely procedure another disadvantage of using an individual-based marker model is that applying markers to the skin requires participants to wear minimal clothing, or tight fit clothing if markers must be attached to the clothes (ie. lycra shorts). This procedure not only increases the time required to conduct this type of analysis, which would not be feasible in a short clinical appointment time, but also may make the patient feel uncomfortable. A cluster-based model provides a viable alternative. Not only can the clusters be secured quickly and easily over the participant’s clothing, but previous research reported that using a rigid plate of markers (constrained) reduced the soft tissue artefact compared to individually placed markers (unconstrained) (Manal et al., 2000; Peters et al., 2010). Manal and colleagues (2000) did not report a significant difference between models (p=0.412), however this was suggested to be a result of the study being underpowered from a participant recruitment of seven compared to the 13 needed.

Previous research has reported good correlation between kinematic output when comparing cluster-based and individual marker models during gait (Collins et al., 2009; Duffel et al., 2014; Millar, 2018). At maximum values the correlations were strongest in the sagittal plane for each joint in all studies. The models showed generally high repeatability and validity for the hip, knee and ankle throughout the gait cycle, and Collins et al. (2009) suggested the cluster-based model may be preferable. More recent research has supported these findings concluding the model outputs of their cluster-based model were comparable to Plug-In-Gait, particularly in the sagittal plane (Duffel et al., 2014, Millar et al., 2018). The agreement was lowest for hip and knee rotations however this has been reported before as a variable outcome. Duffel et al. (2014) presented a higher inter-subject variability but a lower intra-subject variability for the Plug-In-Gait model and suggested the inter-subject variability was not related to soft tissue artefact, and suggested it related to the cluster-based model being less reliant on accurate segmental marker positioning in relation to the anatomical landmarks. Millar et al. (2018) concluded that despite the good agreement in the sagittal plane the individual marker model should be used for gold-standard gait analysis. A cluster-based model however may pose suitable option for motion analysis in a clinical environment.

5.2.1.2 Reference Frame Definitions

Defining all the reference frames is necessary for movement of the body and clusters on the segments to be calculated in respect to one another to produce the desired kinematic results. Reference frames are defined by orthogonal unit vectors in the x, y and z axes. Kinematic calculation is discussed later in the following section.

As part of the final stage of system calibration the wand is placed on the floor to define the ground plane and axes of the global reference frame (GRF) at the point of origin. This is one of three reference frames relevant to this study. The GRF defines the points in 3D space in relation to the cameras and encompasses two further reference frames within - technical reference frame (TRF) and anatomical reference frame (ARF) (Figure 5.3).

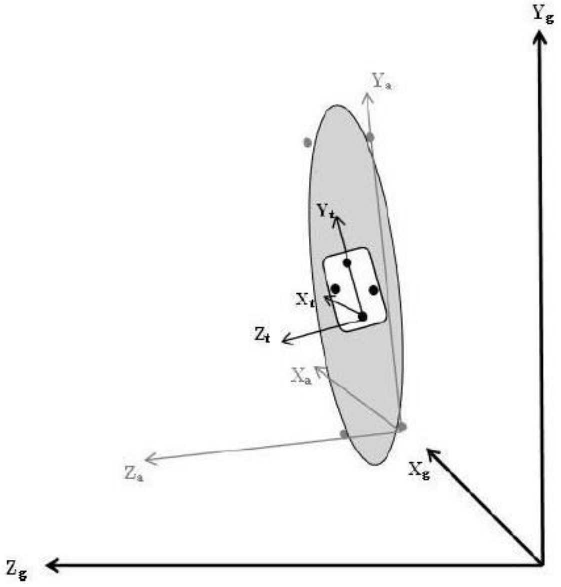
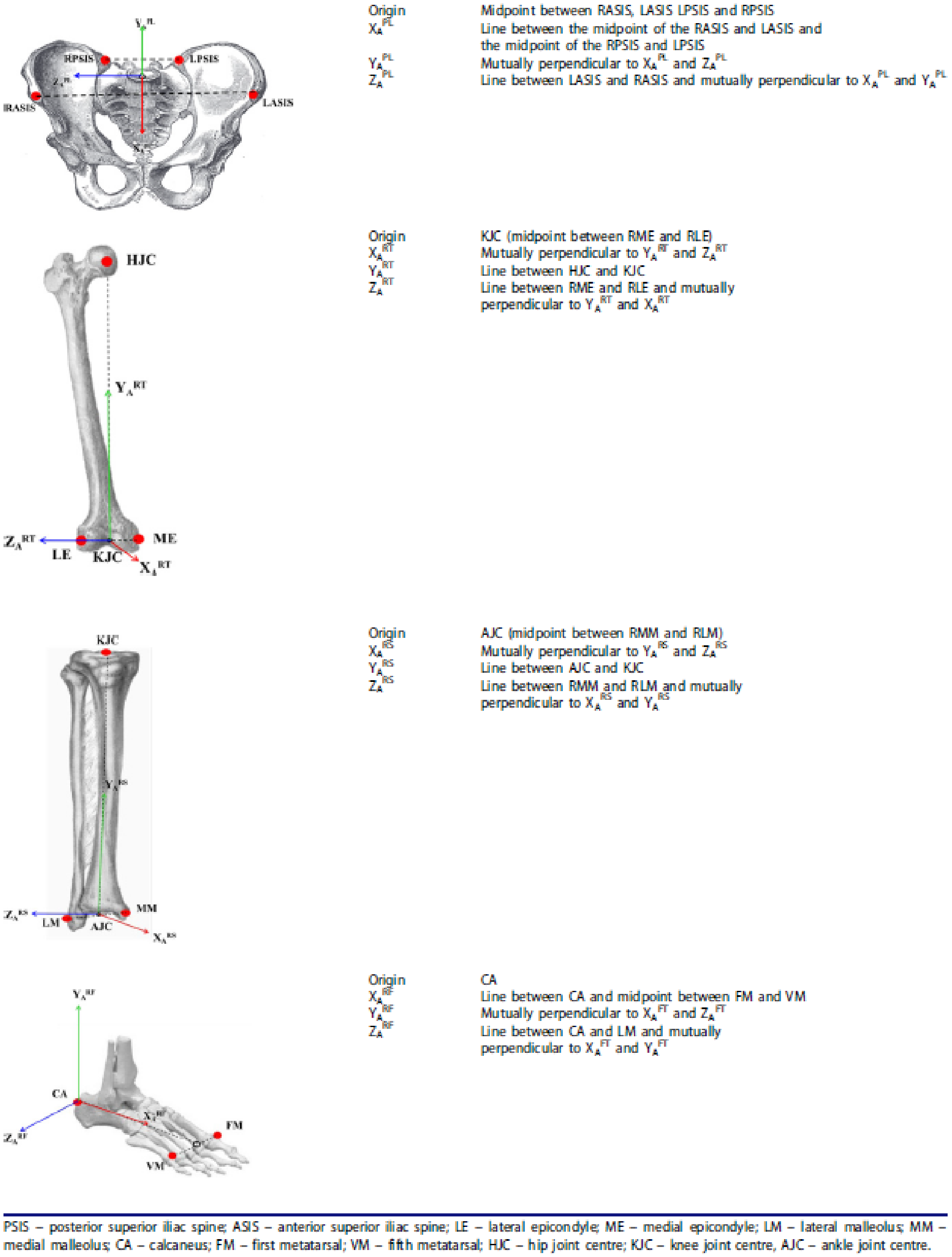


Figure 5.3 Global (g), technical (t) and anatomical (a) reference frames defined for one segment (Millar, 2016)

The TRF describes the movement of the segments and requires at least three non-collinear markers to be attached to said segment for the TRF to be defined. When using a cluster-based model, like in the current investigation, there are four markers which are used to define the TRF of the segment (Figure 5.3).

For the movement of the segments to be understood globally in relation to the moving body the ARF must be defined. The body is assumed to constitute a number of rigid segments, and anatomical landmarks on each are identified globally first before this information is used to define the ARFs. The ARFs of the lower limb model relevant to this investigation are shown in Figure 5.4. Thus, calculation of the ARFs is necessary for accurate calculation of the kinematics in accordance to the relative movement of the segmental TRFs (Millar, 2016). Once both the ARF and TRF are defined transformation matrices are constructed. If there are seven segments this would equate to seven matrices. A series of matrix transformations within ththe software enables real-time tracking of the segments and kinematic calculation. This investigation used the same protocol for this as seen in Millar (2016).



Origin	Midpoint between RASIS, LASIS LPSIS and RPSIS
X_A^{PL}	Line between the midpoint of the RASIS and LASIS and the midpoint of the RPSIS and LPSIS
Y_A^{PL}	Mutually perpendicular to X_A^{PL} and Z_A^{PL}
Z_A^{PL}	Line between LASIS and RASIS and mutually perpendicular to X_A^{PL} and Y_A^{PL}

Origin	KJC (midpoint between RME and RLE)
X_A^{RT}	Mutually perpendicular to Y_A^{RT} and Z_A^{RT}
Y_A^{RT}	Line between HJC and KJC
Z_A^{RT}	Line between RME and RLE and mutually perpendicular to Y_A^{RT} and X_A^{RT}

Origin	AJC (midpoint between RMM and RLM)
X_A^{RS}	Mutually perpendicular to Y_A^{RS} and Z_A^{RS}
Y_A^{RS}	Line between AJC and KJC
Z_A^{RS}	Line between RMM and RLM and mutually perpendicular to X_A^{RS} and Y_A^{RS}

Origin	CA
X_A^{RF}	Line between CA and midpoint between FM and VM
Y_A^{RF}	Mutually perpendicular to X_A^{FT} and Z_A^{FT}
Z_A^{RF}	Line between CA and LM and mutually perpendicular to X_A^{FT} and Y_A^{FT}

PSIS – posterior superior iliac spine; ASIS – anterior superior iliac spine; LE – lateral epicondyle; ME – medial epicondyle; LM – lateral malleolus; MM – medial malleolus; CA – calcaneus; FM – first metatarsal; VM – fifth metatarsal; HJC – hip joint centre; KJC – knee joint centre, AJC – ankle joint centre.

Figure 5.4 ARF definitions for pelvis and segments of the right limb. Left segments defined in the same way and mirrored as Z-axis positive to the right (Millar et al., 2018)

5.2.1.3 Kinematic Calculation

Once the reference frames are defined the kinematics can be calculated to quantify the participant's movement. Generally, this is defined as the joint angles between segments. Different biomechanical models may use different methods to calculate this, however all require the dynamic ARF of each segment. Applying classic mechanics allows for accurate and precise kinematic calculation in all axes (Cole et al., 1993; Grood and Suntay, 1983). Within clinical practice these are described as planes of movement (Figure 5.5, Cole et al., 1993). Specifically, the sagittal plane describes flexion/ extension as the distal segment rotates in said plane about the medial-lateral axis. The coronal plane describes abduction/adduction, where the distal segment rotates about the anterior-posterior axis – away and toward the sagittal plane. Lastly the transverse plane describes internal/external rotation as the distal segment rotates about its long axis.

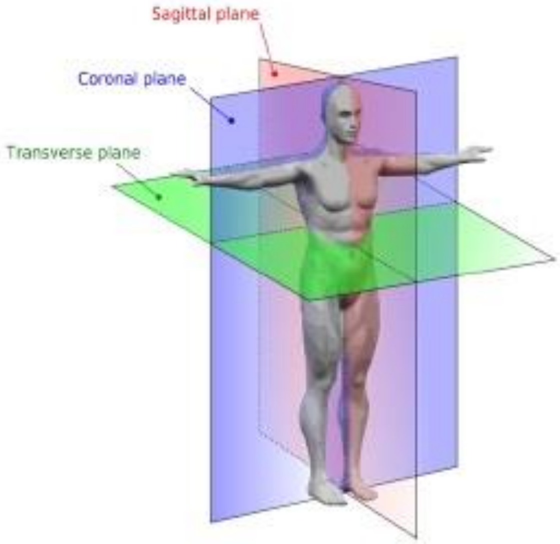


Figure 5.5 Anatomical planes (Millar, 2016)

The angle of the desired joint is calculated using the segments immediately proximal and distal to that joint, and Euler angles describe the rotation in 3D space. However, the result is dependent on the order of rotations about the x, y, and z axes. For 3D motion to be calculated using an independent sequence of rotations for joint angle calculation about the predefined axes the Grood and Suntay (1983) method was introduced, and later modified for general application methods by Cole et al. (1993). Due to its clinical relevance and the standard recommendation from the International Society of Biomechanics the SCM implements this method.

The Grood and Suntay (1983) method comprises of 3 rotation axes ($\hat{e}1$, $\hat{e}2$, $\hat{e}3$) of which 2 are embedded in the 2 relevant segments in relation to the joint and are the unit vectors of said segments ($\hat{e}1$, $\hat{e}3$). The third is a ‘floating’ axis ($\hat{e}2$), due to its movement according to the 2 bodies, and has a directionality perpendicular to both $\hat{e}1$ and $\hat{e}3$ – the cross product of the 2. Rotations about said vectors are defined below:

α = flexion-extension (rotation about $\hat{e}1$)

β = abduction-adduction (rotation about $\hat{e}_2$)

γ = internal-external (rotation about $\hat{e}3$)

5.3 Motion analysis in clinical practice

5.3.1 Current utilisation of 3D motion analysis in clinical practice

From the growing popularity for gait analysis in 1987 Messenger and Bowker predicted it would become an integral dimension to diagnostic and clinical decisions regarding patient’s functional ability and treatment modalities (Messenger and Bowker, 1987). However, more than 20 years later we would debate this has still not yet happened.

Messenger and Bowker’s (1987) original study assessed the clinical usage of gait laboratories in the UK, as well as reviewing the personal opinions of clinicians within this field. Toro and colleagues then effectively repeated this in 2003, finding little change to the state of affairs, although the population sample was estimated to only represent approximately 10.5% of all NHS physiotherapists working in the UK at the time (Toro et al., 2003). Of the 35 centres who advertised to have ‘substantial’ gait facilities in the UK, 16 responded to the questionnaire administered and were accepted for analysis. Equipment to measure temporal/distance information was the most prevalent in 15/16 centres, followed by both kinematic and kinetic information which was available in 14/16 centres. For kinematic data specifically only four had access to optoelectronic cameras. The majority of centres (75%) reported the less accurate video system for analysis, and only two reported no method of kinematic analysis. These results would imply that laboratories trade accuracy for a reduced expense, ease and quickness of operation and analysis. This was confirmed by Toro and colleague’s (2003) results which showed the five main reasons for lack of implementation among NHS physiotherapists in the UK were – 1) Lack of time (41.8%), 2) Budget constraints (38.8%), 3) Lack of space (28.8%), 4) Lack of awareness (27%) and 5) Availability of any tool (27%). These results could also be due to a lack of training, particularly junior grades who had received the least formal training

(31.7%, $p<0.005$), but also in those with a diploma or degree compared to a masters qualification (40 vs. 60.7%, $p=0.001$). This result is reflected in physiotherapists' perceived confidence when conducting gait analysis. Toro and colleagues (2003) reported a confidence of 3.04/5 for respondents who had received formal gait training, and 2.58/5 for respondents who had not. Although gait training led to a consistently higher rating of perceived ability (Kruskal-Wallis, $p<0.005$), the score only just exceeds a half-way rating from which we infer optimal patient care is not being achieved.

Further to these results, Messenger and Bowker (1987) suggested little interdisciplinary communication may be preventing greater utilisation of motion analysis in practice. The results showed that 50% of the centres did not encourage clinicians to be present upon assessment. This prevents immediate implementation of the feedback from the analysis since results would need to be relayed at a different time. At this point the patient would no longer be present, and the utilisation of the results may be determined by the skills of the clinician to interpret the information which could be limited as highlighted above. Secondly, only one centre could be distinguished as to providing a routine clinical service. This highlights that although the patient may benefit from the detailed information from the motion analysis once this is not routinely used for ongoing assessments during the rehabilitative process.

5.3.2 Use of video analysis in clinical practice

As highlighted above, video is the most popular method of analysis among clinicians. However, previous research has highlighted the limited reliability of this method of analysis (Kay et al., 2000; Lofterod et al., 2007; Williams et al., 2009).

Williams et al. (2009) reported a median inaccuracy to range from approximately 20-65% from observational gait analysis (OGA). This equated to a mean inaccuracy of 25.5±7.9% in spatiotemporal parameters and 40±8.2% for kinematic/kinetic observations. This was the result from novice and senior physiotherapists compared to instrumented gait analysis (IGA) in patients post traumatic brain injury (Williams et al., 2009). The OGA were not conducted within appointments but from video footage recorded prior and observers were required to assess patients' gait from the sagittal and coronal perspectives rating 20 gait variables. For the spatiotemporal, kinematic and kinetic variables the assessment tool asked for a simple identification as to whether each aspect of gait was normal, increased or decreased, and this was repeated for 30 traumatic brain injury patients and 25 healthy controls. It is suspected that the inexperience of two of the physiotherapist groups (novice and new graduates, n=18) explains the skewed results, since experienced observers (senior physiotherapists and rehabilitation physicians, n=17) were significantly more accurate, on average, in 8 of the gait variables. However, this difference between experience of physiotherapists was not evident in the remaining 12 variables assessed and did not predict accuracy from one variable to another. Considering this, although experience has affected the accuracy in some aspects of the assessment this is inconsistent and inconclusive, however this may have been influenced by the individual observer inaccuracy. Overall, the researchers concluded that in this population OGA displayed low accuracy and was inconsistent. Not only were these inaccuracies evident regardless of experience, but were the result of observing recordings repeatedly in slow motion. In practice time pressure may not allow for the repeated video observation which presents the opportunity for an even greater inaccuracy upon quick observational gait assessment with or without video equipment.

These results regarding the accuracy of observation are again highlighted in research about surgical decision making. On review, a number of studies found treatment plans pre-surgery to be altered in 40-89% of cases when gait analysis was utilised (Cook et al., 2003; DeLuca et al., 1997; Kay et al., 2000; Lofterod et al., 2007). Moreover only 7 and 49% of gait laboratory reports matched recommendations of referring physicians (5/70 patients and 156/318 procedures, respectively) (Kay et al., 2000; Lofterod et al., 2007). In a more recent study Wren and colleagues (2011) reported that surgeons cancelled 48% of planned procedures not recommended by gait analysis in the sample population of children with cerebral palsy. Without gait analysis surgeons only abandoned procedures in 27% of cases ($p<0.009$) (Wren et al., 2011). Although this research does not relate to stability rehabilitation, it does again highlight the reduced accuracy and reliability when motion capture equipment is not used during movement analysis.

To summarise, the research in this section has highlighted that in order to optimise patient care a more accurate and precise analysis for movement than video is necessary.

5.4 Objective results for balance rehabilitation

The benefits of using motion analysis for impacting clinical decisions and treatment pathways in gait has been well documented as reported above, but there is great potential for it to be utilised during rehabilitation training to monitor and/or assess progress. This would enable the clinician to objectively monitor progress throughout a rehabilitation programme to ensure the process prescribed is being continually effective. Not only does this information aid the clinician, but also presents the opportunity for the patient to be involved in the rehabilitative programme seeing functional capabilities changing, and hopefully improving. As suggested in the previous chapter this is motivational for the patient which is important for rehabilitation adherence.

Currently there are an extremely limited number of devices which can be used to objectively measure balance which are utilised in clinical practice. These are force plates and the Biodex Stability System (BSS - Biodex®, Inc., Shirley, NY, USA). These provide a platform for postural control and centre of pressure to be quantified and monitored, but do not allow for patient movement off the equipment or the analysis of the quality of movement to achieve the outcome on the screen. Force plates are an expensive piece of equipment and require biomechanical knowledge for analysis. As an alternative for use specifically in clinical practice the BSS (Figure 5.6) was designed. The system requires little space and includes a screen for patient feedback and a balance platform that can be manually manipulated by the clinician to adjust the level in order to test the balance capability of the person. It measures the overall, anterior/posterior and medal/lateral stability indexes calculated from the variance of the platform from a level position. However, as with the force plate the quality of the movement resulting in the documented scores cannot be monitored.

Figure 5.6 Biodex Stability System (Biodex, 2017)

Although this system presents many benefits to rehabilitation, there is even less opportunity to increase the functionality of the rehabilitation programme than with the force platforms. Thus, this system would only be useful for monitoring the very initial stages of rehabilitation if used. In this instance, when the level was 4 above baseline, the inter-session reliability has reported to be very good or excellent (ICC > 0.75), but as the level of difficulty increases this reliability decreases (Arifin et al., 2014). Cug and Wikstrom (2014) concluded that the more challenging levels on the BSS display poor test-retest scores over ten weeks meaning it may not be appropriate to use this as an objective marker of progression (Cug and Wikstrom, 2014). It should be considered that the duration of the latter study was 5 times as long as Arifin and colleagues (2014) which suggests that the positive results of the prior study assessing the BSS at an easier level could have been affected if it were conducted for a longer period of time. Considering this, force plates and even more so the BSS do not appear a cost-effective piece of equipment for rehabilitative practice due to a limited scope of use.

5.5 Virtual reality technology

Currently from the literature, incorporating virtual reality into exercise programmes for clinical practice has been achieved predominately using the Microsoft's Kinect (Microsoft, WA) and the Nintendo Wii (Wii, Nintendo Inc., Kyoto, Japan) (Vogt et al., 2019). However, research has highlighted these can only be used for rehabilitation gaming as kinematic information is either not possible, or the accuracy is inadequate for clinical measurement analysis.

The Wii Fit consists of a Wii balance board (WBB) device that tracks body sway via centre of pressure (COP) to control an avatar on the screen (Cone et al., 2015). Therefore, use of the Wii is limited to COP analysis in a standing-only environment, and no kinematic data can be collected, interpreted, or monitored. The WBB incorporates a knowledge of results feedback approach over knowledge of performance as the participants focus on the scores rather than the quality of movement (Tripette et al., 2017). This limits the relevance of using the WBB at home without the supervision of a therapist to check the quality of movement. Further to this, the WBB is not only static but unable to tilt. Historically the use of an unstable surface has been a key factor in the rehabilitation process as an added challenge, particularly for those with balance impairments, and with the WBB this could not be achieved (Tripette et al., 2017).

The Kinect offers a wider scope for analysis with the ability to track a person's body movements without using markers, and in a more dynamic environment if needed (Van der Kruk and Reijne, 2018). However, previous research highlights significant inaccuracies in measurements in comparison to the gold standard optoelectronic systems. In a series of range of motion and balance tests the markerless system showed decreased reliability compared to 3D motion capture (Bonnechere et al., 2014, Clark et al., 2015). Bonnechere et al. (2014) found significant discrepancies for hip abduction, and elbow and knee flexion ($p<0.05$) and poor to no agreement was between systems in the Bland Altman (1986). In balance and reaching tasks the Kinect V2 showed only a modest association (r=0.44-0.47) (Clark et al., 2015).

When performing more dynamic activities the Kinect again significantly differed compared to gold standard movement tracking systems (Van Diest et al., 2014; Vilas-Boas et al., 2019). Results of gait analyses found a poor correlation between the systems regarding the resulting angles, and significantly different angular displacement of the hip and knee in the sagittal plane, as well as stride timing (p<0.05) (Pfister et al., 2014; Vilas-Boas et al., 2019). Pfister and colleagues (2014) reported errors greater than 5° in every case for the hip and knee gait velocities of 3, 4.5 and 5.5mph on a treadmill. This exceeds the value of 2° for clinical acceptability, and the range of 2-5° to be potentially acceptable with interpretation (McGinley et al., 2009). Vilas-Boas et al. (2019) found the results were variable across the body segments, and dependent on whether the participants were walking towards or away from the Kinect, with walking towards the favourable direction (Vilas-Boas et al., 2019). Van Diest and colleagues (2014) found the discrepancies were particularly evident when a task was performed quicker. They concluded the Kinect was best avoided for analysis of quick dynamic movements, however the research above also suggests that the Kinect is not clinically acceptable for gait analysis either.

To adjust the size of the capture volume for the Kinect the device is moved closer to, or further away, from the participant. This ensures the participant is fully visible to the Kinect independent of their height and task being performed. However, research has speculated that precision of the Kinect reduces as the distance between device and participant increases (Yeung et al., 2014).

In summary, despite the popularity of both the Wii and Kinect systems, currently neither can compare to the use of optoelectronic systems for motion analysis where information on quality of movement is important. The Kinect presents a promising opportunity for this as a low-cost, marker-less alternative however this section has highlighted that the reliability of the system is poor which could limit its clinical utility (Clark et al., 2019).

5.6 Motion analysis for the stability-based training package

This chapter so far has introduced 3D motion capture as an accurate and reliable way to analyse movement however it is not commonly utilised in practice (Toro et al., 2003).

From the research presented there are five key areas that should be addressed when developing a motion analysis system and protocol for clinical practice (Toro et al., 2003). These are:

1. The system should be affordable
2. The results provided should be accurate and reliable
3. The system should be easy to use
4. It must not be time consuming
5. The results must be interpretable to people without biomechanical experience and understanding

Currently 3D motion capture presents the most appropriate hardware for the motion analysis in a virtual environment for rehabilitation. The WiiFit cannot be considered further since it is unable to analyse kinematic movement and movement is limited to the balance board. The Kinect offers a cheaper hardware option, however the 2D view with 3D depth imaging, lower sampling frequency (30Hz), smaller capture volume that cannot be altered (1.02-3.06m width, 0.71-2.13m height, 1-2m depth), and reduced reliability and accuracy which is dependent on the task performed and distance from the sensor do not make it the most appropriate choice for this project (Clark et al.,2019; Dutta et al., 2012; Van Der Kruik and Reijne, 2018). It is also important to note that despite the 3D motion capture being more expensive, the cost has been decreasing 10-fold each decade (Tawy, 2018) making the technology more cost-appropriate. Therefore, 3D motion capture was the selected hardware for the stability-based package.

However, it is recognised that although more accurate and reliable, 3D motion capture has been associated with complicating biomechanical analysis and being time consuming, while producing results which are difficult to understand – as per points number 3, 4 and 5 in the criteria above. This is recognised and revisited in Chapter 7, and addressed with the protocol and software selected.

5.7 Conclusions

From the research it is clear that 3D motion analysis remains under-utilised, particularly in favour of video analysis. However, the literature in this chapter shows that video analysis leads to inaccurate and inconsistent results. When virtual reality is considered there have been 2 dominant hardware used in the literature – Kinect and Wii –, however again these lack the accuracy and reliability to feedback lower limb movement in a 3D custom space. This study therefore uses 3D motion analysis to accurately represent movement as feedback in a customisable space to maximise the opportunity for practice in rehabilitation.

Chapter 6 – Healthcare professionals' opinions of biomechanics and visualisation in clinical practice

6.1 Introduction

Biomechanical technology in clinical practice is still under-utilised despite research concluding that motion analysis influences decision-making during both surgery and rehabilitative practice (Toro et al., 2003; Williams et al., 2009; Wren et al., 2011). In Chapter 5 this was associated with the costs, lack of time due to short appointment times, and lack of experience and specific biomechanical knowledge due to lack of training (Toro et al., 2003). Visualisation presents the potential to support healthcare professionals in the clinical environment. However, for visualisation to be utilised optimally it must be developed to meet the needs of those who would use it.

This chapter presents the findings from focus groups conducted. Initially the current status of biomechanics is determined from current healthcare professionals, including the barriers which prevents greater utilisation of motion analysis in practice. Following this, the future of visualisation is established and key components for its the development are identified.

6.2 Method

Focus groups are a type of group interview conducted to gather data on attitudes, perceptions and understandings on pre-determined topics (Plummer, 2017). As well as being an efficient method of gathering data opposed to one-to-one interviewing, they also create a unique opportunity to stimulate discussion as participants react to, build on and justify points made in the group. Facilitating this type of discussion gives an insight to participants' attitudes and perspectives, but also may refine or generate ideas and concepts on the topic (Plummer, 2017). Previous research has recommended homogeneity of focus groups, and a group size of six to eight participants, so participants have plenty of opportunity to, and feel comfortable to, share their thoughts and experiences (Krueger and Casey, 2014).

6.2.1 Protocol

Three focus groups were conducted in this study all of which adhered to the same protocol. First the purpose of the focus group was introduced with a 10-minute presentation, followed by a question-led discussion to provide in-depth information to the researchers on the topic of each focus group. These discussion topics are introduced in each of the specific focus group protocols below. Specifically, a question-led discussion was chosen as it enabled participants to lead the discussion between one another and 'volunteer' information as opposed to providing information 'requested' (Lennon and Ashburn, 2000). This is a popular protocol to promote group interaction during discussion with synergistic effect (Breen., 2006; Cameron, 2005). Specific questions for the discussion were written prior to the focus groups and only used if required (Appendix A). In addition to this prior to leaving participants were invited to comment on a series of statements on the topic of the focus group (Appendix A).

The discussions were audio-taped following which the recordings were transcribed for anonymity. The analysis of the transcription was based on a coding strategy to identify the main themes, and the categories and subcategories within each theme in association with the most prominent and frequent discussion topics (Breen et al., 2006; Cameron, 2005; Krueger and Casey, 2014).

Focus Group 1:

This focus group focussed on healthcare professionals' experiences of using biomechanical techniques – specifically motion capture – in current rehabilitation practice and the future of visualisation.

Health-care professionals were recruited for two separate sites – Glasgow and Livingston. Participant recruitment was conducted via email and social media posts which were distributed to private health practices, local sports clubs and institutions, and local universities.

The Glasgow focus group had two attendees – a Podiatrist and a Performance Sport Manager/Strength and Conditioning Coach. The Livingston focus group had four attendees – one Podiatrist and three Physiotherapists. This totalled six participants, who all reported over ten years of professional experience.

It is recognised by the researchers that the sample size for both of these focus groups is smaller than that recommended for focus group qualitative research (Fusch et al., 2015), and so a second focus group was conducted to address some of the same discussion points.

Ethical approval was granted by the Department of Biomedical Engineering at the University of Strathclyde (DEC.BioMed.2019.270).

Focus Group 2:

This focus group addressed healthcare professionals' experiences of using biomechanical techniques – specifically motion capture – in current rehabilitation practice, and also evaluated the clinicians' perceptions of the design of the proposed stability-based training programme using visualisations. The aim was to understand the feasibility, usability and suitability of the system and application developed before testing.

The recruitment of health-care professionals was conducted in association with Maximise Scotland's professional network, via email. In attendance were nine female healthcare professionals from the Edinburgh region. This consisted of eight physiotherapists and one podiatrist, all reporting over ten years of experience in the profession.

Ethical approval was granted by the Department of Biomedical Engineering at the University of Strathclyde (DEC.BioMed.2017.225).

6.2.2 Data Analysis

All data analysis was conducted by the lead researcher who also conducted the focus groups. The discussions were audio-taped following which the recordings were transcribed for analysis.

Data analysis was conducted using thematic analysis. This involved first becoming familiar with the data. The analysis of the transcription was then based on a coding strategy to identify the main themes, and the categories and subcategories within each theme in association with the most prominent and frequent discussion topics (Breen et al., 2006; Cameron, 2005; Krueger and Casey, 2014). A theme was determined in relation to the aim of the study and its prevalence across the data set (Braun and Clark, 2006).

6.2.3 Study Bias

The potential bias of both the participant and researcher for the focus groups was recognised and different strategies were applied to minimize this.

For the initial presentation the researcher presented the information with a conscious effort to remain objective so as not to lead participants to think a certain way before the discussion (Smith and Noble, 2014).

Before the discussion participants were reminded that the discussion would be anonymous so as no individual could be identified in the study and all were asked to answer as honestly as possible. The first discussion topic was always general before moving to more specific topics for participants to avoid bias from previous answers. The discussion was to be primarily led by the participants. The researcher used questions to ensure all desired discussion points were addressed and to provide clarity by follow up to all discussion points raised by the participants. To do this, open-ended, non-leading questions were used, and questions were asked in different ways (Chenail, 2011; Noble and Smith, 2015).

During data analysis the data were continually re-evaluated to ensure that all responses were interpreted, and data were not omitted for not supporting the hypothesis (Smith and Noble, 2014).

6.3 Results

The three main themes of the gathered data were associated with the concept outline of the focus group regarding biomechanics in clinical practice and visualisation. The categories and subcategories which emerged from the discussion within each theme are detailed in Table 6.1.

All individuals are referred to as patients for language continuity regardless of whether patients, athletes or other.

Table 6.1 Focus group data categories and subcategories

THEME	CATEGORY	SUBCATEGORY
CURRENT STATE OF BIOMECHANICS IN CLINICAL PRACTICE	**Current state of biomechanics in clinical practice**	Current assessment protocols and methods of assessment Benefits to analysing using an assessment tool Barriers to use of biomechanical techniques
DEVELOPING VISUALISATION	**Using visualisation in clinical practice**	Teaching movement in clinical practice Creating a motivational environment Current system costs Fields for use
	Future developments	System requirements Desired software features
FEASIBILITY OF THE PROPOSED STABILITY-BASED TRAINING PACKAGE	**Rehabilitation and application content**	Representative of clinical practice Frequency & duration of exercises & sessions Feedback Importance of normative data Follow up

6.3.1 Current state of biomechanics in clinical practice

Current assessment protocols and methods of assessments

The focus group revealed that gold-standard biomechanical motion analysis equipment had never been used in practice by any of the healthcare professionals, although 1 had been present at a testing session before, and another had been given a report previously. The healthcare professional who had been present at a testing session before was at the England Cricket facility, in association with Loughborough University, and they had not conducted the testing or been made aware of the results upon completion. The other healthcare professional who was not at the testing but was made aware of the results when one of their patients had undergone a biomechanical analysis was given a report of figures only.

Aside from visually analysing movement live and without the use of technology, video was the next most common method for motion analysis among the groups. One healthcare professional discussed their preferred set up in more detail using multiple camera angles and a time-delay so the patient could see the movement being assessed. Another healthcare professional discussed recent purchases of an IMU device and pressure insoles. The main attractions of these included: price, real-time feedback and that they could be worn out with practice in the real-world.

> *'Somebody could have those insoles and go away, run the park run, download the data and send it to me to look at before they come and see me. It gives you something you can use in the field rather than say bring someone into the lab, and put them on a treadmill they are not used to…''*

In sport performance athlete assessments include jump tests, sprint tests over splits (ie. 0-15m, 15-30m), and aerobic and anaerobic testing. Off-the-shelf force plates were now used to complete jump testing since they provided more information than previous methods and reduced the standardisation needed when performing the test.

> *'The output is similar to the Opti-jump-type system… It takes out the need to standardise the test quite so much. If you are doing the test with the Opti-jump system it will really just give you jump height but you can cheat on that a little bit – tuck your knees or change your technique to get a higher score. Whereas with the force plates we can measure a bit more directly. While we still get jump height, we can get force outputs and power outputs.'*

Benefits to analysing movement using an assessment tool

There were 3 reasons that became apparent as to why healthcare professionals stated the use of video to benefit their practice:

- Allows to see movement repeated from multiple angles
- Gets the patient involved in the assessment and/or training
- Can see the player in training/race environment

Using a time-delay, opposed to live video analysis, has been preferred in the past for one healthcare professional because it allowed the patient to be involved in the analysis of their own performance and feedback to the coach. This was seen to make training more appealing if the patient could actually see how they are moving from a different perspective rather than relying on only the coach's voice.

Barriers to using of biomechanical techniques

From the focus group discussion there were four main barriers that materialized. The most prevalent barrier resulting in a lack of objective movement analysis was the minimal knowledge of what is available with the group believing there to be a lack of movement analysis techniques to exist and be commercially available. This was highlighted when there was no knowledge of commercially available products such as the Microsoft Kinect and accelerometers. This was reiterated when an avatar on the screen was presented as part of a demonstration and one of the group reported they had '*never seeing anything like this before'*. In contrast to the group's current knowledge of motion capture and using specialised biomechanical techniques, the healthcare professionals agreed that the new system might be more appealing as it is easier to understand. Feedback and results could be presented in a more simplistic and appropriate manner opposed to large reports of data needing analysed.

Two of the main discussion points involved the cost of the equipment and the time needed to conduct analysis. The healthcare professional who had been present at the cricket biomechanical assessment remarked the labour-intensive nature of applying the markers. Another healthcare professional stated they had conducted MSK screenings in the past, including the Functional Movement Assessment (Functional Movement Systems, Inc., Virginia, USA) but this was too time-consuming, especially when large groups are to be tested, and so was removed from the assessment protocol.

> *'Typically we would film each of those exercises [from Functional Movement System, as example] and then go through and rate each of the exercises… because of the time it takes we have moved away from them [MSK screening/functional movement assessments] and I have just had to accept that it is just not something I can measure at this stage.'*

Considering that professional sports often have the time and money, it is still not common practice to analyse movement using specialist biomechanical assessment tools. This was suggested to be related to the lack of specialised knowledge. This was not necessarily related to using the specialised type of equipment, but the interpretation of the results, and lack of meaningful reports produced, especially if the analysis had been conducted elsewhere.

From previous experiences and perceptions of biomechanical techniques, the prospect of using specialist motion analysis equipment was a final barrier.

> *‘It would scare me to use… I am not very good with these types of things. I am a bit old-fashioned in that I can look at a person and just sort of visualise what they are doing right and what they are doing wrong.’*

6.3.2 Developing visualisation

Using visualisation biomechanics

Teaching movement in clinical practice

All healthcare professionals agreed visualisation is feasible and would benefit clinical practice. This was particularly for patients to get the visual feedback, and the ability to focus on technique and movement correction was *‘excellent’*. Furthermore, the feedback using an avatar was thought to be advantageous over a mirror because it did not require the patient to look directly at themselves.

> *‘If you are non-biomechanical, or just a Joe Bloggs… it is actually really difficult to know how you are meant to be moving. And if you can see how it is meant to happen, and how you vary from that, that would be really helpful.’*
>
> *‘…if you are trying to get them to rotate their trunk more but they are not understanding it, if you have then got the visualisations and they can see where they are meant to be going it becomes a lot easier.’*
>
> *‘I think it is easier having it as an avatar on the screen, than a mirror, because sometimes it is really off-putting looking at yourself... whereas if you are looking at an avatar you are getting the feedback of the movement rather than looking at yourself and being distracted by everything else that you are seeing’*

Creating a motivational environment

The healthcare professionals described stability training as traditionally ‘*quite boring’,* which supported the feedback one person had received from a patient after completing a 12-week balance re-education course as part of the NHS falls prevention programme. Therefore, the visual feedback on the screen was thought to create a more engaging, interesting, and fun environment, which could be more sport-specific, and could motivate patients compared to traditional practice where there is minimal effort. Without feedback there was no objective monitor to understand how the rehabilitation was progressing, and the group stated patients respond extremely well to feedback. An example given of this was seeing improvement from previous sessions. Within the NHS, visualisation was compared to a similar system already used in, and benefitting, clinical practice. The healthcare professionals who had used the Biodex Balance System reported patients to appear motivated from the feedback of their performance. However, it was acknowledged that this system lacked the ability to observe movement quality and perform functional exercises.

The opportunity to address the quality of movement from a clinician's and, more importantly, a patient's perspective, was a key aspect for healthcare professionals. The healthcare professionals felt the patient could use the feedback to learn and understand efficient movement, as determined by the clinician to prevent or rehabilitate injury, as it was believed they often have little body awareness with a disconnect between how they think they move and how they actually move. Furthermore, this would allow the patient to understand a score achieved. If this was a low score it could prevent disengagement from the training, since healthcare professionals highlighted patients '*don't want to come out with zero'*.

Current system cost

The cost of the package used as an example in the focus group received mixed opinions from the healthcare professionals. In one focus group 8/9 agreed that the system presented would be feasible for use within clinical practice, but 1 was not sure about the constraints of the NHS regarding the cost. However, within the NHS the cost of the hardware was likened to the investment of the Biodex isokinetic testing machine in the orthopaedics department. When purchased approximately ten years ago the healthcare professionals estimated a cost of ~£50,000, however stated it is in use constantly every day, including in gym classes for ACL and ankle rehabilitation. Furthermore, all healthcare professionals believed the cost would decrease over time and that the benefits, including the ability for it to be confined to a small space and opportunity for objective feedback for progress monitoring, would outweigh the expense.

Fields for use

Several different fields were suggested for where the healthcare professionals thought that visualisation could be useful and implemented. These included:

- NHS classes

- Large rehab centres and performance units (ie. Police, Military, Sport, NHS)
- Professional sports clubs and sporting bodies
- Education facility

> *'I think any sporting bodies… That is their thing, that is their time, that is their job is to rehab people back to sport… And they work out of specific places where they can have a room set aside and it does not matter if one person is in that room and the rest of the team are doing whatever. They are not just trying to train for a couple of hours, 2 nights a week, where they do not have the time, do not have the space, and do not have the resources, and do not have the money.'*

Specifically, within the NHS, healthcare professionals discussed its use across multiple disciplines, which could warrant the cost of investing in such a system – both hardware and software. These included:

- MSK
- Orthopaedics
- Neurological conditions
- Paediatrics
- Podiatry

Falls prevention classes were described as a key focus within the NHS:

> *'Falls prevention is MASSIVE. Literally massive. They are trying to prevent fractures rather than fix them. That [falls prevention] is a 12-week course at the minute.'*

Expanding on this the healthcare professionals also highlighted its feasibility in the NHS. Currently in similar scenarios the patient is prepared by an assistant, who also then controls the equipment according to the instructions given by the physiotherapist. Previous experiences of the unqualified operators showed them to be great operators, thus the healthcare professional who worked within the NHS felt they could be trained for preparing and operating the visualisation system.

Specifically, for NHS classes, the group also supported the use of visualisation. Classes were reported to usually operate with approximately 7/8 patients for a one-hour class, and each patient would be on different pieces of equipment which they would rotate around each as the class progressed. With an assistant present to help with the equipment visualisation had the potential to be included.

There was also a discussion as to whether visualisation biomechanics would be more valuable as a training or assessment tool to which opinions in the group varied. Results showed at this time more healthcare professionals believed developing a training tool using the visual feedback and having the interaction would be more beneficial to develop as a priority.

Future developments

Package requirements

All healthcare professionals agreed that the highest priority would be the cost of the equipment/software/package, and the time this would take in practice. The latter is not just in relation to the analysis and processing time, but also considering if the testing needed to be conducted in a separate facility which would include travel time. Although accuracy was important, and the groups appreciated the benefit of using multiple cameras for a multi-view analysis, it was not believed that the cost of accuracy to analyse the quality of movement would be worth the investment. Despite removes estimations and assumptions from looking at a 3D image in a 2D plane, if a product with slightly less accuracy came at a far reduced price. The focus groups could not confirm this however for two reasons:

1. The healthcare professionals do not know what hardware/software is available currently, and
2. The healthcare professionals do not know the accuracy of the low-cost systems compared to the gold standards.

All healthcare professionals agreed that real-time feedback was required for any package developed in relation to assessment or training. They acknowledged that the real-time visual feedback could be beneficial for the patient, as highlighted above, even if only reinforcing what healthcare professionals already knew from experience in the field.

> *'As a physio it potentially maybe just reinforces what you have thought about how they move, but for the patient it actually gives them figures, and gives them something to aim for.'*

Presenting the feedback as an avatar on the screen was the majority of the healthcare professionals preferred way to view the information. Although this would limit the analysis to a simulated indoor environment most of the group felt this was the best part of the package.

Although the example of visualisation is for training the healthcare professionals suggested using it also as an objective marker to intermittently reassess patients, finding it useful to have the ability to see the quality of movement. If used in this way this could functionally assess ability, which could identify risk factors or assess return to play readiness. However, a healthcare professional stated test standardisation and confidence that the training and/or assessment tools could detect a meaningful change could impact uptake considering the current cost.

> *'I think there is quite a big push for tests to be standardised… That would be one concern that I would have that even if I went and purchased that I don't know how many other people would do that same… So I might have amazing data but then I can't really compare anything.'*
>
> *'I used to measure 5m split (0-5m acceleration) and I have stopped doing that because I do not see the value in it. Every single athlete I tested for like 10 years had a score of between 0.91-1.0 for 5m, but they all had an error of like 0.02-0.03. Someone could come in on the Tuesday and be the best in the group and then do it on the Thursday and be the worst… the error was so big compared to the actual variation in the group… Can't really distinguish between who is the best and who is the worst.'*

Desired software features

Using VR to create simulations of sporting situations for assessments was suggested which would enable the healthcare professionals to monitor if the athletes could successfully repeat movements in either repeated simulations with the same variables, or random:

> *'The ball is coming out the machine at the same speed, height, and you film them all jumping. Which ones are more efficient? But in netball it is never repeated, it is never that repetitive. You have so many different angles to go at.'*

When designing a package, specific joint angle information was not specifically deemed necessary to monitor for healthcare professionals as these would not always be known, or relevant. However, some form of scoring system would be necessary to monitor progress, but this could be conveyed and tracked as a score using the joint angle information, opposed to giving a joint angle as feedback.

The ability to home-monitor was proposed by one healthcare professional in order to monitor training and/or rehabilitation outside of practice. Training was thought to be more interesting when the athlete was able to interact with a screen, while also enabling the healthcare professional to monitor movement.

6.3.3 Feasibility of the proposed stability-based training package with visualisation

Rehabilitation and application content

Representative of clinical practice

Healthcare professionals stated the exercises of the stability-based training programme (Chapter 4.2) were good stability exercises and represented basic exercises seen in clinical practice. All healthcare professionals agreed progressions were well-thought and highlighted the importance of including an unstable surface to advance the exercises easily, and more than one healthcare professional stated a like for the cognitive additions within the progressions.

Not only did the healthcare professionals find the exercises representative of rehabilitation for ankle stability within clinical practice, but also highlighted the wider application across other rehabilitation practices such as falls, anterior cruciate ligament repair, and lower back pain.

Frequency and duration of exercises and sessions

For the stability-based training programme to be used as a stability intervention, not only should the exercises represent clinical practice, but the overall programme duration and frequency must also be relative to clinical practice. The healthcare professionals agreed that the exercise volume (ie. Number of sets and reps) would be patient dependent. Two healthcare professionals stated that '*more reps for endurance*' were needed and game duration needed to be longer, however another highlighted in one exercise only one set may be possible if the patient tires, opposed to the suggested two.

With respect to the intervention of the current project the majority of healthcare professionals highlighted six weeks would be an ideal programme length, but all agreed that four weeks would be adequate to show a difference if the participants were not in rehabilitation at the time of participation. It would be expected to take longer than 4 weeks, but it was highlighted that physiologically a neuro response should happen by this time resulting in improvements.

Feedback

Visualisation provides accurate movement tracking in real-time shown as an avatar on the screen. As feedback for some exercises the initial design used a score on the screen (7.4.2.1), however a concern from one healthcare professional was how the patient knew if the movement was being performed correctly in order to understand the score. A suggestion was a more interactive acknowledgement of good movement.

> *'something that goes "ding", that would be quite interactive. I think that would be good because you know a way of moving which is incorrect and your brain just doesn't recognise that you're doing it wrong.'*

Importance of normative data

Due to the novelty of visualisation it is currently unknown as to how individuals will perform. However, creating a normative database was said to be very important.

> *'some patients will be like, "What am I aiming for? Am I able to get to level 8?"'*

Furthermore, including a control group of healthy individuals was deemed essential as many patients ask, *"What do the healthy population at a certain age group do?"* This would be another form of motivation.

Follow up

Feedback from the focus group identified the importance of including a follow up to achieve a greater understanding as to the impact of the training intervention. An example given of this was the impact of training on episodes of instability months later, and whether the training had been continued.

6.4 Discussion

This chapter has presented and discussed the results from a focus group on the experiences of biomechanical techniques in rehabilitative and performance environments, as well as future directions for visualisation from a healthcare professional perspective.

From the results the main points highlighted included:

- Lack of interdisciplinary approach within practices
- Need for education of hardware and software packages available for biomechanical use within practice, and the usability of these systems.
- Development of an affordable package, in relation to both cost and time.
- Prioritise the development of a training package, with visualisation including the avatar.

The data analysis highlighted that biomechanical assessment and information is still not implemented in practice, supporting the previous research discussed in Chapter 5 from over 15 years ago (Messenger & Bowker, 1987; Toro et al., 2003). The data here proposed two reasons as to why this might be. Firstly, the interdisciplinary approach either does not include a biomechanical assessment at all, and if it does, this information is not communicated. This means that healthcare professionals are not given the results in an appropriate way which would allow this information to influence practice. For example, tables and figures may be hard to translate to practice if the clinician cannot interpret what the data means. For this reason, video analysis has been commonly used however the subjectivity of analysing the data due to camera angle and position, as well as tester reliability, limits the objective result produced. Secondly, healthcare professionals are unaware of the systems and opportunities currently available. Although a lack of education is clear, there is also limited quality research and advertising of available products. Considering the healthcare professionals responses this has limited the potential impact of these products as little is known regarding performance outcomes. Translation of research and education has the potential to highlight the benefits of incorporating specialist technologies for biomechanical analysis and/or visualisation into practice. The researchers believe this would not only be at a clinical level but also across other disciplines, such as coaches and managers for example. This could alter perceptions and possibly validate why these may be worth investing in, if patient outcomes were better and/or quicker, despite the cost and time.

The healthcare professionals recognised the importance of analysing movement and however the use of the visualisation presented the information which was not only useful for the clinical professional but also the patient. The software produced information that was objective and could importantly be monitored by both parties, which previous research has suggested to enhance the communication between healthcare professionals and patient (MacDonald et al.,2014). However, for the data to be presented in this way the hardware should be accurate and precise to ensure correct scoring. It is thought successful monitoring of patient progress could lead to greater engagement with the process by the patient, while also providing a more encompassing report of the patient for the interdisciplinary team. In the literature, feedback has been extensively highlighted to benefit both motivation and motor learning (Gorman et al., 2019; Neilson et al., 2019; Potdevin et al., 2018), and the discussion from the focus groups has continually highlighted the importance of this and involving the patient in this process throughout this study. This supports the review of the literature in Chapter 3 the research reported how the basic psychological needs were affected, and satisfied, from receiving feedback and knowledge of progress during rehabilitation (Carson & Polman, 2017; Marshall et al., 2012). The acknowledgement that visualisation could make rehabilitation more sport-specific again promotes motivation, a particularly important aspect in the early stages of rehabilitation (Carson and Polman, 2017). However, specifically the use of visualisation as a motivational and educational tool has yet to be determined, as well as its place within the interdisciplinary team.

Finally, the discussion relative to the stability-based training programme in this study found the exercises and progressions to represent current protocols for balance rehabilitation. From this it can be inferred that the programme adheres to the principles of training and progressions for balance rehabilitation outlined in Chapter 4. The feedback regarding the detailed design of the stability-based training with visualisation is discussed in the following chapter (Section 7.4).

Strengths and limitations

The recruitment of all healthcare professionals, all with over ten years of experience, both strengthened and limited the study. The sample sizes were small but allowed active involvement for everyone during the discussion and adequate opportunity for questions to be proposed and answered. The vast experience, different professions, and different practice focus' of the healthcare professionals enabled a great insight into rehabilitative practice, the future development of visualisation, and the feasibility of the stability-based training package and protocol of the current investigation.

Nevertheless, the sample only provided the opinions of a small number of healthcare professionals in Scotland and does not consider the perspectives of more newly qualified healthcare professionals. This means that although the second focus group discussed similar experiences and opinions, revealing the same themes, the results must be interpreted considering that saturation may not have been reached. Considering these limitations, the study would have benefited from a further focus group being conducted, potentially only for newly qualified healthcare professionals, as the presence and opinions of the experience healthcare professionals may have been intimidating and overpowering.

6.5 Conclusion

In conclusion this focus group highlighted key factors as to why biomechanical techniques are still not common protocol out with research and academic institutions. For perceptions of biomechanics and its place within clinical practice to change, and new outlooks to form, hardware and software packages must be developed prioritising usability for the healthcare professionals and patient. The cost and time remain central barriers to this, which supports previous research (Toro et al., 2003), thus should be prioritised in future developments. Nevertheless, the healthcare professionals were very positive towards visualisation and encouraged the development of a training package which utilised the screen and avatar for patient interaction.

Chapter 7 – Development of the stability-based training package

7.1 Introduction

The stability-based training package aimed to create a hybrid tool to enhance rehabilitation for people with CAI, where the feedback from the package would be provided in addition to the clinician. This would enable an external focus of attention and knowledge of performance feedback to be provided verbally from the clinician to supplement the knowledge of performance and knowledge of results feedback to be provided from the on-screen interaction during the training.

This chapter details the development of the stability-based training programme from Chapter 4 using visualisation for use in clinical practice. The following sections include:

- chosen protocol and software for the clinically appropriate motion analysis system
- development of the stability-based training application using visualisation for objective, challenging, and enjoyable training, yet safe for clinical practice

7.2 Conducting motion analysis appropriate for clinical practice

The evidence so far has shown that there is a need for 3D motion analysis within clinical practice, but it is clear there remain substantial barriers preventing the wider applicability of such systems. In Chapter 5 the requirements for a clinically appropriate motion analysis system were outlined, and 3D motion capture was justified and selected as the most appropriate for use for this package.

In Chapter 5 there were five requirements outlined for biomechanical analysis to be appropriate for clinical practice. These were:

1. The system should be affordable
2. The results provided should be accurate and reliable
3. The system should be easy to use
4. It must not be time consuming
5. The results must be interpretable to people without biomechanical experience and understanding

Although not currently the most cost-effective hardware, the most appropriate hardware was the 3D motion capture which addressed the first two requirements. However, this did not address the remaining three barriers that prevent its use in clinical practice:

- ease of use
- time efficiency
- interpretable results.

In order to address the remaining three factors when developing the stability-based training package for clinical practice the biomechanical model, calibration protocol and software were considered.

These are aspects of biomechanical analysis using 3D motion capture that typically require extensive training or time to conduct. The following sections detail how the package uses 3D motion capture and incorporates a bespoke cluster model, pointer calibration, and software which is easy to use, time efficient and produces results understandable to healthcare professionals and patients (Figure 7.1).

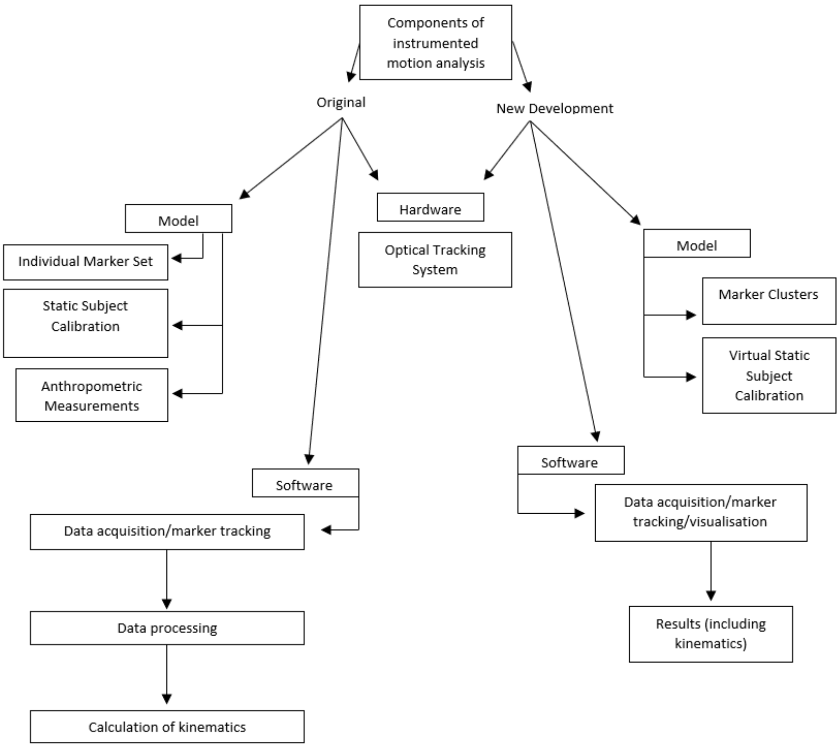


Figure 7.1 Comparison of the components required for motion analysis

7.2.1 Strathclyde Cluster Model (SCM)

Considering the short duration of appointments, hospital dress code policies, and previous findings regarding soft tissue artefacts, a cluster-based model using rigid plates was developed and applied in the current study (Millar, 2016; Millar et al., 2018).

This meant that the process could potentially be more time efficient and easy to incorporate into clinical practice for the patient and clinician. The reasons for this include:

1. Participants would not be required change into tight fitting/minimal clothing
2. Marker preparation would not be necessary
3. Less soft tissue artefact, as discussed in Chapter 5.2.1.1

Currently the SCM is a lower limb model including seven clusters which track the movement of seven segments. Each plate was designed to fit the segments with a slight curvature and small size to ensure maximum comfort and minimise movement relative to the body, while ensuring the 4 markers were spaced far enough apart to prevent confusion when identifying each cluster (Millar, 2016). Figure 7.2 details the positions of the clusters on each segment. The pelvic cluster is positioned inferior to the PSIS to ensure pelvic movement is tracked rather than the trunk. The thigh, shank and foot clusters are positioned on the lateral aspect of the respective segment with correct orientation as defined by the technical reference frame (TRF). This is shown by an arrow directing the correct position on the back of the cluster. Previous research identified significantly reduced soft tissue artefact when plates were positioned more distally on the thigh and shank segments (Manal et al., 2000). This is advised so the placement is not directly above large muscle groups.

Using Velcro straps each cluster is secured to the named segment on top of the participant’s clothing worn to the session. This was as tight as possible while comfortable for the participant to avoid slipping of the clusters. The ability to attach the clusters over clothing is extremely advantageous as it does not require specialised clothing to be worn. Previously motion analysis has required as little clothing as possible to be worn during data collection. This requirement can make participants feel uncomfortable and could be problematic in a clinical setting.

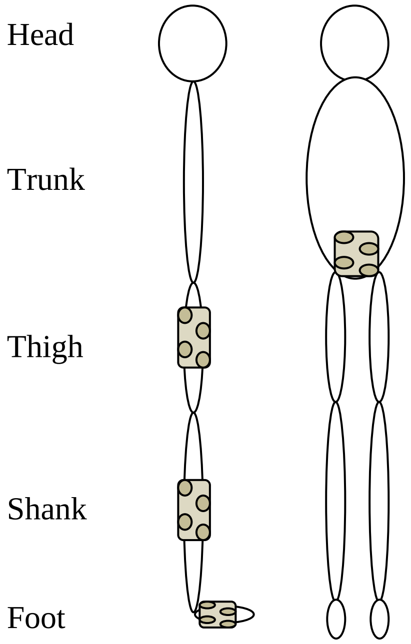
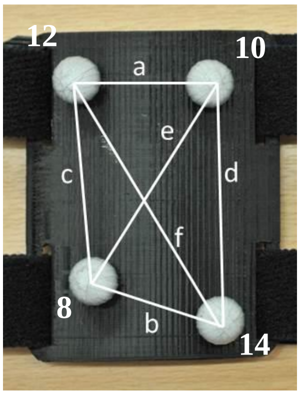


Figure 7.2 Cluster positions on each segment

7.2.1.1 Object Definition

Visualisation uses motion capture to provide feedback in a virtual environment. This occurred in two main platforms – Vicon Tracker 3.2.0 and D-Flow (Motekforce Link, Netherlands). Marker positions in the global reference frame (GRF) were determined in Vicon Tracker and then streamed into D-Flow for processing. The clusters were individually saved as ‘objects’ in Vicon Tracker which enabled automatic recognition when each was in the capture volume. The automatic identification was only possible due to the unique arrangement of the markers on each plate which meant each cluster was assigned a different Vicon Skeleton Template. The inter-marker distances on each cluster were all different, and all arranged with at least a 2mm difference to avoid marker labelling to change when tracking. To put this in greater detail, Millar (2016) arranged the markers so that marker 1 was always at one end of the shortest distance, thus in the example shown in Figure 7.3 marker 1 must be one of the indices from *a*. Here marker 1 is also an index to *c* and *f*, making it marker index 12. Marker 4 is the other index to *a*, the shortest inter-marker distance, thus is marker index 10 in the example. To identify markers 2 and 3 indices *c* and *f* are used (Figure 7.3). This process was repeated for each cluster. The ‘objects’ were saved once only, providing the same clusters were used each time. Once the cluster was located the individual markers were labelled for TRFs to be created.

The TRFs for every cluster were defined using the same cluster orientation and calculations to remain in the same axes, where marker 2 was always the cluster origin. This is shown in Figure 7.4 and Table 7.1.



Distance	Length (m)	Marker Indices	
a	0.0452	12	10
b	0.0536	8	14
c	0.0622	12	8
d	0.0675	10	14
e	0.0724	10	8
f	0.0758	12	14

Figure 7.3 Example of marker labelling algorithm (Millar, 2016) using example indices

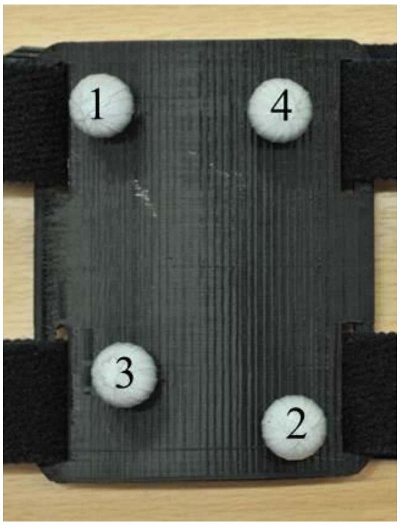
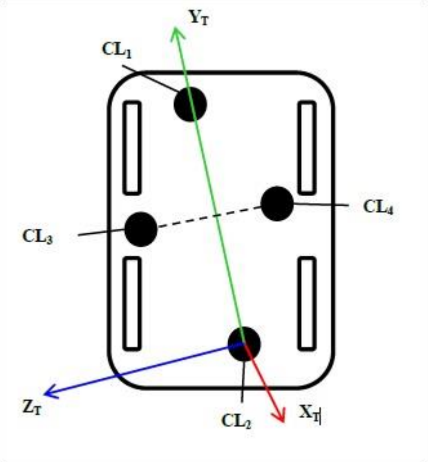


Figure 7.4 Marker labels for each cluster (Millar, 2016)

Table 7.1 Technical Reference Frame for the clusters in this study (Millar, 2016)

	Origin	CL_2
	X_T	Mutually perpendicular to Y_T and Z_T
	Y_T	Line between CL_1 and CL_2
	Z_T	Line between CL_3 and CL_4 and mutually perpendicular to X_T and Y_T

7.2.2 Participant Calibration

When using a marker model for motion analysis the participant must be calibrated for joint centres to be estimated and anatomical reference frames (ARF) determined. Participant calibration is critical whether using an individual or cluster-based marker model as this information enables accurate calculations during kinematic analysis.

Previous research has identified inaccurate identification of anatomical landmarks to be a main source of error of kinematic variables, where decreased accuracy of the landmark position increases the kinematic output error (Della Croce et al., 1999; Stagni et al., 2006). There are two main calibration methods – static and functional. The following text discusses these and presents the reasoning for using a virtual pointer static calibration.

Even when using a cluster-based model a static calibration would still require individual markers for anatomical landmark identification. The outcome of this is dependent on the person identifying the landmarks, although experienced users have shown high reproducibility (Fukaya et al., 2013; Racz et al., 2018). Even though this data can be captured for joint centre estimation and ARF determination quickly and simultaneously in one frame, the individual marker application would be time consuming and require minimal clothing. In addition to this there is a post-processing procedure to label the model. Ultimately this process counteracts the purpose of the SCM and thus decreases the appropriateness of this method of calibration within clinical practice.

The functional method does not use individual markers to estimate joint centres from anatomical landmark positions as this is done using joint range of motion (ROM) (Kainz et al., 2017; Meng et al., 2019). Defining joint centres from joint ROM controls for human error in landmark identification which is beneficial to the model due to high inter-examiner errors reported in previous research (Racz et al., 2018), however it requires that every participant must have an adequate ROM at every joint involved in the calibration. Kainz and colleagues (2017) conducted a systematic review comparing a predictive and functional method for estimating the HJC. The research identified preference for the predictive method opposed to the functional method due to the simplicity of the protocol. The authors concluded that although the functional method resulted in better performance under optimal conditions for each (ie. healthy population for functional method and patient population for predictive method), this was a minimal effect of 3-6mm. Overall authors speculated as to whether the additional effort for data collection using functional methods was warranted, particularly in clinical practice where the patients would likely have conditions and/or injuries which affect movement (Leboeuf et al., 2019).

The pointer calibration is a static calibration however instead of using individual marker placement to identify anatomical landmarks for joint centre estimation a pointer is used. This reduces the time required to prepare the participant for training or testing since no individual markers would have to be prepared or applied, and no post-processing would be required to identify the markers to complete calibration.

Here a virtual point is created when the tip of the pointer is placed on the desired anatomical landmark (Figure 7.5). This virtual point is a known distance from four asymmetrical markers fixed to the pointer, which have been identified as a cluster within Vicon Tracker to create the local coordinate system. The orientation of this pointer was shown to not significantly affect the position saved for the particular point of interest, however it is recommended that the pointer be held consistently in a neutral position throughout calibration (Tawy and Rowe, 2017, Millar, 2016). Each landmark is identified individually one after the other and in this application must be completed in a particular order. This is so the information saved corresponds to the correct anatomical landmark calibrated. Each position was saved using a switch manually controlled by the person calibrating (Figure 7.5).

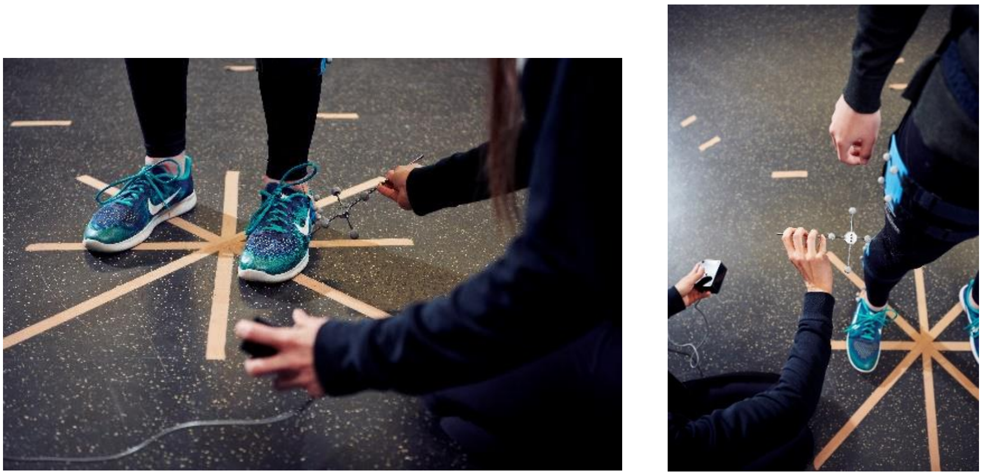
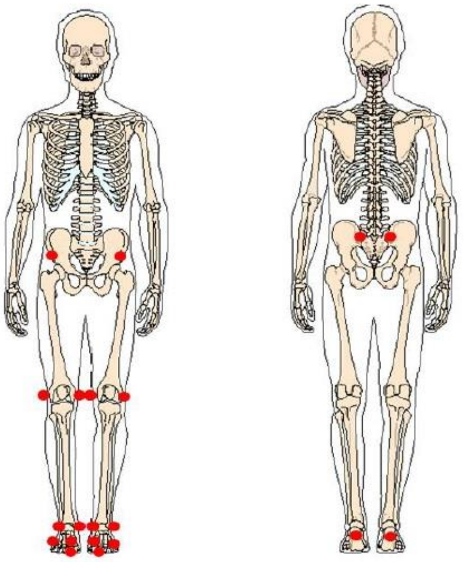


Figure 7.5 Participant calibration using a pointer and switch to save the 5th Metatarsal head position (left) and right lateral epicondyle (right)

The anatomical landmarks identified in this study are detailed in Table 7.2. From the positions saved the joint centres of the hip, knee and ankle are calculated as per Millar (2016), and are used to construct the anatomical-cluster matrices in relation to the clusters on the segments which will establish the live coordinates which are updated each frame (Tawy, 2018). It is important to note that to calculate the joint centres a number of regression equations are used, thus these must also be reliable alongside anatomical landmark positions, to ensure accuracy of joint centre locations for the ARFs (Bell et al., 1989, Harrington et al., 2007). The KJC and AJCs were calculated as midpoints between the LE and ME and LM and MM for the knee and ankle, respectively. The position of the hip joint centre cannot be calculated this way and in this model is calculated using Bell's (1989) equations (Millar, 2016).

Table 7.2 Anatomical landmarks for joint centre calculation and ARF definition

Anatomical Landmarks (Left and Right)	
Anterior Superior Iliac Spines (ASIS) Posterior Superior Iliac Spines (PSIS) Medial Epicondyles Lateral Epicondyles Medial Malloelus Lateral Malleolus Calcaneus Head of 1st Metatarsal Head of 5th Metatarsal Apex of Big Toe	

7.2.3 Conclusion

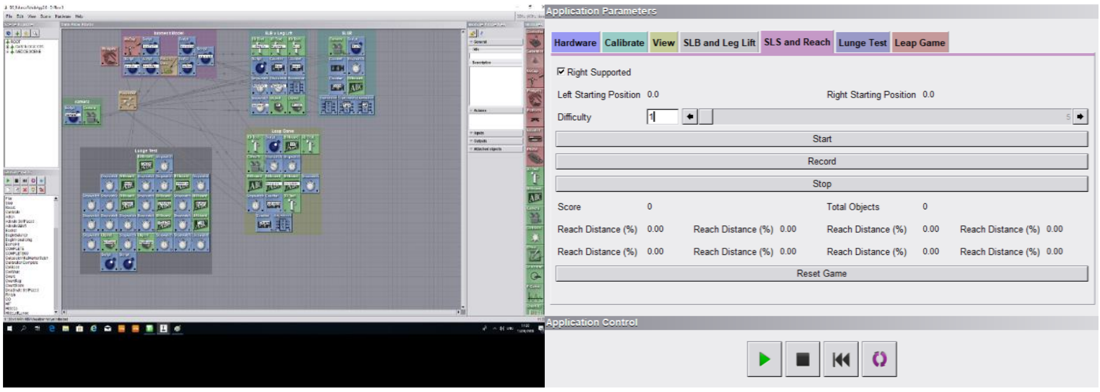
The specific biomechanical model and calibration method for the stability-based training package has been detailed in the preceding sections. The ease of application of the clusters and no need for individual markers reduces the preparation time which makes it feasible for clinical use. A comparison of the kinematic output using the model and calibration method was also conducted (Appendix B). The study supported previous research and concluded it to be the most appropriate model and calibration method for this investigation as part of the stability-based training package.

7.3 Software

Presenting biomechanical data is complex, as highlighted in Chapter 5 as a key factor to overcome when developing a clinically appropriate motion analysis system, and by the healthcare professionals in Chapter 6. This has prevented biomechanical techniques being utilised to optimise rehabilitation (Ballinger et al., 2016).

The D-Flow software presents an opportunity to present biomechanical data in a simplified way to a variety of health care disciplines and service users. It is a graphically based programme from Motek allowing synchronisation of various data inputs and hardware to control visualisations (Collins et al., 2015). Module-based applications are developed, supported by scripting in LUA, to provide real-time feedback, clear and objective data, and motivational gaming elements, all in a controlled environment. However, as it is controlled from a user interface it can be simple for non-experts to use as the internal programming does not need to be understood. Figure 7.6 displays an application (left) compared to an example of the runtime console for the user (right). The user interface can be manipulated by clinicians when needed (ie. To change the level of difficulty or the feedback displayed on screen).

For these reasons, and its compatibility with the motion capture system, the D-Flow software was used as the platform to develop the application of the visualisations for the stability-based training programme outlined in Chapter 4.



☑ Right Supported

Left Starting Position 0.0

Right Starting Position 0.0

Difficulty 1

Score 0

Total Objects 0

Reach Distance (%) 0.00

Reach Distance (%) 0.00

Reach Distance (%) 0.00

Reach Distance (%) 0.00

Reach Distance (%) 0.00

Reach Distance (%) 0.00

Reach Distance (%) 0.00

Reach Distance (%) 0.00

Figure 7.6 D-Flow application (left) compared to runtime console for clinical use (right)

7.4 Development of the Stability-based training application

The development of the application for visualisation for the stability-based training programme designed in Chapter 4 is presented in the following sections.

Criteria for the application as to how the visualisations were to add to the programme already designed was established considering the literature outlined in Chapter 3 regarding performance, feedback, and virtual reality (Table 7.3). This was used to create a non-immersive, third person perspective virtual environment that would provide externally focused augmented feedback, in addition to that from the clinician, to improve and monitor stability, quality of movement, and motivation in rehabilitation.

Table 7.3 Criteria for development of the stability-based training programme application

Criteria	Description	Rationale	References
Third person perspective	Participants can view themselves as an avatar on screen.	Provides externally focussed augmented feedback to participants and clinician. The avatar provides knowledge of performance feedback both visually and verbally.	Magill and Anderson, 2017; Wulf et al., 2013; LaFortune, 2016; Salamin et al., 2010
Challenging	It should be challenging but achievable, and include interactivity that the participant must react to.	Training and rehabilitation should incorporate progressive overload. Easy to play is boring. Representative of activities of daily living, such as avoiding an obstacle.	ACSM, 2018; Lohse et al., 2013; Cota et al., 2015; Kerr and Rowe, 2019; Vershueren et al., 2019
Competitive	Games should include a competitive aspect.	To provide an external focus of	Salmon et al., 2017

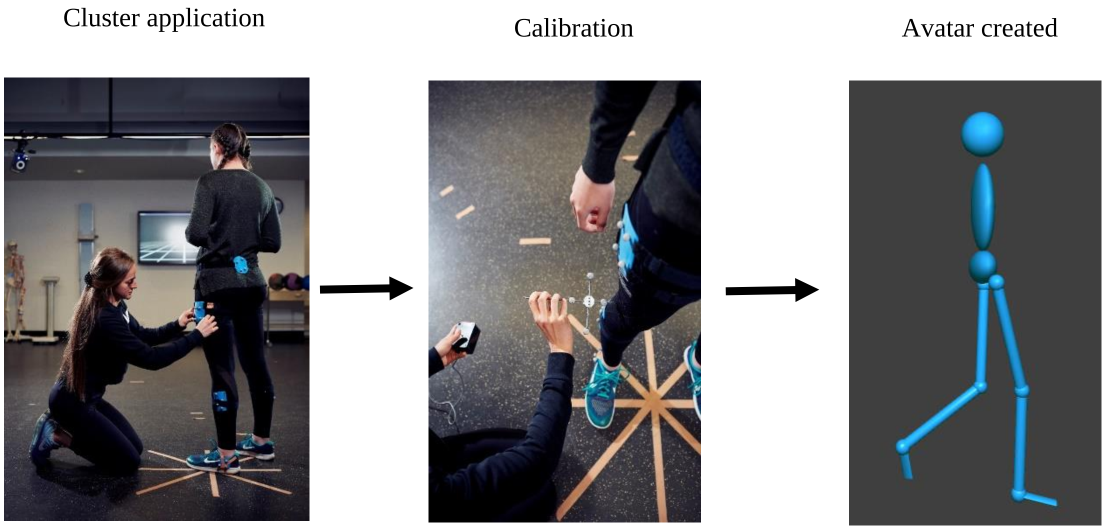
		attention, a comparative aspect for the participant, and make games more enjoyable.	Lohse et al., 2013; Ravyse et al., 2017; Shah et al., 2014; Gorsic et al., 2017
Simple virtual environment	Virtual environment should be kept plain. Screen should be kept as simple as possible.	Little distractions and avoids information overload for participants during the initial stages of learning. Increased immersion leads to cognitive distraction.	Magill and Anderson, 2017; Parong, 2019
Reward	There should be the opportunity to be rewarded in games either by scoring maximum points, or keeping points to a minimum. Use of levels for a clear pathway of progression.	For enjoyment and motivation. Levels set a goal to achieve and provided clear directionality. A lack of this has limited adherence to exercise in previous rehabilitation research.	Ryan and Deci, 2000; Lohse et al., 2013; Marshall et al., 2012
Feedback	Participants should receive feedback both visually, verbally and by biofeedback from the avatar and exercises.	Learning and motivation is influenced by feedback.	Lauber and Keller, 2014; Magill and Anderson, 2017; Utley and Astill, 2008; Lohse et al., 2013
Easy to learn	Exercises should not include rules or instructions that are difficult to follow.	For time efficiency in clinical practice. Games that are easy to learn and have clear goals are more	Salmon et al., 2017; Toro et al., 2003; Lohse et al., 2013

		enjoyable for those playing.	
Choice/interactivity	Connectivity and interactivity between rehabilitation and participant.	For enjoyment and motivation.	Deci and Ryan, 2000; Carson and Polman, 2017; Lohse et al., 2013

The following sections introduce the avatar and detail the development of each of the exercises individually.

7.4.1 On-screen avatar

Once the participant was calibrated an avatar was created on the screen that provided real-time feedback of movement of the individual wearing the clusters and who had been calibrated. This was developed by Millar (2016) (Figure 7.7).


Cluster application

Calibration

Avatar created

Figure 7.7 Participant process to create avatar.

The avatar allowed for real-time feedback that is not perceived backwards, like from a mirror, and provides a digital representation rather than a true image, which may be distracting or distressing (MacDonald et al.,2009; Millar, 2016).

Only the lower limbs and pelvis are driven by the biomechanical model. The trunk and head were only extensions of the pelvis for aesthetic purposes. The 3D motion capture allowed for the avatar to be viewed from any angle on the screen which would be useful when providing real-time feedback to participants to help understanding during the initial stages of skill development.

7.4.2 Single Leg Balance and Leg Lift (SLB)

The SLB was as described in Chapter 4.2.1.

7.4.2.1 Visual Feedback on screen

The screen displayed not only the avatar of the participant performing the movement but also the hip flexion angle threshold for both the right and left sides, the score and the number of reps (Figure 7.8).

The simplicity of the background chosen allowed the participant to focus purely on the task and movement with no distractions. This was important initially when focusing on developing and altering movement patterns, however D-Flow is a platform where this could be altered.

Figure 7.8 Screen display during SLB (no avatar present)

7.4.2.2 Successful reps and score

Initially to successfully score a point a hip flexion of 90° was to be achieved (Table 7.4). This angle was chosen as it was an angle participants could visualise in order to repeat. However, the ability to achieve 90° hip flexion required participants to have a large range of motion, which may not be possible in all cases. For this reason, this was adapted. Before completing the exercise, the participant was instructed to lift their leg twice on each side to as close to 90° as possible but to a position that remained comfortable to achieve and could be replicated in the exercise. The system saved the maximum hip flexion angle achieved. During the SLB the participant was then to reach this position, or within 5% of it, to achieve a count towards the final score. If this was not reached, then no score was counted. If the required ROM was exceeded a minus score was counted. This was to eliminate the score which would have been counted as the participant passed through the 'count score' range of motion. The upper limit on the ROM required the participant to control the hip flexion while maintaining the SLB. If the hip flexion was not controlled enough when replicating the comfortable ROM, then the score they had achieved from reaching this point was taken off. Table 7.4 details this.

Table 7.4 Joint thresholds determining success/failure. X=hip flexion angle.

ORIGINAL HIP FLEXION THRESHOLD	FINAL HIP THRESHOLD	REP COUNT	SCORE COUNT
88° > X < 92°	-5% > X < 5% of comfortable ROM	Success	Success
88° < X > 92°	-5% < X > 5% of comfortable ROM	Success	Failed
X => 50°	X => 50% movement	Success	Failed, unless reaches the 50% threshold

Not every rep may be successfully counted towards the score, as explained above, thus the following was computed to monitor the number of reps that had been completed. As the exercise started the vertical distance between the HJC and KJC of the limb while straight was saved (Figure 7.9: START DISTANCE). As the hip flexed this distance decreased towards 0 as the KJC becomes parallel to the HJC (Figure 7.9). Once the limb had moved more than 50% of this distance a rep was counted.

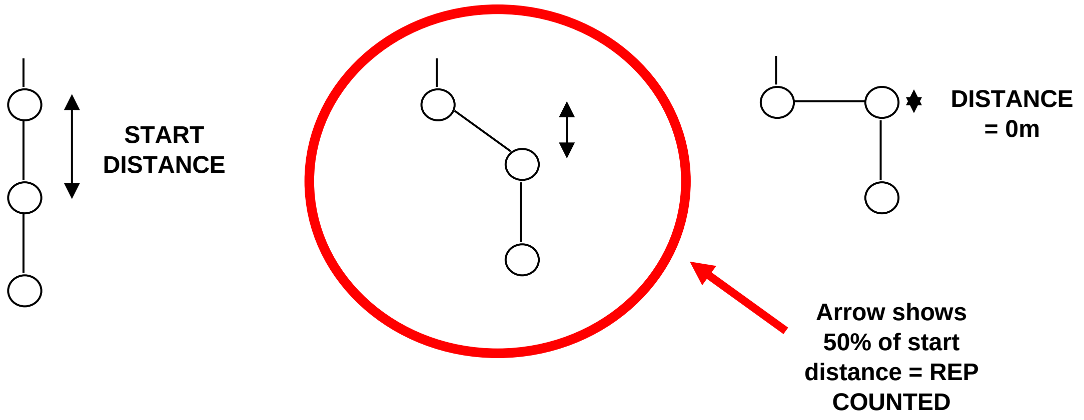


Figure 7.9 Calculation how rep counted as hip flexes in SLB. View is in the sagittal plane. Circles represent hip, knee and ankle joints proximal to distal from the pelvis

Hip hiking was highlighted in Chapter 4.2.1.2 as an important technical consideration during the SLB but it was removed as a determinant of success. Initially movement without hip displacement was included in the application for reps to be successfully counted towards the total score and displayed on the screen numerically. However, after preliminary small tests and difficulty addressing this movement in 3-dimensions, and a desire to keep the screen as simple as possible for the basic stability exercises, this was removed. The participants were made aware of hip positioning, verbally by the tester if necessary. This was given by externally focused knowledge of performance feedback by drawing attention to the pelvic segment of the avatar which would tilt if the participant was hip hiking.

7.4.2.3 Exercise progressions

Regardless of level the screen visuals remained constant throughout. For consistency within the VIS group the progressions followed are depicted in Table 7.5. These are as close to the progression framework detailed in Chapter 4 as possible with the visualisations present (Section 4.2 and Section 4.2.1.1).

Table 7.5 . Exercise progressions for the SLB

SLB EXERCISE PROGRESSIONS	EQUIPMENT	DESCRIPTION
1	None	Leg lift only. Progress from 2 – 3 sets.
2	None	Eyes closed while lift leg up. Open at top and lower leg back to start position. The No-VIS group completed with eyes closed the entire time.
3	Wobble Board	Leg Lift only.
4	Wobble Board	Forward hinge + leg lift.
5	Wobble Board	Eyes closed while lift leg up. Open at top and lower leg back to start position. The No-VIS group completed with eyes closed the entire time.

Since this is a hybrid tool the score card for the participant included a ‘comments’ section for clinical notes to be added related to the individual’s performance, as knowledge of performance feedback. It is important to report this alongside the information on screen in order to enhance quality of movement, as well as exercise success, since progress in human rehabilitation is difficult to define by a number only due to the different movement strategies (both optimal and suboptimal) to achieve this.

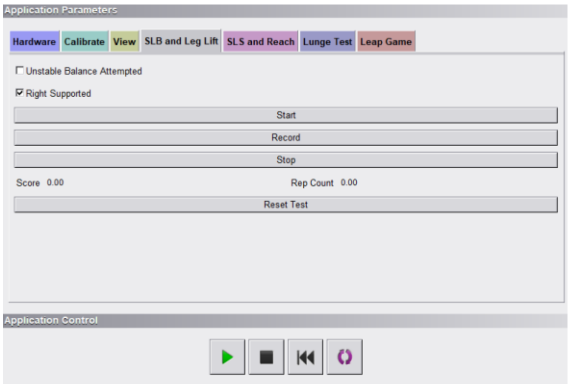
7.4.2.4 Final design of the SLB

The preliminary design of the stability-based training application was presented to the group of healthcare professionals as detailed in the previous chapter. Following the feedback from the focus group in Chapter 6 the design of the SLB using visualisation was adapted to not only make it easier to identify success, but also improve the ability to associate that success with the exact movement causing that. It was inferred that this way it would be easier to understand the final score.

It was suggested that the final design of the single leg balance removed the numerical information from the screen as healthcare professionals did not see the relevance of this for participants, and present this information in a different way.

The final design of the SLB therefore removed the numerical information, apart from the rep count, and added a coloured spot in the middle of the screen (Figure 7.10). Each time the participant reached the desired position a white spot in the middle of the screen turned green to feedback to the participant that the task was successful, and leg can be lowered again. The number of times this was successful, out of a possible 10, was calculated on the clinician’s runtime console (Figure 7.11). This gave the clinician the option to share the results with the participant or not and simplified the screen for the participant.

Figure 7.10 Final visuals projected during SLB highlighted by red circle



☐ Unstable Balance Attempted

☑ Right Supported

Score 0.00

Rep Count 0.00

Figure 7.11 Runtime console for SLB

Leaving the rep count on the screen was seen to benefit the patient and clinician:

- The clinician could focus on the technique of the patient without having to count the number of reps to act as a distraction.
- The participant could focus on the technical cues from the clinician without having to count the number of reps as a distraction.

This final design enabled the participant to externally focus on the avatar with knowledge of the result every time a rep was performed, and successful, to improve the perceptual trace during the initial stages of learning. The clinician could supplement this with additional feedback drawing attention to the movement of the avatar to ensure reps were achieved with quality movement.

7.4.3 Single Leg Stand and Reach

For this single leg stand and reach exercise the star excursion balance exercise (Chapter 4.2.2) was adapted for training with visualisation. Here the pre-planned reaching protocol was adapted to visually present eight spots on the screen randomly. Verschueren and colleagues (2019) highlighted the pre-planned nature of balance tests to lack applicability relative to performing open skills requiring balance in unpredictable environments (ie. Cutting tasks and/or sports). The person must be able to adapt to complete the skill while maintaining postural control (Vershueren et al., 2019). The test which the researchers developed used a Fitlight-training system (Fitlight Corp., USA) which uses lights to test reactivity and accuracy. This research outlined the protocol of a test only, however the concept has been developed further as a training exercise for this project.

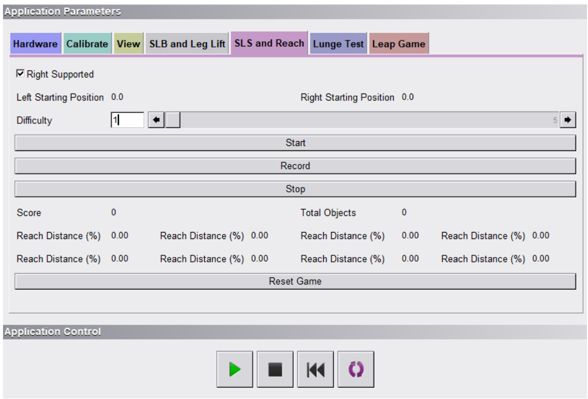
The single leg stand and reach exercise used the participant's leg length to predetermine the positions the spots which would randomly appear on screen 1 at a time. When a spot was visible the participant was required to hold the toe of the reaching leg over the spot for as long as possible while it was shown on screen. Successful performance resulted in an increase in the score which was displayed on screen (Figure 7.12). The longer the toe was in contact with the spot before it disappeared, the greater the score. The researchers believe it is important that the interaction is with the screen opposed to a device on the floor (as per Verschueren et al., 2019) so the participant was not looking down at the foot moving to the object. Outside of the training environment where concentration cannot be given to task (ie. Foot placement) directly this would be important to have practiced during training, so we believe.

Figure 7.12 Participants performing single leg stand and reach exercise. Right image has shoes on for picture purposes only

7.4.3.1 Exercise Progressions

At the tester’s discretion the difficulty of the test could be manipulated by changing the level in the runtime console before starting the test (Figure 7.13). Details of this are shown in Table 7.6. The reach distances were decided based on the literature of CAI SEBT performance (Jaber et al., 2018; Kosik et al., 2019; McCann et al., 2017; Pionnier et al., 2016). The starting level and the degree of incremental progression the game then underwent small preliminary tests to guide the development and final design so that it was at an appropriate level.

A final progression not in Table 7.6 would be to complete the test on a wobble board, for reasons highlighted previously in Chapter 4. This would reset the levels to the beginning again as the unstable surface limited reach distance capabilities.



☑ Right Supported

Left Starting Position 0.0
Right Starting Position 0.0
Difficulty 1
Score 0
Total Objects 0
Reach Distance (%) 0.00
Reach Distance (%) 0.00
Reach Distance (%) 0.00
Reach Distance (%) 0.00
Reach Distance (%) 0.00
Reach Distance (%) 0.00
Reach Distance (%) 0.00
Reach Distance (%) 0.00

Figure 7.13 Runtime console for the user to control single leg stand and reach exercise. Here the standing leg is chosen, level manipulated, and number of spots that have appeared and their distances are shown.

Table 7.6 Star Test level descriptions. Show time = time spot appears on screen for. Interval = time between spots

EXERCISE		**LEVEL**				
SEB EXERCISE		**1**	**2**	**3**	**4**	**5**
	Reach Distance (% leg length):	50-60	55-65	57-67	60-70	65-75
	Display time on screen (s):	4	4	3	3	3
	Time between spots (s):	1.5	1.5	1	1	1
	Size of spot:	0.25				

7.4.4 Lunge with distractive techniques (dual-tasking)

Dual tasks representative of real-world situations can be difficult to simulate within the typical rehabilitation environment, due to predictability and lack of space, equipment or people. This section outlines how we incorporated visualisation into the lunge exercise from Chapter 4.2.3. By doing so we do not only create virtual environments and simulations as a secondary task for the participant to complete but also allow the clinician to focus on the participant's movement and stability rather than on actually carrying out the secondary task.

To initially test this the application specifically adopted the Stroop Test (Stroop, 1935), as a widely used yet valid and reliable clinical test (Teel et al., 2013). The Stroop Test requires the participant to relay the colour of word rather than the word itself to the tester as the words appear on the screen.

7.4.4.1 Exercise Progressions

The lunge exercise here lasted up to 1-minute duration. The lunge was initially performed with only the avatar on the screen and could be viewed from any angle, depending on which aspect of the lunge the participant was to focus on (Figure 7.14). This was so the technique could be the only focus before performing under dual-task conditions. The technique specifications of the lunge were as described in the design of the stability-based training in Chapter 4.2.3. Under the tester's discretion the task was progressed following the progressions detailed in Table 7.7.

Figure 7.14 Participants performing lunge exercise

Table 7.7 Lunge exercise progressions

EXERCISE	LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5
LUNGE	Reverse lunge	Say words/direction on screen	Stroop Test	Stroop Test & directional lunges	On wobble board

7.4.5 Leap Game

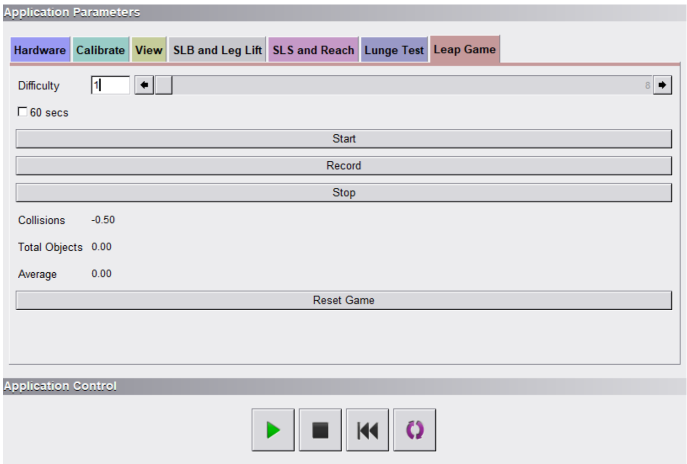
The leap game adapts the Dynamic Leap and Balance Exercise (Chapter 4.2.4) to challenge reactivity since successfully maintaining postural control is often dependent on a person's adaptability and reactivity across different environments in daily activities. Rehabilitation must emulate this in order to properly assess an individual's capability when outside the clinical practice. As with the Dynamic leap and balance exercise the Leap Game remained centred around maintaining balance on a single limb but also during serial changes to the base of support to challenge the participant’s stability however was performed without the predetermination of movement which was created by the visualisations.

In the Leap Game objects randomly appear on the screen, coming towards and past the participant for either 30 or 60 seconds, and these must be avoided (Figure 7.15) Each time the ankle joint centre of either foot collided with an object (ie. In the same position) a point was scored (Figure 7.15), and the aim was to keep the score to a minimum. If the individual scores 3 or less the next level could be attempted, providing the tester believed the leaping movement was acceptable (ie. non-hopping limb off the ground for the duration of the test, upper body not being used to provide excessive balance support, and no fixing support strategy). The participant’s hands did not have to remain rested on iliac crests throughout to allow for ease of a natural leaping patterns.

Figure 7.15 Examples of leap game being

7.4.5.1 Exercise Progressions

The Leap Game consisted of 8 levels (Figure 7.16). Each level challenges the participant by manipulating the speed and size of the moving objects, as well as the distance from the individual the object appeared (Table 7.8). A feasibility study assessing which of these manipulations’ participants found most challenging was conducted prior to finalising the stability-based application design (Appendix C). This was used to inform the final design of the game and progressions detailed below.



Difficulty 1

☐ 60 secs

Collisions -0.50

Total Objects 0.00

Average 0.00

Figure 7.16 Runtime console to control the leap game. This is used to choose level and time for game, start and stop the game, and see the final score and average number of objects hits as a percentage of the total number of objects projected

Table 7.8 Leap game levels. Interval = time at random between objects appearing on screen

EXERCISE	**LEVEL**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
LEAP GAME	Object speed:	Level*1.1							
	Time between objects (s):	2-4	2-4	1-2	1-2	1-2	1-2	1-2	0-1
	Max Distance objects appears (m):	15	15	15	10	10	10	10	5
	Object size:	0.25	0.25	0.25	0.25	0.75	0.75	0.75	0.75

7.4.5.2 Final design of the Leap Game

To assess task difficulty in order to increase the potential engagement with the game as per the principles outlined above, a study was conducted to validate the progressions of the leap game in the application (Appendix C). The results of this then influenced the final design and exercise progressions of the leap game which are detailed below (Table 7.9).

For participant enjoyment the speed was maintained and increased linearly as the levels increased. Considering the remainder of the results, the distance the objects appeared on the screen relative to the participant now remained constant across all levels, although random within the levels, and did not exceed 8m. The study highlighted object size to greatly influence the final scores and perceived difficulty thus was monitored carefully between levels, and very gradually increased with level progression. This was coupled with a small increase in the ‘collision zone’ about the centre of the ankle joint. This meant the objects were not only larger in size but had to be avoided even more so to ensure not to touch the ‘collision zone’. Finally, the perceived difficulty on average only just exceeded a neutral score, suggesting that only manipulating the speed, object size and distance may not be adequately challenging. For this reason, as the levels progress objects begin to move on the screen using zigzag pathways, differing in amplitude and frequency, opposed to just straight-line paths. This aims to ensure the game constantly provides new challenges for the player to overcome so to remain situated on the boundary of their ability. This has been discussed further in Appendix C.

Table 7.9 Finalised game level progressions. Path of cones = straight (s), 1 zig-zag (z) or many zig-zags (zz). AJC = ankle joint centre

EXERCISE	**LEVEL**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
LEAP GAME	Object speed (m/s):	Level*1.1							
	Time between objects (s):	1-3	1-3	1-2	1-2	1-2	1-2	0-1	0-1
	Max Distance objects appears (m):	8							
	Object size:	0.4	0.4	0.4	0.6	0.6	0.6	0.8	0.8
	AJC ‘collision zone’ size:	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.05
	Object path:	S	S	S	Z	Z	Z	ZZ	ZZ

7.6 Conclusion

In summary, this chapter has detailed the development of the stability-based training package.

In Chapter 5 the requirements for a clinically appropriate motion analysis system were defined and 3D motion capture was chosen as the hardware for the package. This chapter then detailed how the package used 3D motion capture but still aimed to be time efficient, easy to use, and produce interpretable results. A cluster-based method and pointer calibration for tracking movement was chosen, and the D-Flow software enabled a custom-made application to be designed and developed for the stability-based training, which would be usable for a clinician with little biomechanical expertise.

The criteria used for the development of the stability-based training programme from Chapter 3 to incorporate motion capture and feedback has been outlined in this chapter and each exercise has been detailed. This has resulted in the design of the final product which is tested for feasibility in Chapter 8.

Chapter 8 – Feasibility of stability-based training with visualisation

8.1 Feasibility Randomised controlled study methodology

8.1.1 Overview and study design

The previous chapters have detailed the chosen biomechanical model and development of the stability application to establish a final product to pilot on people with CAI. This chapter will outline the protocol to test the feasibility of the stability-based training package before presenting and discussing the results.

The research questions addressed in this chapter are:

- Is the stability-based training programme effective at improving stability?
- Is the stability-based package feasible for stability-based rehabilitation?
- Does visualisation enhance the outcome of stability-based training for people with CAI?

To investigate the feasibility of the stability-based training package a multi-centre randomised control trial (RCT) was adopted as the Ankle Stability Training Application with Visualisation study.

This study was ethically approved by the University of Strathclyde and Deakin University ethics committee (DEC 2018.243) and received NHS R&D approval for testing on an NHS site (IRAS project ID 247615).

8.1.2 Experimental Locations

As a multi-centre RCT, testing and training was conducted in three different laboratories across two different countries. Experimental locations included Glasgow and Edinburgh in the United Kingdom, and Geelong in Australia. Each site had a Vicon 3D motion capture system, a computer to run the hardware and software, and a screen for the visualisations.

8.1.2.1 Glasgow, United Kingdom

The Glasgow testing site was located in the Human Performance Laboratory in an NHS Clinical Research Facility (Figure 8.1). A Vicon Bonita camera system was used and the 16 cameras were attached to railings surrounding the room. A moveable stand supported the LCD TV screen in front of the participant.

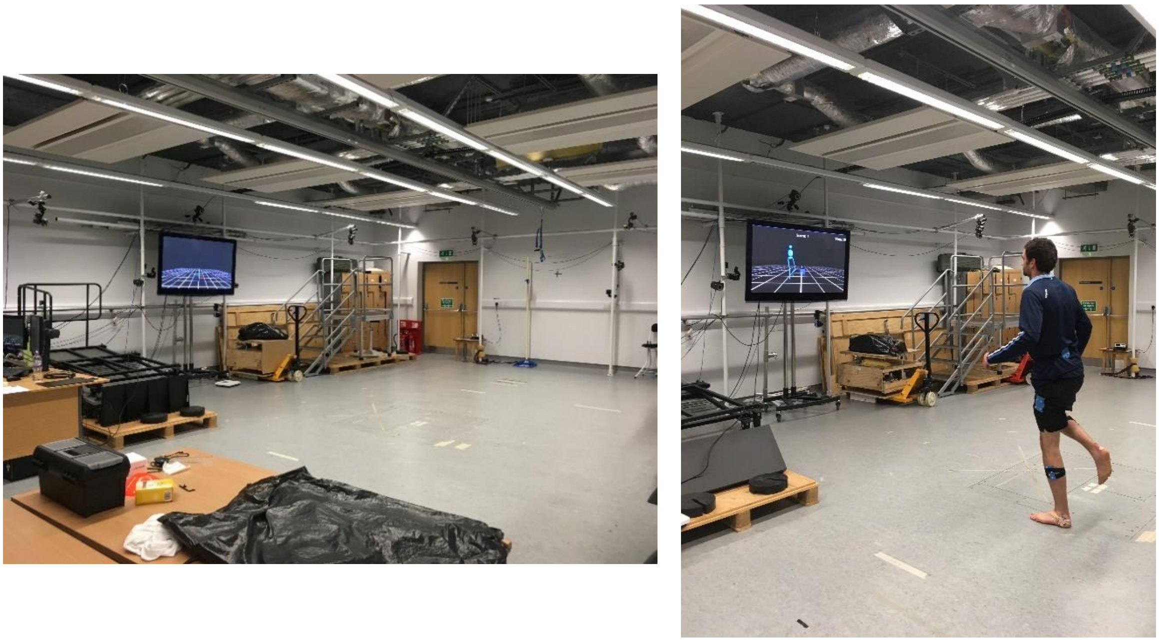


Figure 8.1 Motion Analysis Room in Glasgow

8.1.2.2 Edinburgh, United Kingdom

The Edinburgh site location was the motion analysis laboratory at sportScotland Institute of Sport. A 10-camera system was set up attaching Vicon MX cameras to overhead railings surrounding the training space. Development of this lab was primarily for golf analysis and included safety netting. This prevented camera position optimisation for the study as no camera could be positioned further forward than the edge of the netting (see Figure 8.2) and could not be placed behind the netting as the netting obstructed the camera view. Due to the golf simulation work in this lab, the screen was larger than any of the other site locations.

Figure 8.2 Motion Analysis Room in Edinburgh

8.1.2.3 Geelong, Australia

A collaboration was established between Dr Jason Bonacci, of the Exercise Science department of Deakin University, and Miss Lauren Forsyth, the primary researcher. This led to a visit by the primary researcher to complete testing in the biomechanics laboratory of the Waurn Ponds Campus in Geelong over a 3-month period (Figure 8.3).

In the biomechanics laboratory six Vicon MX Cameras were secured to overhead railings in positions to optimise the capture volume for data collection. Due to the positions of the railings this meant the TV screen (attached to the wall) was further from the participant than desired, however was still suitable.

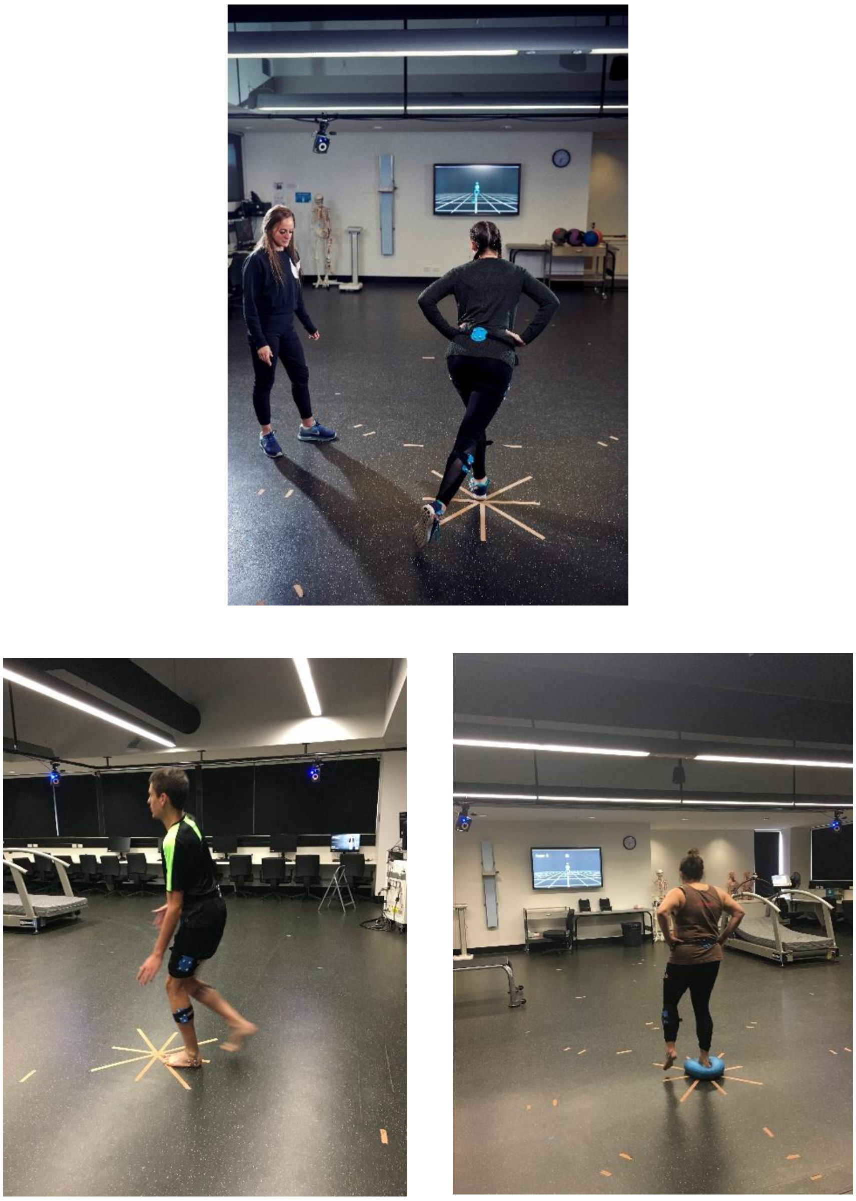


Figure 8.3 Biomechanics Laboratory in Geelong

8.1.3 Study population

A sample of people with chronic ankle instability was the proposed population of interest. A sample of healthy individuals were also recruited to provide a controlled comparison for the outcome of the visualisation intervention, and identify the specificity of sample population for visualisation.

8.1.3.1 Sample size estimation

The sample size was calculated using the formula as seen in Kadam and Bhalerao (2010):

$$n = 2(Za+Z1\text{–}\beta)^2\sigma^2 / \Delta^2 \qquad (8.1)$$

, where Za = a constant in accordance to the accepted α error, $Z1\text{–}\beta$ = a constant in accordance to study power, σ = standard deviation, and Δ = estimated effect size. The key outcome of the intervention is the Cumberland Ankle Instability Tool (CAIT) score, with an estimated effect size of 50% and standard deviation of 0.5. Considering these values, and a power of 80% with 95% confidence intervals ($\alpha = 0.05$), the sample size estimated is 16 for each group. Thus, researchers aim to recruit 20 people to account for 15% drop out rate. This would total 80 participants (20 x 4 groups – CAI/VIS, CAI/No-VIS, No-CAI/VIS, No-CAI/No-VIS). This is a comparative population size to most ankle rehabilitative studies previously reviewed which predominantly included a sample size of between 14–26 per group (Cug et al., 2016, Borreani et al., 2014, Donovan et al., 2016, Pionnier et al., 2016), however none reported sample calculations.

8.1.3.2 Participant selection

The inclusion/exclusion criteria shown in Appendix D were used to check the eligibility of the participants prior to taking part in the study. This enabled each person to be identified as healthy, with CAI, or not eligible to take part. The CAI participant selection criteria was taken from the position statement of the International Ankle Consortium (Gribble et al., 2014). Using these recommendations produces a consistent and valid CAI population for research.

The CAIT was used as part of the inclusion criteria to subjectively assess symptoms of ankle instability to screen potential participants, identifying those with CAI (Hiller et al., 2006). The CAIT was used as a recommended, valid, and widely used tool by the International Ankle Consortium (Wright et al., 2017). It has an excellent test-retest reliability ([$ICC_{2,1}$] = 0.96), and high sensitivity to discriminate between CAI and uninjured controls (95.5%) (Wright et al., 2014; Wright et al., 2017). It is a 9-item questionnaire scored from 0 to 30. A score of 30 highlights a healthy participant, with lower scores indicating decreasing feelings of stability. The items are all focused on the degree of difficulty in performing different physical activities and functional movements. The injured ankle only, or both ankles, are scored and the score is independent of the contralateral ankle. In support of recent literature, a score of ≤24 in the CAIT indicated the presence of CAI and initially addressed suitability for inclusion in the study (Gribble et al., 2013). Despite Wright et al. (2014) suggesting using a recalibrated score of ≤25, here a lower cut off was used to ensure 'copers' were not included in the study. These are individuals who may have had an ankle injury but are not chronically unstable (Wright et al., 2014).

8.1.3.3 Study Recruitment

Potential candidates were recruited from universities and colleges, sports clubs, private health clinics and the general public in the surrounding areas of the testing locations. This was done by means of posters, social media advertisements, and email. Upon noting interest, potential participants then received the participant information sheet and screening questionnaire (see Appendix E). If all inclusion criteria were adhered to, participants were enrolled accordingly, and consent forms signed prior to testing.

8.1.3.4 Randomisation

Participants were randomly assigned to the VIS or NO-VIS training groups using a random number generator (RANDOMIZATION.com). This was generated prior to participant recruitment based on the sample size calculation of 20 participants per group and concealed in a file until allocated by the lead researcher following the pre-intervention test. This was to avoid selection bias and participant allocation being influenced by the researcher and their beliefs.

Participants were allocated the next slot on the randomised file regardless of the site at which they were to attend for testing and training.

8.1.3.5 Blinding

Participants and tester were not blind to the intervention group. Both did remain blind to group allocation until after the pre-training test was complete. The researcher acted as the tester during assessment, and also clinician during the training intervention. This meant they were not blinded to multiple aspects of the study. The researchers were aware of this prior to the study. This chapter outlines the study and training protocols. The tester was conscious to avoid differential treatment when conducting the testing and training, particularly when providing verbal feedback as highlighted below, and the results were interpreted considering this. This bias is further discussed in Section 8.3.6.3.

8.1.4 Experimental procedures

The experimental protocol of the RCT is shown in Figure 8.4. For each participant the study lasted six weeks, encompassing the pre-training test in week one, a 4-week intervention of eight training sessions, and a post-training test in week six.

After consenting to the intervention participants were randomly assigned to the experimental or control group, as per the protocol above. Both groups underwent the same pre- and post-testing protocols, and the difference lay in the interventions. The control group (No-VIS) completed the stability-based training programme outlined in Chapter 4, while the experimental group (VIS) completed the stability-based training programme with visualisations outlined in Chapter 7.

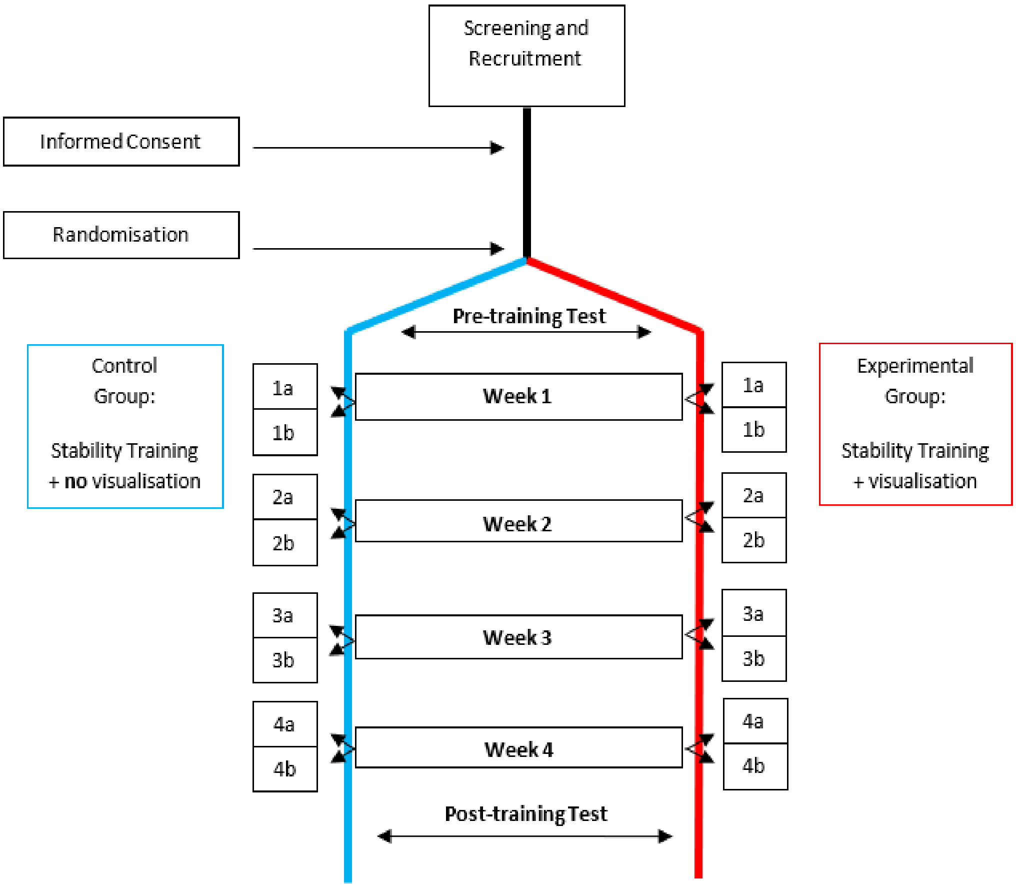


Figure 8.4 Experimental protocol

8.1.4.1 Laboratory protocol

Each time the participant entered the lab the Strathclyde cluster model was applied, and participant calibrated – the procedure detailed in Chapter 7.2. At this point the specific application calculated participant leg length and found the session's comfortable range of motion, as explained in Chapter 7.4.2.2. This was conducted for every participant in both the VIS and No-VIS groups so that movement could be quantified during testing and progression objectively monitored throughout the training. For the VIS group this also created the visuals for the screen interaction. Prior to starting testing and training the participant was given time to become accustomed to the environment and wearing the clusters. The participant was instructed to wear comfortable clothing that was suitable for rehabilitation exercise and all exercises were performed barefoot.

8.1.4.2 Pre- and post-testing protocol

To assess the effectiveness of the intervention testing was conducted pre- and post-intervention. When the participants entered the lab for the first time, information was collected including age, weight, and dominant side. Dominancy was described as the foot you would kick a ball with. For participants with CAI, at this point a history of ankle injuries, treatment and rehabilitation experience was discussed.

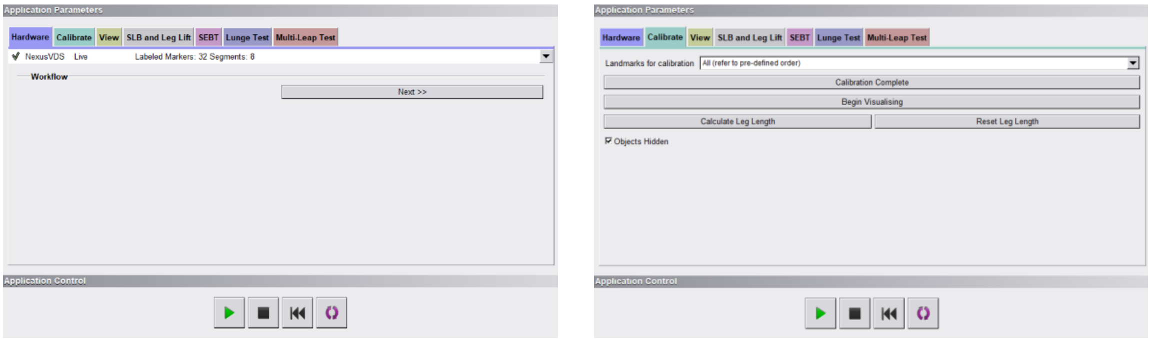
Every participant performed the same testing protocol with no screen interaction. The testing protocol consisted of four exercises based on the exercises selected for training and standard testing procedures evident in current clinical practice for stability. Table 8.1 details the test exercises and assessment measures. As the recommended test for dynamic stability by the International Ankle Consortium when assessing ankle injuries, the Star Excursion Balance Test (SEBT) was chosen as the primary outcome measure (Delahunt et al., 2018). The 3 remaining tests were included to test stability under different conditions relative to the exercises that were performed in the training programme.

All participants were instructed to perform to the best of their ability for every test and the tester remained consistent with instructions as outlined below to minimise bias.

Table 8.1 Testing protocol and assessment measures conducted pre- and post-intervention

Test	Assessment	Data analysis and result
Single Leg Balance with Eyes Closed	Time (s)	Real-time result
Star Excursion Balance Test	Maximum distance reached for each direction (% leg length) Average distance reached (% leg length)	Real-time result
Reverse Lunge	Step Length (m) COM range of movement (m) COM ML velocity (m/s)	Post-processed
Multi-Leap Test (Adapted from Groters et al. (2013) hop test)	Average ML leap distance with stabilisation (% leg length)	Real-time result

The testing protocol was controlled by the tester using a specifically developed D-Flow application. Figure 8.5 shows an example of the user interface. Each tab signified a new task which were displayed in the order to be completed.



✓ NexusVDS Live Labeled Markers: 32 Segments: 8

Landmarks for calibration: All (refer to pre-defined order)

☑ Objects Hidden

Figure 8.5 User interface for the testing protocol. Examples are of the hardware, calibrate, and single leg balance with leg lift tabs.

Action on the Hardware tab was completed before the participant arrived for testing, and ensured that the D-Flow software was connected to the motion capture. Once the participant had the clusters secured to the body a calibration was completed using the Calibrate tab. This was necessary for D-Flow to track movement for each of the tests. At this point the leg length was also calculated. The display on the screen was controlled using the View tab, however this was automatically controlled within each of the tests thus did not need to be controlled by the tester. The remainder of the tabs were for each of the tests to control the test, record the data, and display the result. The user interfaces for the SEBT and ML Test are included as examples in their respective sections below.

Single leg balance with eyes closed

The single leg balance is a common measure of stability as described for the exercise in Chapter 4. For this specific test the participant was required to balance on one leg for as long as possible with eyes closed. The participant was instructed to hold the non-support limb in the air at approximately 90° hip flexion, so neither the thigh, leg, or foot was touching the support limb or the floor. Hands were placed on iliac crests. The stopwatch on the user interface was stopped by the tester if the lifted foot touched the floor, the support foot moved, or the hands moved off the iliac crests. This was repeated three times, giving the participant two practices before recording the final balance.

Star Excursion Balance Test (SEBT)

The SEBT was introduced in Chapter 4.2.2 as a valid and reliable method for assessing dynamic stability. This makes it an accepted measure of dynamic stability in clinical practice and has been commonly used to identify CAI populations and assess outcome from stability-related interventions (Anguish and Sandrey, 2018; Delahunt et al., 2018; McKeon et al., 2008; Pozzi et al., 2015; Wan et al., 2018).

To guide movement the eight reach directions were identified by tape on the floor (Figure 8.6). The starting position was set when the heel of the support limb was in the centre of the star – position (0,0,0) for the motion analysis system. Participants were instructed to reach the non-support limb maximally in each direction, in a pre-determined order (Table 8.2), followed by a small pause. When moving the reaching limb, the toe was to be lifted so as not to touch the floor. Once maximally reached there could be a light tap with their toe while the position was held but no weight transfer from the supporting limb was to occur (Gribble et al., 2012). The SEBT was performed on both the dominant and non-dominant sides for up to four practice trials and one test trial (Pionnier et al., 2016). Previous research has indicated a need for approximately four practice trials before testing due to a learning effect (Robinson and

Gribble, 2008), however if the participant felt ready and believed they could perform their best with less practices than this then the test trial was completed. In accordance with previous research, hands remained on the hips throughout. Failure to comply with the verbal instructions meant the trial was discarded and repeated. Each maximal reach was normalised to participant leg length (height difference between left ASIS and left medial malleolus):

$$\text{(Reach distance / leg length)} * 100 \tag{8.2}$$

These calculations were made in real-time as part of a testing application. As the participant paused at the end of each maximal reach, recording a toe velocity of ~0m/s, the computer saved the position of the toe at this point, and output this number as a percentage of the participant's leg length for the tester to record (Figure 8.7).

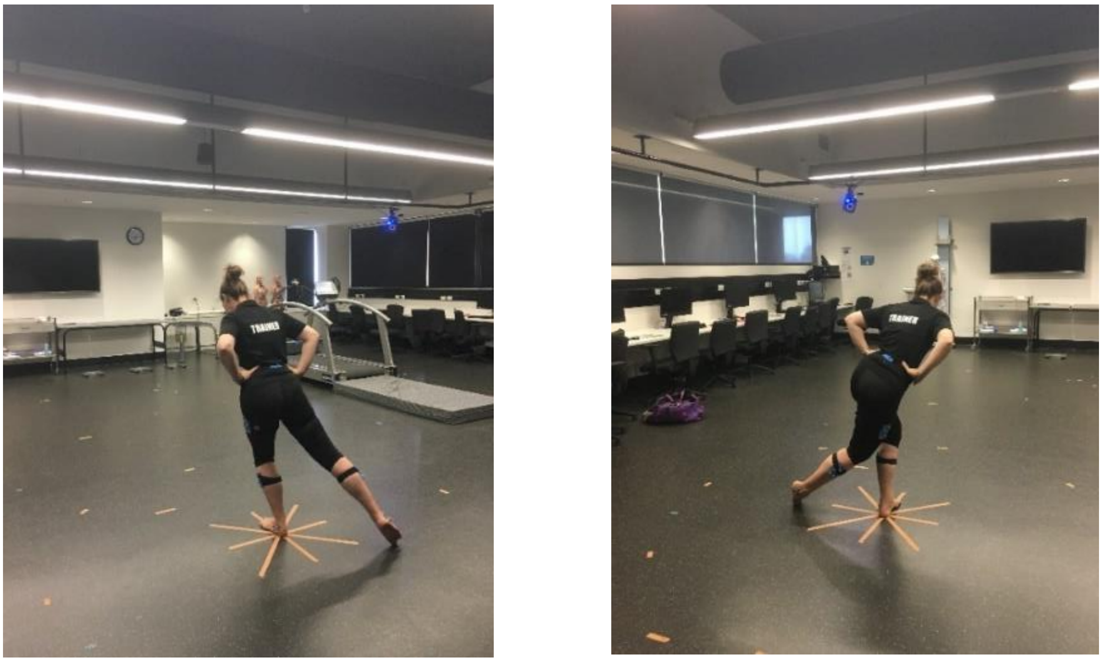
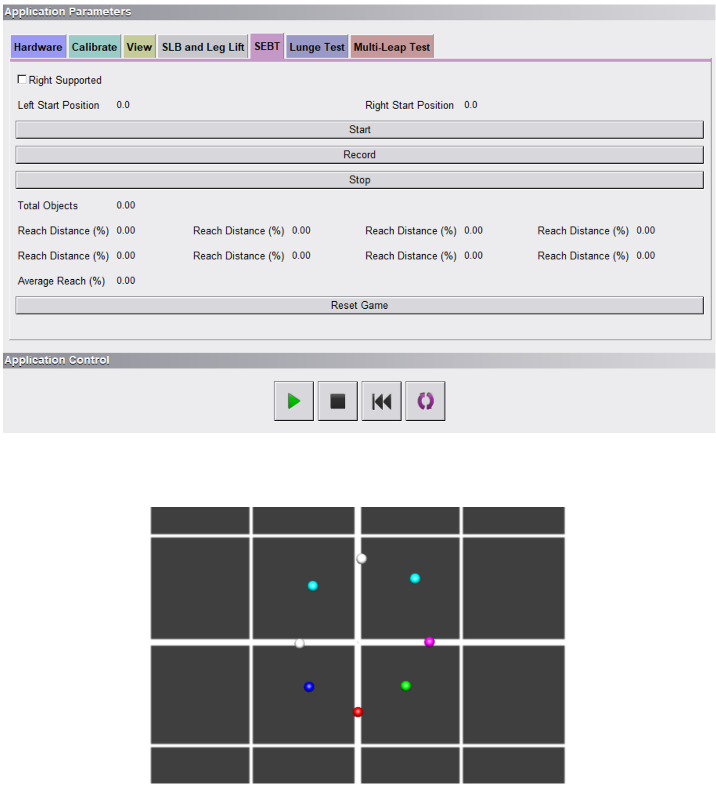


Figure 8.6 Participant performing SEBT in pre- or post-training test. The tape was used to guide the direction of the leaps

Table 8.2 Direction and order for reaches for the SEBT

Reach Number	**SEBT Reach Direction** **(relative to support leg)**
1	Anterior (A)
2	Anterior Medial (AM)
3	Medial (M)
4	Posterior Medial (PM)
5	Posterior (P)
6	Posterior Lateral (PL)
7	Lateral (L)
8	Anterior Lateral (AL)



☐ Right Supported

Left Start Position 0.0

Right Start Position 0.0

Total Objects 0.00

Reach Distance (%) 0.00
Reach Distance (%) 0.00
Reach Distance (%) 0.00
Reach Distance (%) 0.00

Reach Distance (%) 0.00
Reach Distance (%) 0.00
Reach Distance (%) 0.00
Reach Distance (%) 0.00

Average Reach (%) 0.00

Figure 8.7 User interface for the SEBT (top). Each ‘Reach Distance’ on the console displays the distance of the saved coloured spot (bottom) from the centre point as a percentage of the participant’s leg length

Lunge

In previous research the CAI population showed reduced scores compared to the uninjured controls for the inline lunge ($p<0.05$), as part of the Functional Movement Screen (FMS) (Choi and Shin, 2015). The FMS has become a popular clinical test. It was originally developed to test fundamental movement, requiring both stability and mobility, which is relevant for athletic performance (Cook et al., 2006). However, despite the research reporting good reliability and validity of the overall FMS score across the seven movement patterns in various sample populations, the content validity is questionable (Chimera and Warren, 2016). To date only the deep squat has been biomechanically analysed leaving the clinical relevance and functionality of the remaining movement patterns unknown. Although the CAI population has shown reduced scores, in relation to performance outcomes a previous study by Hartigan and colleagues (2014) reported no relationship of the FMS inline lunge score to balance ($p>0.05$). Considering this, although the exercise presents a standardised test, support for the inline lunge is unknown and the score does not report the quality of the movement (Chimera and Warren, 2016). For this reason, the lunge test here was designed to mimic the exercise selected for the training programme rather than the FMS inline lunge (Chapter 4.2.3). Chapter 4 discussed the appropriateness of this exercise during rehabilitation, and since there may be a performance deficit in people with CAI, it has been included to test the maintenance of postural stability throughout the entire movement.

For this test the participant was verbally instructed to reverse lunge for 12 reps, alternating leg each time. This totalled six reps on each leg. Hands were either relaxed by side or placed on iliac crests, and with head facing forward. This was performed for one set only and movement was recorded.

The data was post-processed in MATLAB to normalise the 12 reps to 6 lunge cycles, of which one lunge cycle is explained in Figure 8.8.

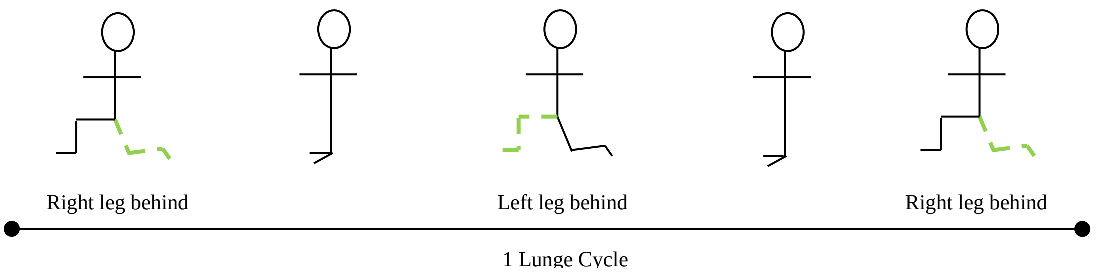


Figure 8.8 Performance of 1 lunge cycle

Multi-leap test

The multi-leap test was adapted from Groters and colleagues' (2013) hop test which was conducted to measure dynamic stability in a population with functional ankle instability. This study switched the hop for a leap action, for reasons discussed previously in Chapter 4.2.4, as well as to more closely match the demands of the dynamic leap and balance exercise performed during training. The test required the participant to leap maximally from unilateral stance on one limb to the other in a series of horizontal and diagonal leaps (Figure 8.9). There were up to two practice trials performed for each leg, before completing a test for each.

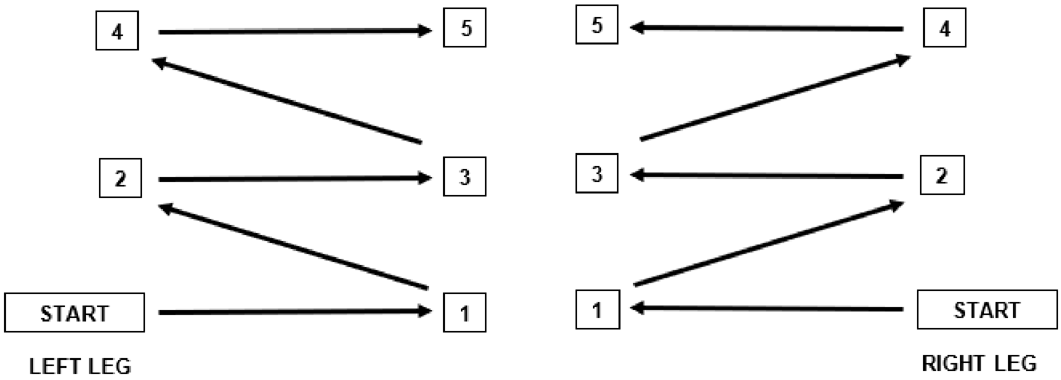
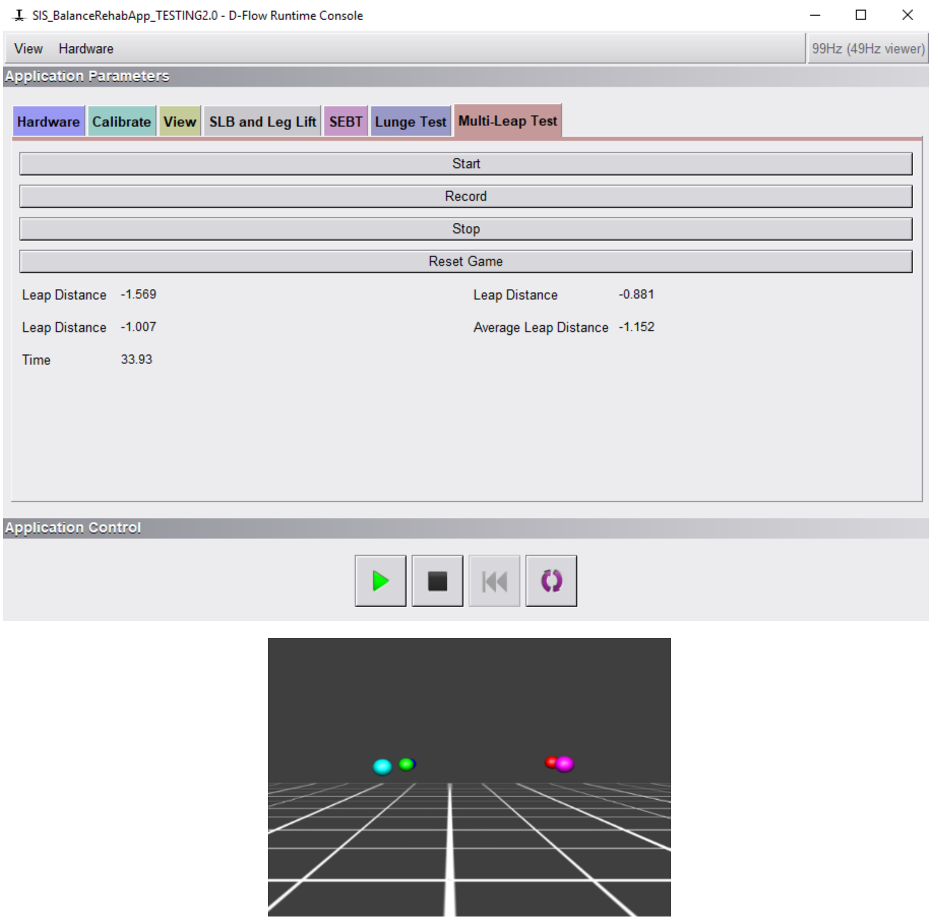


Figure 8.9 Direction and order for reaches for the Multi-leap Test

The result was the average of the three mediolateral leaps, calculated from the mediolateral displacement of the centre of mass. Progression from one leap position to the next was only allowed once stabilisation had been achieved. The calculations were made in real-time as part of the testing application. As the participant found stabilisation after each leap, recording a COM velocity of ~0m/s, the computer saved the position of the COM at this point. Each leap displacement was output to the tester before an average calculated and displayed as a percentage of the participant's leg length for the tester to record (Figure 8.10).



Leap Distance -1.569

Leap Distance -1.007

Time 33.93

Leap Distance -0.881

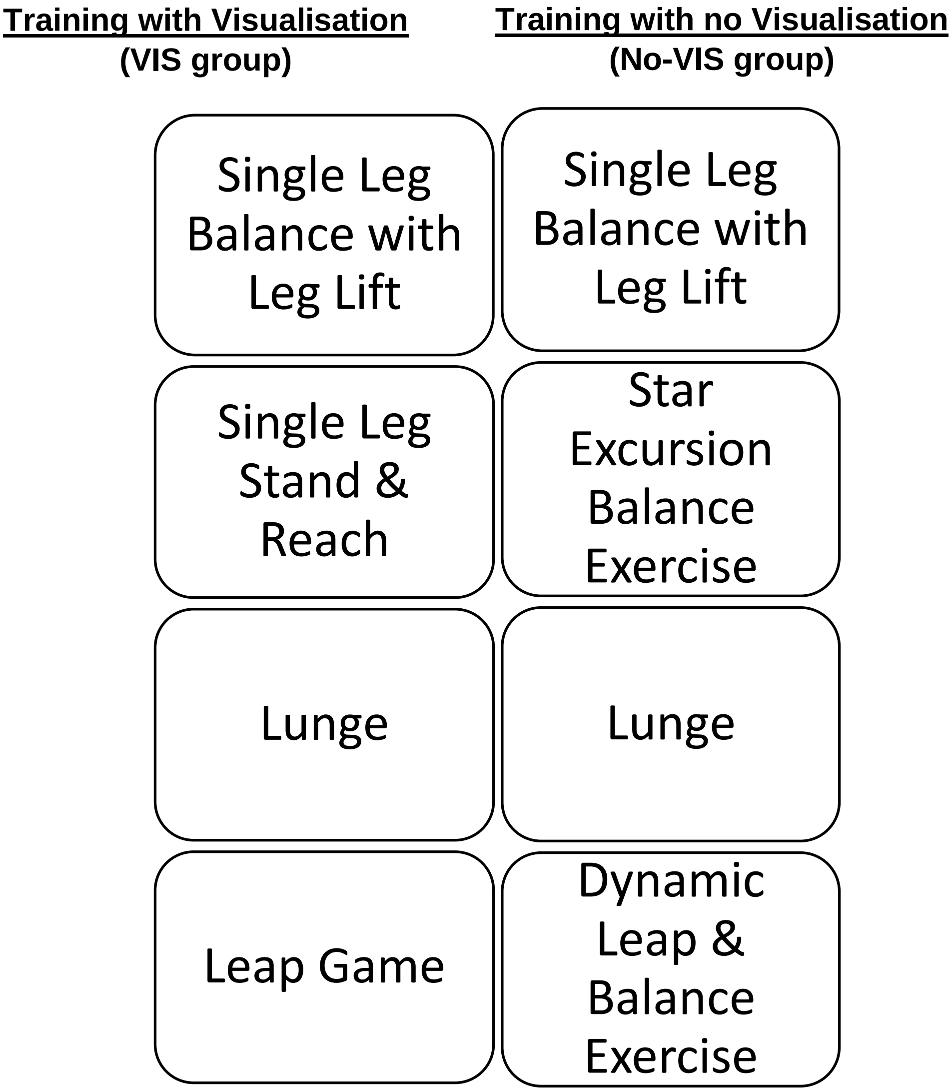
Average Leap Distance -1.152

Figure 8.10 User interface for the Multi-leap Test (top). Each ‘Leap Distance’ on the console displays the distance leaped which is calculated from the saved positions of the coloured spots (bottom)

8.1.4.3 Stability-based training intervention

The No-VIS group completed the stability-based training programme detailed in Chapter 4. The VIS group completed the adapted stability-based training programme which was detailed in Chapter 7. Both protocols are shown below in Figure 8.11 for comparison, and the type of feedback received, and the delivery of the feedback is shown in Table 8.3. This shows the similarity of the VIS and No-VIS programmes, with the visualisations adding additional options of feedback regarding knowledge of performance and knowledge of results, and focus of attention, that does not rely on verbal communication and interpretation from the tester/participant alone. Verbal feedback was provided by the tester for both groups following each trial, if appropriate. This was provided using clear and concise cues, as detailed in Chapter 3 regarding how to relay feedback verbally. The researcher was aware of the potential for performance bias and remained as objective as possible so as not to treat the groups differently during training.

The VIS and No-VIS exercises were very similar to avoid a potential confounding effect if a standard rehab protocol was used including less functional exercises. This enabled the No-VIS group to be the control group and to allow a direct comparison as to the effect of the visualisations.



Training with Visualisation (VIS group)	Training with no Visualisation (No-VIS group)
Single Leg Balance with Leg Lift	Single Leg Balance with Leg Lift
Single Leg Stand & Reach	Star Excursion Balance Exercise
Lunge	Lunge
Leap Game	Dynamic Leap & Balance Exercise

Figure 8.11 Exercises included in the training for the VIS and No-VIS groups

Table 8.3 Feedback during training intervention

			Feedback			
			Knowledge of Result	**Knowledge of Performance**	**Internal Attentional Focus**	**External Attentional Focus**
Exercise 1	VIS	SLB with leg lift	Visual from spot/avatar on screen	Verbal from tester	Biofeedback from image of avatar on screen	Verbal from tester Visual from spot/avatar on screen
	No-VIS	SLB with leg lift	n/a	Verbal from tester	Verbal from tester Biofeedback from own movement	Verbal from tester
Exercise 2	VIS	SLSR	Visual from score/avatar on screen	Verbal from tester	Verbal from tester Biofeedback from image of avatar on screen	Verbal from tester Visual from score/avatar on screen
	No-VIS	SEB	Visual from tape on ground	Visual from tape on ground	Verbal from tester Biofeedback from own movement	Verbal from tester Visual from tape on ground
Exercise 3	VIS	Lunge	Visual from avatar on screen	Verbal from tester Visual from avatar on screen	Biofeedback from image of avatar on screen	Visual from avatar on screen
	No-VIS	Lunge	n/a	Verbal from tester	Verbal from tester Biofeedback from own movement	Verbal from tester
Exercise 4	VIS	Leap Game	Visual from game/avatar on screen	Verbal from tester	Verbal from tester Biofeedback from image of avatar on screen	Verbal from tester Visual from game/avatar on screen
	No-VIS	DBLT	Time to perform exercise Visual from tape on ground	Verbal from tester Visual from tape on ground	Verbal from tester Biofeedback from own movement	Verbal from tester Visual from tape on ground Time to perform exercise

Participants attended training for two sessions a week for four weeks. This was shorter than the healthcare professionals in Chapter 6 would conduct a stability intervention for, and that of some previous research in stability-based training for people with CAI where 3 sessions over 4 weeks were conducted (Anguish and Sandrey, 2018, Cruz-Diaz et al., 2018, Comfort et al., 2015). However, this was representative of other literature (Hale et al., 2014; Linens et al., 2016), and was most appropriate given the time available of the researcher and the labs at each of the testing sites.

Each session the exercises were repeated 2-3 times on each leg, with the score of the final set recorded on the participant progress sheet for monitoring. For the No-VIS group there was no scoring for the single leg balance, and in the star excursion balance exercise the maximum and average reach distances were recorded at each session, but the participant was not made aware of these results. This information was used by the tester to monitor progress and provide additional information to help the tester decide on when and how to progress the training. The dynamic leap and balance exercise recorded the time taken to complete the exercise on the participant's notes to monitor progress and could be used as a performance motivator if necessary.

8.1.5 Data analysis

8.1.5.1 Data analysis for pre- and post-training testing

The outcome measures for the tests were detailed in Table 8.1. The scores were output immediately and test score cards updated.

Text files were recorded for post-test analysis of the lower limb kinematics. This was imported into MATLAB where programmes were created for specific analysis, including centre of mass displacement of the lunge exercise.

8.1.5.2 Data analysis for intervention

During the intervention there was no post-processing. All outcomes were displayed on the screen and/or control panel of the computer, allowing for the participant's report card to be immediately completed during the training session.

8.1.6 Statistical analysis

All statistical analyses were carried out in SPSS (SPSS Statistics: v. 26, IBM, USA). Shapiro-Wilk normality tests were conducted to establish the appropriate test for statistical analysis.

For the statistical tests the VIS and No-VIS groups for the No-CAI group were compared and then the VIS and No-VIS groups for the CAI group were compared.

Assuming normality, the testing sessions were compared using separate two-way mixed ANOVAs with Bonferroni adjustments for the SLB, SEBT, and multi-leap Test and lunge to identify time*group differences, as well as main effects of time and group differences. Univariate analyses were performed if there was a significant group*time difference.

8.2 Results

8.2.2 Participants

The process of participant recruitment, data collection, and final analysis is displayed in Figure 8.12.

Participant recruitment was conducted for the maximal time available – approximately 4 months in the UK and 1.5 months in Australia.

The Australian site received more interest than both Glasgow and Edinburgh combined, for reasons which the researchers hypothesise, and address, in the discussion. The uptake from the initial interest was 16.2% and 29.3%, for Australia and the UK respectively. After showing initial interest people primarily declined to participate due to time constraints and having to attend 10 sessions in the lab. The ineligibility of potential participants screened was due to ankle surgery, other lower limb injuries, and/or lateral ankle sprains which had not led to chronic ankle instability as per the CAIT questionnaire.

There were two dropouts from the study. These were both from the CAI population (one VIS and one No-VIS) and were due to injuries which were unrelated to the study. These led the participants to be unable to continue in the study. In the No-CAI population all participants completed the intervention and testing sessions however the researchers removed one participant’s data from the final analysis. This was due to the inability to follow the specific guidelines for exercise standards to be met during the pre- and post-testing sessions, as well as extreme outlier results for the exercises too.

Due to the small sample size, the populations of the Edinburgh and Glasgow site locations were combined to form the UK population for comparison to the Australia population. These comparisons are described in the descriptive analysis for CAI and No-CAI populations.

Attendance at the supervised training sessions was 100% for participants in both the VIS and No-VIS groups. There were no adverse events reported for either training group.

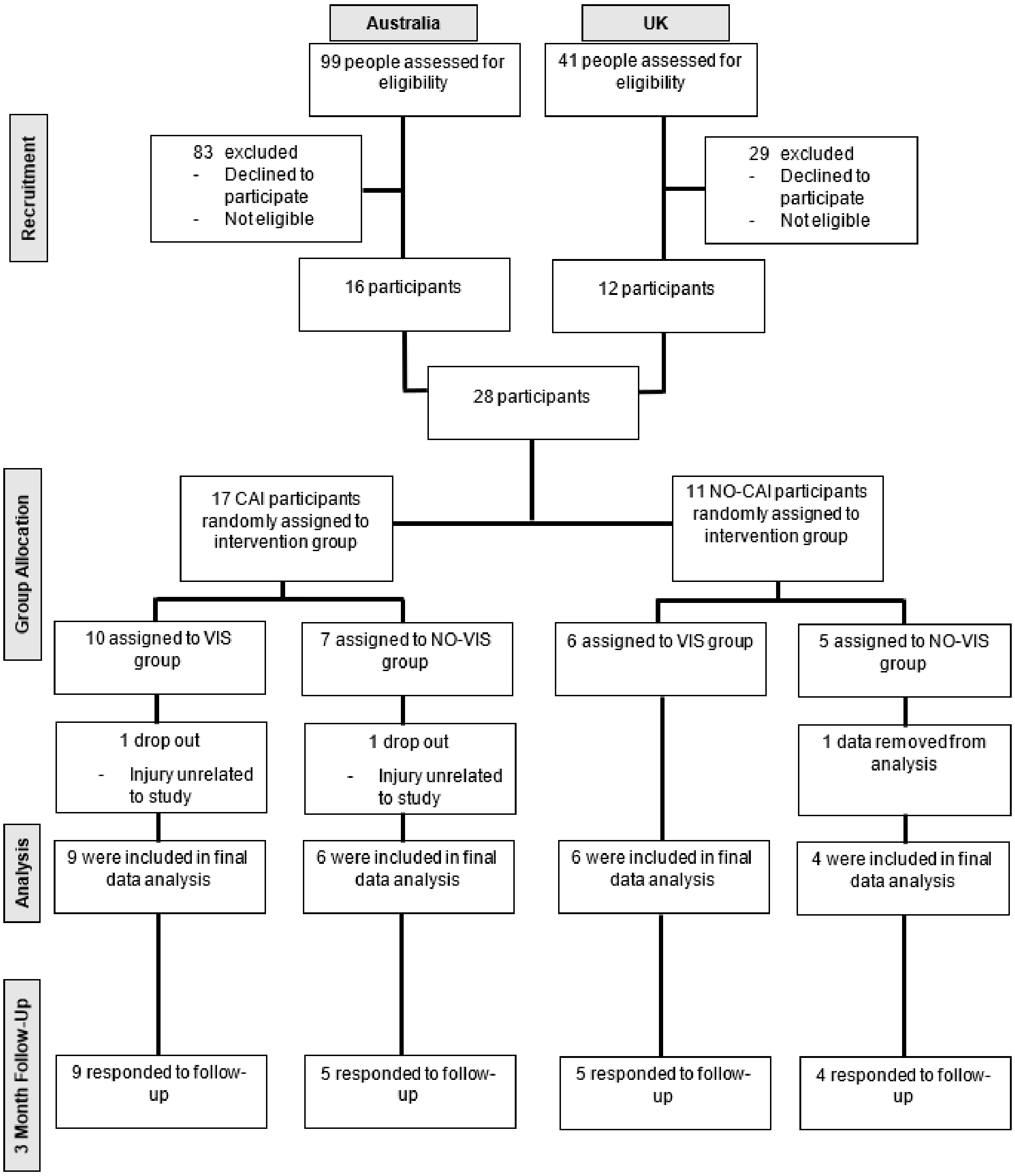


Figure 8.12 Flow chart of participant process

8.2.3 Descriptive Analysis

Table 8.4 Descriptive statistics for the No-CAI and CAI populations.

	NO-CAI		CAI	
	VIS	**No-VIS**	**VIS**	**No-VIS**
SITE (UK/AUS)	3 / 3	3 / 1	4 / 5	2 / 4
AVERAGE AGE (YEARS)	31 ± 13	24 ± 6	28 ± 9	29 ± 14
GENDER (M/F)	3 / 3	2 / 2	5 / 4	3 / 3
AVERAGE WEIGHT (KG)	70.4 ± 6.1	64 ± 11.2	78.9 ± 37.3	72.1 ± 9.6
DOMINANT (R/L)	6 / 0	3 / 1	9 / 0	6 / 0
PHYSICALLY ACTIVE (%)	100	100	77.8	100
COMPETITIVE ATHLETE (%)	33.3	25	22.2	66.7

No-CAI

The age of the UK and Australian populations differed significantly between the two populations (UK vs. AUS: 22±3 vs. 39±7, *p*=0.003). As this was the only difference in a healthy population the data was combined for further analysis to create a larger sample size.

Descriptive data of the No-CAI participants is displayed in Table 8.4. There were no significant differences between the VIS and No-VIS groups pre-training (*p*>0.05). Each group had a 1:1 gender split of males to females and all participants described themselves as physically active. The VIS group had 1 more competitive athlete – defined as participating in regular competitive sport – than the No-VIS group (*p*=0.807).

CAI

Between the UK and Australian populations the number of ankle sprains reported signifcantly differed (UK vs. AUS: 2±1 vs. 5±3, *p*=0.05). As this was the only difference data was combined for further analysis.

Table 8.4 shows the participant information of the CAI sample. There were no significant differences between the VIS and No-VIS groups pre-training (*p*>0.05). Each group had 44.4% and 50% female representation and at least 75% of each group was physically active. In the No-VIS group all participants were physically active compared to 7/9 participants in the VIS group. Of these active participants the No-VIS group classed four as competitive athletes, and the VIS group classed two.

In the VIS group all participants who had had treatment previously also completed some form of supervised and professional rehabilitation (Table 8.5). In the No-VIS group not everyone who underwent rehabilitation had sought treatment for the injury. Treatment and supervised rehabilitation were commonly sought for one injury only – usually the initial sprain – and further injuries were self-managed. Treatment strategies and rehabilitation processes were varied, including administration of moonboots, periods of rest prescribed, and self-management strategies. From previous rehabilitation interventions 50% or less of the participants in both groups were satisfied with the treatment received, to which one participant reasoned this to be because the rehabilitation was 'boring so [I] didn't do it'.

Table 8.5 Injury and treatment history for CAI group

CAI	**VIS**	**NO-VIS**
	Mean ± SD	
INJURED ANKLE (R/L)	4 / 5	2 / 4
NUMBER OF ANKLE SPRAINS	3.7 ± 2.8	3.5 ± 1.8
TREATMENT SOUGHT (%)	77.8	66.7
REHAB UNDERTAKEN (%)	77.8	83.3
REHAB SATISFACTION IF REHAB UNDERTAKEN (%)	44.4	50

8.2.3 Objective results

8.2.3.1 Single leg balance with eyes closed

No-CAI

Performance of the SLB did not significantly differ between groups over time (*F*(1,5) = 0.32, *p*=0.6), but it did favour the VIS group with medium effect, with an increase of 26.96s compared to the No-VIS group's increase of 8.94s (Table 8.6). The main effect of time in the SLB did not reach significance (*F*(1,5) = 1.27, *p*=0.31). Performance for the VIS group at both pre- and post-testing sessions was highly variable between participants.

CAI

The VIS group improved time by 0.04s and the No-VIS group decreased time post-training by 6.19s (Table 8.6). This result favoured the VIS group with medium effect, but was not a significant interaction (*F(*1,10) = 0.5, *p*=0.5). There was no significant main effect of time or group (*F(*1,10) = 0.489, *p*=0.5 and *F(*1,10) = 0.164, *p*=0.69, respectively).

Table 8.6 Mean (SD) difference between pre- and post-test results for the SLB.

*significant difference between VIS and NO-VIS groups (p≤0.05).

SLB	**VIS**	**NO-VIS**	**MEAN DIFF.**	***D***	***F***	***P***
	Difference (s)					
NO-CAI	26.96 (42.56)	8.95 (4.87)	18.01	0.76	0.32	0.60
CAI	0.04 (4.18)	-6.19 (21.13)	6.22	0.49	0.50	0.50

8.2.3.1 Star excursion balance test

No-CAI

There were no significant interactions between the VIS and No-VIS groups over time for the SEBT (Table 8.7). Performance of the SEBT at post-test, averaged over all 8 directions, was increased in both the VIS and No-VIS groups by 5.67% and 6.05%, respectively. This favoured the No-VIS group by 1% but was not statistically significant (*F*(1,8)=0.01, *p*=0.92). In the AL, PM, M and AM directions the increase performance favoured the VIS group, and in the A, L, PL and P directions it favoured the No-VIS group, with small effect only. The difference between the VIS and No-VIS groups did not exceed 3.32%, and was not significant.

For all directions the improvement in performance from pre- to post-test ranged between 3.52-9.65% for the VIS group and 3.89-10.09% for the No-VIS group. For the VIS group this was greatest laterally, followed by the PM, P and PL directions. Similarly, for the No-VIS group the greatest increase was posteriorly, followed by the PL, L and M directions. There was a statistically significant main effect of time for the A (*F*(1,8)=8.73, *p*=0.02), AM

(*F*(1,8)=9.06, *p*=0.02), M (*F*(1,8)=5.91, *p*=0.04), PM (*F*(1,8)=5.48, *p*=0.05), P (*F*(1,8)=6.56, *p*=0.03), AL (*F*(1,8)=11.45, *p*=0.01), and average directions (*F*(1,8)=11.32, *p*=0.01).

CAI

Performance on average across all 8 reach directions significantly improved in the VIS group compared the No-VIS group (*F(*1,13)=10.03, *p*=0.01) (Table 8.7). This was a significant difference within the VIS group over time of 6.74% (*F*(1,8)=24.81, *p*=0.001), but not for No-VIS group with an improvement of 0.13% (*F*(1,5)=0.01, *p*=0.94). There was not a significant difference between the VIS and No-VIS groups at either time point (pre: *F*(1,13)=1.89, *p*=0.19, post: *F*(1,13)=0.24, *p*=0.63).

Performance in all individual directions favoured the VIS group with medium-large effect. This was a significant group x time difference in the PM, P, PL, and L directions (Table 8.7). For each of these directions the VIS group showed a significant improvement over time and the No-VIS group did not (VIS PM: (*F*(1,8)= 15.03, *p*=0.01), No-VIS PM (*F*(1,5)=0.22, *p*=0.66); VIS P: (*F*(1,8)= 14.13, *p*=0.01), No-VIS P (*F*(1,5)=0.22, *p*=0.67); VIS PL: (*F*(1,8)= 23.19, *p*=0.001), No-VIS PL (*F*(1,5)=0.02, *p*=0.89); VIS L: (*F*(1,8)= 22.46, *p*=0.001), No-VIS L (*F*(1,5)=0.06, *p*=0.82). There were no significant differences between the VIS and No-VIS groups at either time points (pre PM: *F*(1,13)=1.33, *p*=0.27, post PM: *F*(1,13)=0.18, *p*=0.68; pre P: *F*(1,13)=1.54, *p*=0.24, post P: *F*(1,13)=0.54, *p*=0.47; pre PL: *F*(1,13)=3.16, *p*=0.10, post PL: *F*(1,13)=0.64, *p*=0.44; pre L: *F*(1,13)=1.85, *p*=0.20, post L: *F*(1,13)=0.47, *p*=0.51).

For the A, AM, M, and AL directions the main effect of time was not significant (A: (*F*(1,13)= 0.05, *p*=0.83), AM: (*F*(1,13)= 1.05, *p*=0.33), M: (*F*(1,13)= 2.80, *p*=0.12), AL: (*F*(1,13)=0.33, *p*=0.56).

For the A, AM, M, and AL directions the main effect of group was not significant (A: (*F*(1,13)= 0.08, *p*=0.78), AM: (*F*(1,13)= 0.32, *p*=0.58), M: (*F*(1,13)= 0.10, *p*=0.76), AL: (*F*(1,13)= 0.10, *p*=0.76).

Table 8.7 Mean (SD) difference between pre- and post-test results for the SEBT. *significant group*time difference between VIS and NO-VIS groups ($p \leq 0.05$)

SEBT		**VIS**	**NO-VIS**	**MEAN DIFF.**	***D***	***F***	***P***
		Difference (% leg length)					
ANTERIOR	**No-CAI**	3.51 (4.03)	5.09 (5.25)	-1.58	-0.34	0.29	0.60
	CAI	0.77 (3.47)	-1.18 (3.82)	1.94	0.53	1.03	0.33
ANTERIOR-MEDIAL	**No-CAI**	5.16 (3.31)	4.72 (7.12)	0.44	0.09	0.02	0.90
	CAI	2.31 (4.09)	0.00 (4.60)	2.31	0.53	1.04	0.33
MEDIAL	**No-CAI**	5.37 (7.54)	6.56 (7.70)	-1.20	-0.16	0.06	0.81
	CAI	5.41 (7.5)	0.80 (6.19)	4.61	0.67	1.54	0.24
POSTERIOR-MEDIAL	**No-CAI**	7.08 (10.46)	7.15 (7.36)	-0.07	-0.01	0.00	0.99
	CAI	8.43 (6.52)	0.97 (5.07)	7.45	1.29	5.55	0.04*
POSTERIOR	**No-CAI**	7.95 (13.19)	10.10 (5.28)	-2.14	-0.23	0.09	0.77
	CAI	10.96 (8.75)	1.47 (7.62)	9.49	1.16	4.67	0.05*
POSTERIOR-LATERAL	**No-CAI**	8.13 (14.64)	6.27 (3.61)	1.86	0.20	0.06	0.81
	CAI	12.42 (7.74)	0.33 (5.57)	12.10	1.82	10.80	0.01*
LATERAL	**No-CAI**	9.65 (15.98)	6.34 (1.71)	3.32	0.36	0.16	0.70
	CAI	10.04 (6.36)	0.56 (5.82)	9.48	1.56	8.54	0.01*
ANTERIOR-LATERAL	**No-CAI**	5.18 (4.43)	3.89 (3.65)	1.29	0.32	0.23	0.64
	CAI	0.34 (6.58)	-2.61 (8.73)	2.95	0.39	0.56	0.47
AVERAGE	**No-CAI**	5.67 (5.89)	6.05 (4.44)	-0.38	0.07	0.01	0.92
	CAI	6.74 (4.06)	0.13 (3.80)	6.61	1.69	10.03	0.01*

8.2.3.1 Multi-leap test

No-CAI

The No-VIS group showed a larger increase following training with small effect, but the result was not significant (*F*(1,13)=0.19, *p*=0.67) (Table 8.8). The main effect of time for distance leapt showed a significant difference between time points (*F*(1,8)=8.64, *p*=0.02). The main effect of group did not show a significant difference between groups (*F*(1,8)=1.08, *p*=0.33).

CAI

The performance of the multi-leap test post-training favoured the VIS group with small to medium effect and a 7.16% greater improvement, but this was not a significant interaction (*F*(1,13)= 0.53, *p*=0.48) (Table 8.8). The main effect of time showed a statistically difference in mean distance leapt at the different time points (*F*(1,13)= 11.01, *p*=0.01). The main effect of group showed no significant difference between groups (*F*(1,13)= 1.00, *p*=0.34).

Table 8.8 Mean (SD) difference between pre- and post-test results for the ML Leap Test.

*significant difference between VIS and NO-VIS groups ($p \leq 0.05$).

MULTI-LEAP TEST	**VIS**	**NO-VIS**	**MEAN DIFF.**	***D***	***F***	***P***
	Difference (% leg length)					
NO-CAI	7.36 (11.28)	9.95 (3.14)	-2.59	-0.36	0.19	0.67
CAI	19.88 (21.66)	12.73 (12.38)	7.16	0.42	0.53	0.48

8.2.3.1 Lunge

No-CAI

Following training the VIS group achieved a 5.9cm larger reverse step on average compared to the No-VIS group, however this was not significant (*F*(1,8)=0.94, *p*=0.36) (Figure 8.13). There was no significant main effect of time or group (*F*(1,8)=2.32, *p*=0.17, and *F*(1,8)=0.34, *p*=0.58, respectively).

The range of movement of the COM in the AP direction decreased in the VIS group by 0.004cm and increased in the No-VIS group by 0.006cm, but this was not a significant difference (*F*(1,8)=0.09, *p* =0.77) (Figure 8.14). There was no significant main effect of time or group (*F*(1,8)=0.002, *p*=0.96, and *F*(1,8)=0.002, *p*=0.97, respectively).

In the ML direction the VIS group increased the range of movement following training by 12.3cm, compared to the No-VIS group which showed a 2.5cm increase, but this was not a significant difference (*F*(1,8)=2.03, *p* =0.19) (Figure 8.15). There was no significant main effect of time or group (*F*(1,8)=4.61, *p*=0.06, and *F*(1,8)=2.57, *p*=0.15, respectively).

An increased maximum velocity mediolaterally during the lunge was seen in both groups by 0.01m/s and 0.001m/s in the VIS and No-VIS groups, respectively. This was not a significant group x time interaction however (*F* (1,8)=3.13, *p*=0.12) (Figure 8.16). The main effect of time showed a significant change over time (*F* (1,8)=8.14, *p*=0.02) and there was no main effect of group (*F* (1,8)=1.87, *p*=0.21).

CAI

Following training the reverse step length, range of movement of the COM in the AP and ML directions, and COM velocity in the ML direction did not significantly differ between groups (*F*(1,12)=0.01, *p*=0.91, *F*(1,12)=2.18, *p*=0.17, *F*(1,12)=0.04, *p*=0.84, and *F*(1,12)=2.27, *p*=0.16, respectively) (Figures 8.13, 8.14, 8.15, 8.16). The range of movement in the AP and ML directions did show a significant main effect of time (*F*(1,12)=6.40, *p*=0.03, and *F*(1,12)=16.42, *p*=0.002), respectively) but not a main effect of group (*F*(1,12)=3.09, *p*=0.10, and *F*(1,12)=4.12, *p*=0.07, respectively).

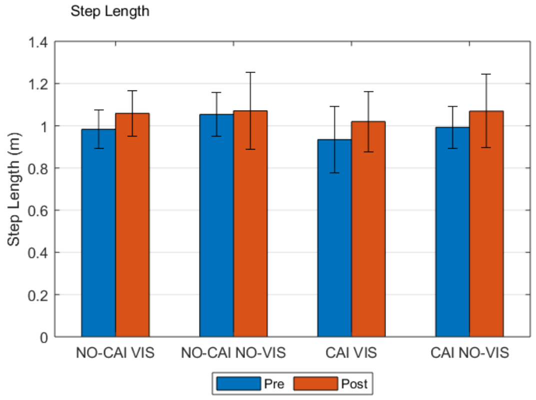


Figure 8.13 Average step length pre- and post-test for the reverse lunge

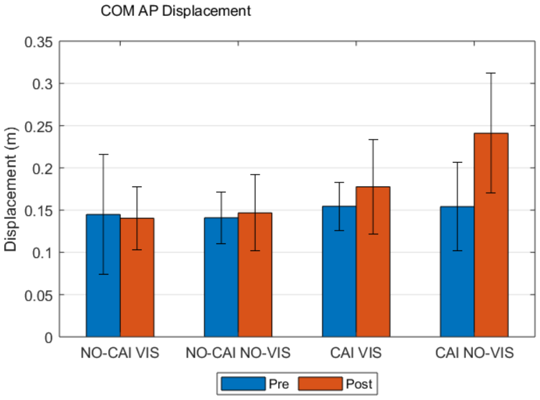


Figure 8.14 Range of movement of COM in AP direction

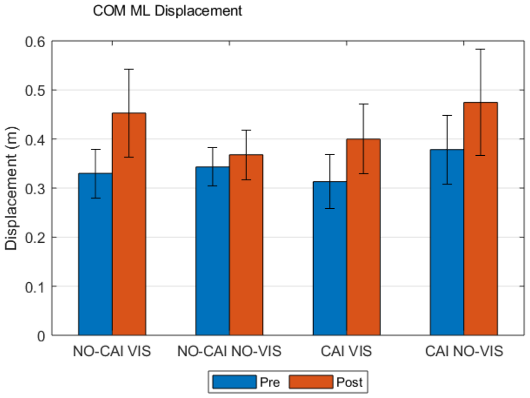


Figure 8.15 Range of movement of COM in ML direction

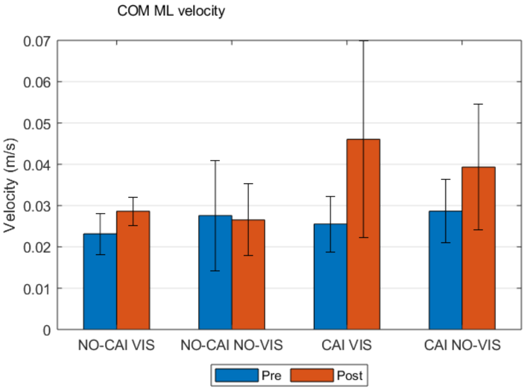


Figure 8.16 Range of velocity of COM in ML direction

8.3 Discussion

This feasibility randomised controlled trial assessed the stability-based package and in terms of feasibility and safety of the four-week stability-based training programme with visualisation. This section discusses in greater detail these results in relation to the feasibility of visualisation for both the No-CAI and CAI groups.

The protocol and training intervention using visualisation was shown to be feasible as indicated by the retention and adherence of participants. This was seen across the multiple sites that all included different laboratory set ups. Safety of the programme was evidenced by no adverse events reported. This suggests the package could be conducted in different clinical environments.

8.3.4 No-CAI

Overall the results for the group with No-CAI were inconclusive as to the effectiveness of using visualisation during stability-based training. The package was successfully used but the outcome measures reported small effect sizes and no significant results. The main effect of time was analysed when there was no interaction between the groups over time. There was a significant improvement for the ML Leap test and the SEBT in the all but the L and PL directions. These results suggest that the balance training programme may be effective at eliciting change over time, however the visualisations did not indicate improvements statistically. When interpreting this result it is important to first consider that the study was underpowered. Theoretically there are two other reasons believed could have led to this result:

1. The training was a new phenomenon for people who have never experienced a lower limb injury, thus have never performed a rehabilitation programme before, and
2. The training being unnecessary as the population were not injured.

Exploring these further, if participants had never experienced stability-based training before there may have been an increased engagement in the process for both the VIS and No-VIS groups. This may have elicited the equal performance improvement in both groups as participants in the No-VIS group were motivated to use the traditional clinical feedback they received to improve.

Alternatively, as per the second point above, the addition of training with visualisation may have been ineffective if the training was not necessary. The training focused on both static and dynamic balance exercises to improve stability, as opposed to alternative aspects of fitness such as strength and flexibility. Without a reduced balance ability then the inclusion of visualisation to the programme may have been redundant, or too specific to elicit a change.

These results support previous research from Tripette and colleagues (2017). The systematic review, which included a meta-analysis of 25 studies, also found no effect from a balance VR rehabilitation programme for healthy adults. The study reported insignificant findings for the Activities-specific Balance Confidence test (ABC), Borg Balance Scale (BBS), and Timed-Up-And-Go Tests (p>0.05), but these were not discussed possibly due to the limited number of studies which it had included in the analysis. A more recent review identifed SEBT performance following VR training to also be comparable to a traditional programme, or less effective, in 5 healthy populations (Vogt et al., 2019). Although the pre- to post-test improvements for the groups were smaller than those in the current study, the results also suggested that the addition of the VR to training did not enhance performance. Of the studies reviewed by Tripette et al. (2017) and Vogt et al. (2019) all but one used a Wii balance board protocol for VR training. Despite the limitations of the Wii Balance board which we believe creates a more basic, less functional and potentially less challenging environment than the current study, our results report similar findings.

Summarising, the stability-based training package for healthy adults is feasible. The stability-based training did elicit a change over time in the SEBT and ML Leap tests. However the effect of the visualisations is inconclusive. The visualisations did not clearly enhance the outcome , thus for this sample population it may not be effective.

8.3.5 CAI

Unlike the No-CAI group who had no previous experience of rehabilitation, the majority of participants with CAI had previously sought treatment and completed a rehabilitation programme following an ankle sprain. As a consequence rehabilitation was not a new experience. However, the 50% satisfaction rate reported from previous rehabilitation experienced highlights current clinical practice is not effective enough. Subsequently this led to participants not seeking professional services for further injuries and opting for self-management, supporting the previous findings of Hiller et al. (2012). As stated in Chapter 2 this focuses on pain and inflammation thus the stability deficits of the ankle are not addressed. The results from this investigation suggest that visualisation may enhance rehabilitative outcomes and experience, however further investigation is necessary, The following sections discuss each of the outcome assessments in more detail, relating to previous research.

8.3.5.1 Single leg balance with eyes closed

Firstly, the results from three participants in the VIS group were not recorded thus analysis was of a smaller VIS group of six participants. The sample size would suggest the reason as to why the results were highly variable, however this has also been found in a previous study. The previous study concluded that despite the reliability of the SLB as a test of postural control when the participants eyes were closed, the standard error across participants reached 13.9 seconds for the best score from 3 trials (Springer et al., 2007).

The overall lack of improvement in both groups was unexpected although recent research did report similar results (Oungphalachai and Siriphorn, 2020). In their study, following eight weeks of SLB training both the experimental group who received visual feedback and the control group, who did not, improved single leg balance scores by -0.03 and 0.11 seconds, respectively, when eyes were closed. The study inferred that the number of repetitions completed during training was insufficient for transference to the eyes closed condition even though it included 900 repetitions with eyes open. This may have been the case in the current study where despite performing the exercise with their eyes closed as SLB progressions throughout the training, there may have needed to be more practice of this.

There are a few alternative explanations we can address. Firstly, only one trial was recorded as opposed to the result being an average of numerous trials. This may have increased the pressure felt by the participant to perform on that one trial. Further to this, if the participant had deemed previous trials to be successful, this may have added a stress that they felt they had to repeat this effort or that they might not be able to perform better. This was noted by the researcher, however the system was unable to record three trials and take an average due to the real-time nature of the software. This meant only the best time was used for analysis rather than an average of performance. To prevent the need to perform calculations manually during the testing or for post-processing of results, the protocol used was the most appropriate.

Another reason for this could be the participants' skill level or ability to use compensatory methods to remain balanced, such as fixing the ground with the foot. If we reconsider Bernstein's (1967) theory during the stages of learning from Section 3.2 participants could have frozen degrees of freedom to create a more rigid structure to allow for better performance by influencing assessments and signifying improved stability. This would support the research, particularly during the initial stages of learning, where joint coupling was present when learning a task and flexibility of movement patterns is low (Gray, 2020; Guimaraes et alk., 2020; Vereijken et al.,1992). This assessment, however, is an objective measure of stability and does not consider quality of the movement, and so when these straegies cannot be used the stability deficit is still present and the risk of re-injury remains.

In summary, it is inconclusive as to the effect stability-based training with visualisation has on performance of the SLB. This is likely due to the sample size which has limited the interpretation of these results, and so although there was a moderate effect size favouring the visualisation group this was not significant.

8.3.5.2 Star excursion balance test

The SEBT was the primary outcome measure of this study, as detailed in Section 8.1.4.2, and the training with visualisation enhanced performance of the SEBT significantly. Not only was this evident for the average result over all eight reach positions, but specifically in the PM, P, PL and L directions significantly and with greatest effect.

For each of these directions – PM, P, PL, and L – the significant within group time effect for the VIS group was also in accordance with a recent meta-analysis using a minimal detectable change of 8.15% to determine intervention success (Burcal et al., 2019). From this it is inferred that the intervention was successful. This was not apparent in the No-VIS group. It is important to recognise the specific directions where these significant changes in reach distance performance have occurred. Research has suggested reaching posteriorly to the body requires an increased reliance on somatosensory feedback since there is no visual awareness when reaching this way, and would suggest that an increased level of stability is required to maintain position (Bulow et al., 2019). Moreover, to perform maximal reaching in the PL direction there are limited options for the body to position itself, mainly the trunk, above the base of support while remaining stable, as opposed to when performing reaches in the medial-oriented directions. Considering this, it is promising for potential future implementation of visualisation into rehabilitation practice that the greatest effect of the training with visualisation occurred in these directions where remaining stable is more challenging.

Aside from stability deficits there are a few variables which may have limited reach distance progression in the other directions where limited difference was found:

- Joint range of motion
- Age

Explaining this in more detail, in the anterior direction a greater increase in range of motion (ROM) is required to increase reach distance thus since this programme included no stretching, as increased ROM was not an outcome, this may have limited the reach distance. This could explain why anterior result pre- to post-training was minimal, and thus possibly too small for a between-group difference to be seen. This has been previously identified in a study by Basnett and colleagues (2013). The results published a fair positive correlation between ankle dorsiflexion and SEBT reach in all directions of the modified SEBT, but particularly in the anterior direction (Basnett et al., 2013). Other previous studies by Gribble and colleagues (2007, 2004) have also found that reduced range of motion of the hip and knee in those with CAI predicted 49% of the variance in SEBT performance for shorter reach distances. If we compare this to the posterior reach directions, there has been a greater association with eversion strength shown (Gabriner et al.,2015). This could also suggest that the visualisation training was more multifaceted than the No-VIS training by developing more strength, but we do not think this is a plausible reason since the training interventions were designed to be very similar with neither proposed to have a greater strength element.

The second factor of particular relevance to this study which may have accounted for the variance in results is related to the age of the participants in the CAI group. The study presented a large age range of participants. Recent research found a significant effect of age on SEBT performance (Kosik et al., 2019). The study reported a significant main effect between younger-aged and middle-aged adults in the A, PM and PL directions ($p<0.001$). This was apparent for those with and without CAI and resulted in a reduced reach distance in the older group. The study inferred this to be related to decline in function of the sensory and motor systems as we age, as well as an increased risk of falling as the SEBT pushes the participant to the edge of their ability (Vogt et al., 2019).

Lastly, although not previously researched, the athletic ability – from being either physically active or competitive athletes – may have also affected the participants ability, however this is speculative only and is not known.

In summary, the results suggest that training with visualisation may be more effective than training without on SEBT performance.

8.3.5.3 Multi-leap test

The multi-leap test was included in the study to analyse the ability to control the COM during a series of leaps. It was hypothesised that as with the multi-hop test, which this test was adapted from, a higher degree of instability would incur a shorter leap distance on average so as to maintain the ability to control the COM on landing. Although the main effect of time showed that test performance significantly improved from pre- to post-test, this was not a significantly greater improvement when the visualisations were added. Thus a conclusive result cannot be reported as to the effect of training with the visualisation.

Considering the final testing protocol it is interesting that the results showed a medium effect size in favour of the VIS group. On reflection of the test, the assessment required both stability and strength in order to perform the leaping task. This represented the No-VIS leap training to a greater extent since the dynamic leap and balance exercise in training had also focussed on these components. This was unlike the leap game in the VIS training which required multiple repetitions of leaps for a period of time. During the game the distance of each leap was not focused on and would not have exceeded approximately 1m, and the game addressed reactivity while focusing on control. These results suggest that the training required adequate joint coordination and lower body neuromuscular control to enhance performance without the primary focus on leap distance, and strength, like in the No-VIS group. The results of this investigation support the motor learning principles from Chapter 4 that practice should be variable, as also highlighed in the results of a previous study in people with chronic ankle instability (Hall et al, 2018). The study reported that both balance and strength training protocols improved performance of a hopping task with large effect (both Hedges g = 0.8), compared to a weak effect in the control group (Hedges g = 0.1) (Hall et al., 2018). In that study the balance training group also reported significantly improved perceived instability scores, which may have increased confidence when performing the hopping task. This may have been the case in our study too as a result of the VIS training, which led to comparable performance between the VIS and No-VIS groups.

The results from the multi-leap test are inconclusive when the visualisations were incorporated into training. This occurred despite the training being more representative of the No-VIS training exercise. Considering this, it would be interesting for future research to assess the participant's ability to cope with unexpected situations and reactivity. Conducting this may have been challenging since testing did not involve use of the visualisation software but it may have been more relevant when identifying the effect of visualisation.

8.3.5.4 Lunge

In the investigation the training with visualisation did not lead to significant changes in these temporal parameters compared to those who trained without.

The interpretation of these results in relation to previous literature is limited due to the lack of research in this area. Closed kinetic skills (ie. Lunge) have been included in training programmes previously since successful movement is complex requiring the simultaneous movement and coordination of multiple joints, as well as stability as the base of suport changes during the step (Lee et al., 2013). However as an outcome assessment in the context of this investigation the lunge has not yet been researched. The inline lunge as part of the Functional Movement Screen (Cook, 2006) is similar and has been used as a measure of balance training success, but the parameters analysed in this study which may relate to the participants' stability have not been assessed using the inline lunge. Furthermore, research by Hartigan and colleagues (2014) concluded that the inline lunge did not relate to, and should not be attriuted to, balance performance.

Following the training there was no effect on the step length when taking the leg posteriorly into the reverse lunge, however there was a main effect of time for the displacement of the COM in the AP and ML directions. This may suggest an increased confidence in ability to control the body through dynamic movement about a small base of support both mediolaterally and anterioposteriorly, and also infer that the ground reaction forces acting on each limb would be more symmetrical – an aim of the lunge as outlined in Chapter 4. Loading primarily through the front limb would reduce the load through the back leg during the lunge. This would be favourable since the ankle of the limb posterior to the body is in a more unstable position. Therefore this main effect between pre- to post-test may suggest an increased confidence in ability to control the body in a more unstable position than before. Without kinetic data however this theory cannot be confirmed. The addition of the visualisations did not enhance the improvement from the training, however the study was underpowered and so no conclusions can be made as to the effect of the visualisations during the lunge.

Despite the training including a cognitive element this was not measured in the final assessment. This was so the same protocol could be conducted in the pre-and post-test, and also so only a single task was demanded of the participants. Including a secondary task which was both new and different to that in the training in the assessment may have led to more evident changes. This may have more clearly identified the effectiveness of the training and the ability to cope with additional tasks, like we do daily.

In summary, training with visualisation for the lunge appears comparable to training without visualisation in relation to the step length, and COM displacement and velocity.

8.3.6 Strenths and limitations of the study protocol

8.3.6.1 Participant recruitment

The main limitation of the current study was the sample size. According to the sample calculation (Section 8.1.3.1) the study was underpowered due to a less than successful recruitment. This has limited the inferences that can be made regarding the impact of the visualisation on stability-based training, as discussed in the preceding sections.

Participants were recruited from both Scotland, UK and Geelong, Australia and as there were no differences in the demographics of the two groups this allowed for the populations to be combined into one group. Australia showed a greater initial interest which resulted in a larger number of participants recruited in comparison to the UK. This was also completed over a shorter period of time. Considering the population of each city where the testing was completed (Table 8.9) this cannot be due to the size or density since Geelong has less people over a greater area than both Edinburgh and Glasgow (Division, 2020).

Table 8.9 City populations where study took place (Division, 2020)

City	Population
Geelong	261,208
Edinburgh	482,005
Glasgow	1,209,143

Therefore we believe there are 2 main reasons for this:

- Primary method of recruitment in Australia
- Site location

Firstly, the two countries used different recruiting strategies as primary sources of recruitment. In Australia a sponsored advertisement on Facebook was used as an additional method of recruitment due to time restraints. Over a 2-month recruiting period, compared to a 4-month recruiting period in the UK, this successfully reached a very large number of people from demographics related to the study. This therefore statistically increased the likelihood of successfully recruiting people which is evident since more potential participants were assessed for eligibility, and more were excluded than in the UK, but this ultimately still led to a greater number of participants recruited in Australia compared to the UK.

Secondly, the testing site in Glasgow was situated in the city centre with limited access via public transport and no free parking. Further to this the congestion when accessing the city centre by car, particularly during rush hour, makes people more reluctant to do so. This was not the case for both Geelong and Edinburgh where the testing sites were located on the outskirts of the city and could be accessed easily by public transport and car, with free parking available. This could have been a deciding factor for potential participants declining to participate.

8.3.6.2 Population sample

The population was represented by a diverse athletic ability and amount of participation in physical activity. Although this may have been advantageous for the study, as it shows a generalised representation of people with CAI, it is believed that considering the small sample size this may have confounded results, as suggested in this study for SEBT and multi-leap test.

In the CAI population the randomisation of participants into treatment groups led to unequal group sizes in the VIS and No-VIS groups. This may have further limited the statistical significance of the study, and preventing stronger conclusions being made.

8.3.6.3 Study Protocol

After allocating the participants to the VIS or No-VIS group following the pre-training testing the participants were no longer blinded as to the training group they were part of. Due to the nature of the study this was not possible but is a limitation to the study leading to possible bias. This may have influenced participant behaviour due to the knowledge of group allocation. However participant adherence was 100% due to the nature of the study protocol and no training required to be completed outwith the supervised sessions, and retention was high. This suggests that knowledge of group allocation had limited effect, despite what is reported (Karanicolas et al., 2009). This may be a reflection on the stability-based training programme designed in Chapter 4 that acted as the control group, and differed to typical ankle rehabilitation. Nevertheless, on reflection, future work could put a protocol in place to blind participants to the study aims.

Despite the control group protocol providing an appropriate proxy for the study to compare the effect of adding the visualisation, the study did not include a crossover trial. This meant each participant only completed one four week block of training as part of either the VIS or No-VIS group and neither group could compare their training and experience directly to the other group. Future work should consider recruiting participants to complete a prolonged training block which includes training both with and without visualistion. This would need a considerably longer intervention however, particularly since a washout period may be necessary for baseline data to be comparable and to reduce carry over effect. Randomising the order as to which the training blocks are completed across participants could potentially be used to overcome this. Nevertheless, this would reduce the bias since participants would be performing both training interventions.

To conduct the testing and training the lead researcher was the only tester present at every session – both a strength and limitation to the study. Although the tester remained consistent throughout the data collection period this may have created an unconscious bias toward the VIS group since the research aims were known. However, we believe this more positive since the training would have provided inconsistent feedback had the tester been different for different sessions. Further to this, it is the norm in clinical practice for patients to have 1 physiotherapist with whom the rehabilitative process is completed. This was evident prior to the study as detailed in Section 8.1.4.3, and so the study and training protocols have been clearly outlined in this chapter and the tester was conscious to this bias when conducting the testing and training, particularly when providing verbal feedback to keep the VIS and No-VIS training interventions consistent with one another.

8.3.6.4 Training intervention

A strength of this study was the design of the stability-based training programme which was then adapted for the visualisations. A framework for the design of the stability-based programme was detailed in Chapter 4 and the development of the programme with visualisation was detailed in Chapter 7. This ensured that the rationale of the training was clear, and the programme supported the principles of training and motor learning principles discussed in Chapters 3 and 4. The stability-based training programme with visualisation is discussed in greater detail in Chapter 11, outlining future developments following the feasibility study.

The training intervention lasted four weeks and consisted of eight training sessions. The optimum duration for balance rehabilitation is unknown (ACSM, 2018). As detailed in a previously (Section 8.1.4.3) the chosen intervention was representative of previous balance rehabilitation research for chronic ankle instability (Hale et al., 2014; Kim et al., 2015; Linens et al., 2016), but was a shorter intervention than the healthcare professionals from the focus groups in Chapter 6 would routinely complete an intervention for. From the results in this study it may be inferred that 2 sessions a week for 4 weeks is enough to improve performance for people with CAI since a main effect of time was evident across the primary outcome measure – SEBT –, as well as the ML leap test and the lunge. However a training plan more representative of routine clinical practice with higher volume, such as two sessions a week for six weeks or three sessions a week for four weeks, may have resulted in greater clinical significance. This would allow more confident inferences to be made about the results.

8.3.6.5 Participant Leg Length

For the training to be personalised to each individual, and for the SEBT and multi-leap test assessments, the participant leg length was required. The software automatically calculated the leg length, however on average there was a discrepancy between pre- and post-test leg length. Consequently the results of the SEBT and multi-leap tests were affected since these reported a change relative to the participant's leg length.

Retrospectively participant leg length was analysed and statistically tested using a paired t-test (SPSS Statistics: v. 26, IBM, USA). The average difference between the pre- and post-test saved leg lengths across all participants was 2.6 ± 2cm. This equated to a non-significant average difference of 1% and 1.2% for the CAI and No-CAI groups ($p>0.05$), respectively, between the actual SEBT results and the hypothetical SEBT results had the leg length recorded been the same pre- and post-test. As a consequence of this the SEBT and multi-leap test distance results were affected. The importance, and implications of this, are discussed below.

The reason for this is not believed to be a calibration error, but rather dependent on how the participant was positioned when the system calculated the leg length between the ASIS and medial malleolus on the left side. Participants were instructed to stand straight and face forward during this process, but if this was not followed the resulting leg length would be affected. Examples leading to an altered leg length include:

- increased flexion/extension of knees
- increased eversion/inversion of the ankle
- increased anterior-posterior pelvic tilt
- increased mediolateral pelvic tilt
- trunk rotation causing pelvic tilt.

The final example – trunk rotation causing pelvic tilt – is less likely but has been included due to the layout of the labs. During the sessions the computers were situated and controlled from behind the participant and during leg length calculation the tester was at the computer. Since the participants often tried to continue conversation during this time this may have resulted in a rotation of the trunk.

The discrepancy between the leg lengths at the different assessments is predicted to most likely be due to increased knee flexion. To avoid this in the future participants should be instructed very clearly to stand tall, with straight legs, and facing forward, and the tester should make sure this is enforced.

8.4 Conclusion

This chapter has outlined the feasibility RCT conducted, before reporting and discussing the results. The results of stability-based training package were inconclusive in the population with no CAI, however the study may demonstrate the feasibility of the stability-based package for people with CAI. This is discussed further in Chapter 11, specifically the stability-based training programme with visualisation, as well as future work to develop this for further tesing using a larger sample size to work towards implementation into clinical practice.

Chapter 9 – Subjective analysis of stability-based training with visualisation

9.1 Introduction

Understanding patient experience for rehabilitation provides an important insight from which level of engagement and motivation can be determined. As highlighted in Chapter 3, if a programme is not adhered to, the reliabilty and validity of the exercises included in the training will be redundant since the training is not completed.

The research question addressed in this chapter is:

- Does visualisation enhance the rehabilitation experience for the patient?

This chapter details the participants perceptions of the feasibility of training using visualisation. To further develop this package these perceptions are important to inform and guide future work to produce a package which is well-received by the population it is designed for.

9.2 Methods

This study was part of the Ankle Stability Training Application with Visualisation study outlined in Chapter 8.

Participant feedback was collected immediately following the post-training test, and again three months later as a follow-up. The specific measures and analysis are presented in the proceeding sections.

9.2.1 Physical Activity Enjoyment Scale-8 (PACES-8)

VR systems present the opportunity to create a more engaging and motivational environment for rehabilitation, as discussed in Chapter 3. To gain insight of the participants' perceptions of the rehabilitation with visualisation the PACES-8 was used (Appendix F). This measure has been frequently used in literature relating to virtual reality and balance in rehabilitation (Padala et al., 2017; Teques et al., 2017; Tripette et al., 2017; Vaziri et al., 2016; van Diest et al., 2013), and has been validated and shown good internal consistency in various studies (Mullen et al., 2011; Teques et al., 2020; Teques et al., 2017). For these reasons and because of the dynamic nature of the stability training programme it was an appropriate tool to measure user experience.

PACES-8 is an eight-item questionnaire which used a five-point Likert Scale to evaluate the participants' level of enjoyment – 1 being 'strongly disagree' and 5 being 'strongly agree'. Each item response was added to give a total score out of 40. A high overall score signified high enjoyment of the training, and a lower score a lack of enjoyment.

9.2.2 User Satisfaction Evaluation Questionnaire (USEQ)

When developing a package to be used by clinicians in clinical practice it must be user-friendly and appropriate. If not, no time or money will be invested into it. This means regardless of the benefit to rehabilitation it has it will go unused.

The USEQ measures the usability of a product, specifically in virtual rehabilitation (Booth et al., 2019; Cuthbert et al., 2019; Gil-Gomez et al., 2017; Kern et al., 2019). It consists of five items which are evaluated using a five-point Likert scale – 1 being 'strongly disagree' and 5 being 'strongly agree' (Appendix F). The questionnaire has been tested previously in patients undergoing virtual rehabilitation for balance disorders and was reported to show reliability and suitable internal consistency, while remaining easy to understand and complete for patients (Gil-Gomez et al., 2017). For this reason, it was implemented here to address the appropriateness of use of the visualisation software and system within rehabilitation.

For the current study item three was not appropriate and was removed from the questionnaire. Using the complete questionnaire showed the greatest internal consistency (Cronbach's alpha = 0.716), however this decreased to 0.637 Cronbach's alpha when item three was removed. Gil-Gomez and colleagues (2017) discussed an alpha coefficient ranging from 0.7-0.9 to be considered acceptable, with a value over 0.9 making scores redundant. Removing item three the USEQ does fall short of this 0.7 value, however those results are specific to the sample population used in Gil-Gomez et al.'s (2017) study and the question was not relevant to the training programme being carried out in the current investigation. Considering this, the USEQ was determined an appropriate tool for this study to assess user satisfaction.

9.2.3 Cumberland Ankle Instability Tool (CAIT)

As stated previously, the CAIT was implemented to ensure adherence to the inclusion criteria. As this was completed prior to the training intervention it provided a baseline for participant's perception of instability. On completion of the post-intervention test each participant completed the CAIT for a second time to quantify perception of stability, and to evaluate the effect of the intervention.

Previously the CAIT has not frequently been used to determine effectiveness of an intervention. However, when it has the research has reported increases of 3.8-5.7 points following 4-6 weeks balance interventions (Wright et al., 2017). Wright and colleagues (2017) proposed a difference of ≥3 to be considered as a minimum threshold to indicate a clinically meaningful improvement.

9.2.4 Participant feedback

When completing the PACES-8 and USEQ questionnaire the participants were invited to add any additional comments regarding any aspect of their experience as a participant in the study (Appendix F).

All comments written were collated depending on the study group. A thematic analysis was applied in the same way as described in Chapter 6 to identify the main themes.

9.2.5 3-month follow up

Three months following completion of the study each participant was contacted with a final 12-question survey. This survey reviewed participant experience during the study and following study participation, as well as recording ankle sprain incidences and feelings of instability for the CAI group (see Appendix G).

Each set of questions was group-specific thus varied depending on assigned intervention group (ie. VIS or NO-VIS). The survey questions were clear, understandable for the participants, and short, to avoid misinterpretation. The questions were open-ended and avoided bias context to give participants the opportunity to provide information in their own words but without being led to a desired answer (Glasgow, 2005).

The survey questions were focussed on the themes:

- training experience
- visualisations
- perceptions of stability
- impact to current training

- comparison to previous rehab experiences

The survey answers were thematically analysed to further sub-categorise within each theme.

9.2.6 Statistical analysis

All statistical analyses were carried out in SPSS (SPSS Statistics: v. 26, IBM, USA). Shapiro-Wilk normality tests were conducted to establish the appropriate test for statistical analysis.

The testing sessions were compared using a two-way mixed ANOVA with Bonferroni adjustment for the CAIT score to identify time*group differences, as well as main effects of time and group. Univariate analyses were performed if a significant group*time difference resulted. The PACES and USEQ were analysed using a one-way ANOVA. All tests were analysed at a 0.05 level of significance.

9.3 Results

9.3.1 Physical activity enjoyment scale

Table 9.1 PACES score for No-CAI and CAI participants completed after final testing session. *significant difference between VIS and NO-VIS groups ($p \leq 0.05$)

PACES-8	**VIS**	**NO-VIS**	**DIFF.**	***D***	***F***	***P***
	Score					
NO-CAI	34.83 (3.76)	31.25 (6.08)	3.58	0.73	1.36	0.28
CAI	32.00 (3.81)	29.67 (3.67)	2.33	0.62	1.39	0.26

No-CAI

The VIS group recorded a higher score in the PACES-8 questionnaire by 3.58 points, resulting in a medium-large effect size of no significance in favour of the intervention with visualisation ($F(1,8)=1.36$, $p=0.28$) (Table 9.1).

Differences in responses between groups was particularly highlighted for the statement 'It's a lot of fun' where an average score of 4.7/5 was recorded for the VIS group whereas the No-VIS score averaged 3.8 points. The VIS group felt stimulated by the training scoring 4.5/5 for this statement compared to the No-VIS group scoring 3.5/5.

CAI

The VIS group recorded a higher score with medium-large effect in the PACES-8 questionnaire by 2.33 points (*F(*1,13)=1.39, *p*=0.26) (Table 9.1). Both groups were neutral or positive responders to the statements, with the VIS group stating 'strongly agree' more often and the No-VIS group responding 'neither agree/disagree' more often. This led to the difference between final scores.

The VIS group reported the training to be refreshing with a score of 4.2/5, compared to the 3.5/5 score of the No-VIS group. The greatest difference was seen in the second statement of the PACES-8 questionnaire where the VIS group gave the statement 'a lot of fun' a higher score on average with 4.3 points compared to 3.5 points.

9.3.2 User satisfaction evaluation questionnaire

Table 9.2 USEQ score for No-CAI and CAI participants completed after final testing session.

*significant difference between VIS and NO-VIS groups (p≤0.05)

USEQ	**VIS**	**NO-VIS**	**DIFF.**	***D***	***F***	***P***
	Score					
NO-CAI	19.33 (0.82)	17.25 (2.06)	2.08	1.45	5.18	0.05*
CAI	18.22 (1.09)	17.00 (1.41)	1.22	0.98	3.58	0.08

No-CAI

The VIS group recorded a significantly higher score in the USEQ questionnaire by 2.08 points, resulting in a very large effect size of significance in favour of the intervention with visualisation (*F(*1,8)=5.18, *p*=0.05) (Table 9.2).

All participants scored the statement 'I enjoyed my experience' positively, with all participants in the VIS group 'strongly agreeing'. No participants reported discomfort during the training experience while using the system, and 8/10 participants 'strongly agreed' that this system would be helpful for rehabilitation.

CAI

The VIS group recorded a higher score with large effect of no significance in the USEQ questionnaire by 1.22 points (*F(*1,13)=3.58, *p*=0.08) (Table 9.2). Both groups were neutral or positive responders to the statements, with the VIS group responding 'strongly agree' more and the No-VIS group responding 'neither agree/disagree' more often. This led to the difference between final scores.

All participants 'agreed' that the experience was enjoyable. Discomfort was not felt while using the system during training regardless of the group, where 11/15 participants responded 'strongly agree'. Furthermore, all participants felt the system would be helpful for rehabilitation.

9.3.3 Cumberland ankle instability tool

Table 9.3 Mean (SD) difference between pre- and post-test results for the CAIT.

*significant difference between VIS and NO-VIS groups (p≤0.05)

CAIT	**VIS**	**NO-VIS**	**DIFF.**	***D***	***F***	***P***
	Difference					
CAI	3.56 (1.1)	4.17 (1.4)	-0.61	-0.14	0.76	0.79

The CAIT scores improved for both the VIS and No-VIS groups following the intervention by a score of 3.56 and 4.17, respectively. This showed a small effect of no significance in favour of the No-VIS group (*F(*1,13) = 0.76, *p*=0.79) (Table 9.3). The main effect of time showed a statistically significant difference (*F(*1,13) = 12.08, *p*=0.004), but the main effect of group did not (*F(*1,13) = 3.53, *p*=0.08).

For the VIS group the statement of the CAIT relating to the the greatest difference post-training was the feeling of stability when walking/jogging/running on uneven surfaces. This improved by 1 point, on average. For the No-VIS group the greatest difference reported was regarding feelings of instability when making sharp turns during walking/running. This improved on average by 1 point. The statement second to these in both the VIS and No-VIS group related to the ability to control the ankle and stop it when it starts to roll, which increased in score by 0.89 and 0.83 points on average, respectively.

9.3.4 Participant feedback

For both the VIS and No-VIS groups with and without CAI the immediate feedback collected at post-test identified two main themes:

- Enjoyment
- Improved stability

Enjoyment

All participants enjoyed the training because of the challenging nature of the exercises and progressions throughout the programme. However, only those who had experienced the visualisations referred to how the competition to improve scores motivated them to fully engage with maximal effort with every exercise and want to continue training.

> *'Motivation levels were kept high when trying to beat own score. I wanted to do better and feel like that made me do better.'*
>
> *'Very motivational. Felt progress, could visualise process… Would like to do more. Motivated me to do exercises at home.'*

Perception of stability

Participants in the No-CAI and CAI groups both reported a noticeable improvement and new confidence in their balance ability and ankle stability regardless of the visualisations being incorporated into training. Not only this, but from the feedback the training effects appeared to be transferred out with the training environment and into other daily tasks and sporting activities. This finding was again reported by both the VIS and No-VIS groups.

> *'I have noticed improvements in my own workouts. I can lift heavier weights with better technique when performing squats, lunges and Olympic lifts.'*
>
> *'I have felt much more stable and balanced when bowling at cricket.'*

The influence of external factors on postural control was a concern for two participants in relation to performance and the objective monitoring of rehabilitative progress.

> *‘wondering if some of the scores were affected by loading leading up to the testing (ie. Playing squash or a long drive).’*
>
> *‘Noticed my balance changed considerably with my changing health (ie. When I felt slightly unwell and my balance was really poor).’*

9.3.5 3-month Follow Up

From the 25 participants contacted three months post-training, 90% responded (Figure 8.12 in Chapter 8). The results from the questionnaire identified three main themes which are detailed in the following 3 sections:

- training experience
- visualisations
- perceptions of stability
- impact to current training
- comparison to previous rehab experiences

The following sections discuss these themes in greater detail from the CAI participants only – the target sample population of this project. Participants with No-CAI mainly identified study participation to be for personal interest, however other answers are represented by the responses of the CAI group which are presented in the following sections.

9.3.5.1 Training Experience

Training experience was sub-categorised into 3 sections:

- motivation
- level of difficulty
- favourite aspects of the training

Motivation

All participants reported remaining motivated to attend the training sessions, with only one response declaring their motivation did begin to decline near the end of the four weeks. The interactive and progressive outlook engaged the participants to come back each session and helped distract from the repetitive nature of some of the exercises.

In the VIS group a lot of this motivation was related to the scoring, clear levels of progression, and seeing results improving. In the No-VIS group participants were motivated from the challenge and the desire to improve results, alongside potentially increasing body/spatial awareness.

Level of Difficulty

Both the VIS and No-VIS groups reported feeling appropriately challenged throughout the training programme. The single leg stand and reach exercise was specifically included in two participants responses for the VIS group, identifying there to be too much challenge on this exercise occasionally leading to a *'love/hate relationship'*.

Favourite Aspect

Participants in the VIS group all identified the visualisations to contribute to their favourite aspect of the training, with the leap game being the only exercise to be singled out as a highlight. Specifically, the participants enjoyed the interactive nature of the visualisations and real-time feedback from the avatar. For some participants this helped to detach them from the rehabilitative environment as it did not feel like a physio routine of prescribed exercises and created a more immersive and intense experience which felt professional.

> *'Enjoyed the interactive touch see how my body moves during exercises on the screen, felt like a pro!'*
>
> *'Being able to visualise the motions was helpful because sometimes when you're told to do an exercise it's hard to know if you're doing it right or not.'*

Unlike the VIS group, participants of the No-VIS group reported the improvements, results and challenge of the exercises to be their favourite part of the training.

9.3.5.2 Visualisations

Visualisation was sub-categorised into 3 sections:

- effort
- autonomy
- overall visualisation experience

The effect visualisation had on effort and feelings of autonomy for participants is detailed below in respective sections. Following this the impact visualisation had on the overall experience is presented.

Effort

For the VIS group 56% stated that the visualisations had a positive impact on the effort put into the training, causing them to work harder. The remaining responders in the VIS group (44%), and 80% in the No-VIS group, stated that having, or not having, the visualisations did not influence the amount of effort put into the training. Participants reported to still put in maximum effort. Both groups stated this was a result of increased concentration either from the external focus and immediate knowledge of the results from the visualisations or being forced to focus internally on body position.

> *'I think in some cases I put more effort in if I wasn't reaching the mark and could see that on the screen.'*
>
> *'Forced me to focus more on the position of my body, which required more concentration and effort.'*

In the No-VIS group the remaining participant reported that without experiencing the visualisations themselves they could not know how their efforts could have differed. However, they did feel that the visualisations may have made it a more gamified experience which may have encouraged them to push harder.

Autonomy

Throughout the questionnaire participants in the VIS group continually referred to the visualisations leading them to understand positioning, as well as clear programme progressions and aims from the stability training programme.

> *'Gave me a better understanding of what we were trying to achieve and could take this away at the end of the block… gained a lot of knowledge from the programme to take away.'*
>
> *'Improved my understanding of why/how the modes of exercise would improve stability.'*

Unlike the VIS group, the No-VIS group did not refer to learning or gaining an understanding of movement or the rehabilitative process.

Overall visualisation experience

Overall, participants reported the visualisations added an element of fun, which was engaging and a mental distraction from the task. Moreover, participants felt it was helpful when understanding movement and specific technical direction.

> *'I feel like it is great to use as you can see yourself in ways you wouldn't be able to otherwise.'*

The No-VIS group did not feel their experience had been affected by the lack of visualisations, and understood that they were completing a more traditional rehabilitation programme. In this group participants reported a greater focus on internal cues, particularly when eyes were closed.

> *'Not having visualisations made me learn more about responding to internal stimulation, focus on feedback from my body. I had to feel more the position of my limbs, as opposed to visual feedback.'*

9.3.5.3 Perceptions of stability

The theme of stability has been sub-categorised into two sections detailing the perceptions of:

- ankle stability
- overall postural control

Ankle Stability

All participants in both the VIS and No-VIS groups reported increased ankle stability following the four-week stability-based training programme. In turn this led to a reduced number of ankle sprains in the months following the training.

> *'None [referring to number of ankle sprains] – which is less than usual. Feel more stable than ever.'*

> *'I have been playing basketball and boxing since and haven't felt like spraining. I was very self-aware of my ankle stability prior to training programme and would limit myself to how hard I went in training and sport.'*

Following participation in the study, without continuation of training, increased feelings of instability was felt by three participants (VIS: n=2, No-VIS: n=1).

> *'I felt more ankle stability after the training was done, but after a couple of months after the testing and not continued training, I felt it more unstable at times.'*

Overall Postural Control

Confidence in overall stability was *'definitely improved'* in all participants in both VIS and No-VIS groups, which led to increased confidence and performance out with the training environment.

> *'At the start I was scared I was going to roll it still but with every day I feel much stronger.'*

> *'Significantly improved – I felt invincible!'*

9.3.5.4 Impact to current training

Noticing the benefits from the programme, many participants in both the VIS and No-VIS groups continued to implement aspects of the stability programme into their lifestyles. As a result of this they have continued to see the benefits. Continuation of this work has also enabled participants to return to sport and activities that they felt unable to perform previously.

> *'I did it at work [retail sales assistant] and it has made it easier for me at work.'*

> *'I have continued with proprioceptive training along with strength and mobility exercises, and this has definitely improved the overall stability of my ankles. I have even begun playing basketball without my braces in recent weeks and taken up rock climbing which I would never have been able to do a few months ago.'*

9.3.5.5 Comparison to previous rehab experience

Both the VIS and No-VIS groups voiced that the training programme from the current study incorporated a more vigorous and full-body approach to training and a lot more progress monitoring than previously experienced. Some of the exercises were familiar to participants, but most previous rehabilitation had focussed on ankle strength and mobility only. The approach in this study led to better outcomes than after following any other rehab previously.

> *'The training was much more active and physically intensive than other rehab I've done in the past, and I found it to be most effective.'*

> *'The best rehab I have done for my ankles.'*

In comparison to previous rehabilitation experiences, three participants specifically reported the impact the visualisations had made.

> *'The exercises were similar to some rehab material I've had to do… In comparison, this experience was more motivating because of the monitoring results and therefore records of progress being taken.'*

> *'The screen visualisations were great as it gave me something to focus on compared to just the joint or movement, example being able to get a better range of motion with regards to lunging, being able to focus on my technique on the screen was very good… This was good to mentally focus not just physically.'*

> *'Much clearer understanding developed in understanding 'why' and how exercises in the programme contribute to rehab process. Articulated with real-time and clear, visual evidence of progress or even lack of in some exercises that stimulated motivation. Miles better than 'do 10 of these, 3 sets etc… Come back in a week and we will see how it's gone.''*

9.4 Discussion

9.4.1 No-CAI

The results for both the VIS and No-VIS groups show that the participants found the experience highly enjoyable. These participant perceptions are believed to be because the exercises and training exposed participants to a new experience regardless of the visualisation. This supports the discussion point from Chapter 8.3.4 following comparable improvements of the VIS and No-VIS groups in the outcome measures. The feedback here suggested participants in both groups remained motivated throughout the process through continual challenge and competition.

Summarising, the participants responded positively to the experience but the inclusion of the visualisations is inconclusive.

9.4.2 CAI

Perceptions of stability

The inclusion of visualisation did not lead to a greater change for the VIS group compared to the No-VIS group regarding perception of stability, however no conclusions can be drawn from this study due to the sample size and lack of statistical sigificance.

On a group level, the results of the CAIT showed that both the VIS and No-VIS groups subjectively reported significantly improved stability. This was to be expected since balance training has been found to be effective at improving stability (Anguish and Sandrey, 2018, Kosik et al., 2017, Clark and Burden, 2005). The improved perception of stability was better not only at the ankle but also for overall postural control, and transferred out with the training, as reported for both training groups. This suggests that the programme was effectively designed to target both ankle stability and postural control, as detailed in Chapter 4. Specifically the CAIT identified daily activities were affected by improved ability to walk/jog/run on uneven surfaces and make sharp turns, which is likely due to the increased ability to control the ankle complex if it started to roll. Participants also acknowledged the functional and dynamic approach to training, stating it demanded more from the body. This led to confidence which in the three months following the study had led to new activities being attempted, and old activities being returned to. The improvement from VIS and No-VIS training collectively as a main effect in this investigation supports results seen in previous populations of a 10.7-19% improvement, as well as exceeding the threshold denoting a clinically meaningful improvement as a result of the stability-based training (Cruz-Diaz et al., 2015; Wright et al., 2017). On a group level this suggests both training with and without visualisations to be clinically relevant interventions, supporting our expectations considering what we know about the effect of balance training.

In summary, this perceived enhanced stability suggests that this programme is feasible for stability training from the start of the rehabilitation process in those with CAI regardless of whether visualisations are used or not. However it is unknown how this programme would compare to that of current clinical practice or previous research.

Motivation and enjoyment during training

The stability-based training in this investigation was effective at improving aspects of both objective and subjective stability as shown by the main effect of time. However, in practice a programme is only effective if it is adhered to, which is more likely if the programme is enjoyable and the participants are motivated. In this study the results showed that participants in both the VIS and NoVIS groups enjoyed the training, thus it is not clear as to the effect of the visualisations. The findings that both groups enjoyed the stability-based training and feedback, support the expectations from the focus groups in Chapter 6, as well as the results of previous balance research in other populations (Fitzgerald et al., 2010; Llorens et al., 2015; Meldrum et al., 2011). However the effect of the additional augmented feedback provided by the visualisations cannot be concluded following this feasibility study.

As with Meldrum and colleagues (2011), the participants in this study reported the addition of the visualisations created an external focus which provided a distraction for when practices were repetitive. As a result of this, the interaction with the screen was the lead encourager for motivation both during and prior to the sessions in this group. The visualisations were designed specifically to create an external focus of attention through the third person perspective and game development criteria detailed in Chapter 7.4, thus it is an interesting finding that this was acknowledged by the participants as a source of motivation.

During training, external cues were integrated into the No-VIS training in the form of challenges, such as timing exercises. In the follow up questionnaire the No-VIS group stated this to be their favourite aspect of the training – the challenge. However, it is believed that the ability to continually challenge and progress the No-VIS training, and give feedback which is easy for the person to understand, may become more difficult in clinical practice without the use of visualisation. This has been reported before in the Morel et al. (2015) study, where a pendulum system was set up to throw balls towards the patient's head, and prompting them to move to avoid them and recover. The study simulated the pendulum system using VR which allowed for the height of the ball throw to be adjusted automatically for the patient's height, as well as the speed of the ball throws to be conducted at a consistent speed which could be easily manipulated as and when required (Morel et al., 2015). As with this study we speculate how easily you could progress this exercise without the aid of visualisation while being practical, safe and simple to be completed in clinical practice.

A greater difference between the VIS and No-VIS groups for enjoyment was hypothesised. Had the No-VIS training protocol exactly followed that of routine clinical practice, current ankle treatment guidelines, or a programme from a previous study, as opposed to the training programme conducted here, it is believed the difference of enjoyment reported between groups would have been greater. Like the VIS group, the No-VIS training was designed as a more functional and progressive programme to those seen before, just without the visualisation. This does seem to have positively affected the enjoyment of the No-VIS group as highlighted in the feedback, and this may have led to a higher enjoyment score than would have been reported during rehabilitation in clinical practice. For the No-VIS group the evidence of improvements was reported as a favourite aspect to the training, which is not surprising considering a large majority of the group had been unsatisfied with previous rehabilitation inferring little, or no, evidence of improvement. Consequently the participants' previous experience may have influenced satisfaction of the basic psychological needs. The participant saw evidence of improvements not experienced previously, and the training's effectiveness would have also increased trust in the process. This would satisfy both the need for competence and relatedness. In turn, this will have increased motivation which may have resulted in increased effort and engagement (Carson and Polman, 2017; Marshall et al., 2012). Although this may have been subconscious, this could have resulted in further performance improvements leading to greater enjoyment from the programme, as it is seen as more successful than previous experiences, and ultimately resulting in only a small difference between VIS and No-VIS enjoyment scores.

It is speculated that the groups may have been subject to the Hawthorne effect given the similar outcomes and high levels of enjoyment reported for both the VIS or No-VIS groups (McCambridge et al., 2014). This regards awareness of being studied and monitored in research, and consequenctly how this may influence participant behaviour (Sedgwick, 2012; Sedgwick and Greenwood, 2015). Although not often quantifiable, it should be considered when interpreting results as reponses may be over-estimated and not true representations of clinical treatment or rehabilitation (McCarney et al., 2007). In this study it could be considered that the laboratory environment, motion capture equipment, and newly designed stability-based programme influenced the participant's effort, engagement, and overall rehabilitative experience. This may have therefore led to the No-VIS group recording high levels of enjoyment and motivation without the visualisations, thus influenced by the Hawthorne effect. However, it should also be considered that both the experimental (VIS) group and the control (No-VIS) group were subject to the same protocol including 100% supervision during training and verbal feedback from the same tester, as detailed in Chapter 8.1.4.3. For this reason we believe the Hawthorne effect may have been smaller than if the control group had been an unsupervised or at home rehabilitation programme where the environment was not changed and supervision not present.

In addition to this, the Hawthorne effect also reflects question behaviour and how this may influence participant response (McCambridge et al., 2019). This means that participants may have answered how they feel they should have answered, or they would not have thought about the question had they not been prompted by the question. The design of the 3-month follow up survey was detailed in Section 9.2.5 and aimed to mimimize this risk of bias.

Satisfaction of the basic psychological needs

The SDT presents a continuum for motivation, as detailed in Chapter 3.5. Intrinsic motivation has been associated with greater persistence and more time spent doing a task, and higher quality performance, likely from the greater enjoyment and interest experienced when a person is more intrisically motivated (Ryan and Deci, 2020; Teques et al., 2017; van der Kooij et al., 2019).

The results of the current study suggested that all participants enjoyed the stability-based training programme, however we did not directly assess motivation using a specific measure – a limitation of the study which prevented us analysing the specific type of motivation the training may or may not have created relative to the SDT continuum. The between group interaction did favour the group with the visualisations, but this result was not conclusive. This is believed to be for the reasons discussed in the section above.

Encouraging behaviour change or maintenance for the SDT is determined by creating an environment to satisfy the psychological needs (Ryan and Deci, 2000). From the feedback and follow up results both the training groups – VIS and No-VIS – suggest the needs for competence and relatedness may have been satisfied by the stability-based training programme. Participant feedback reported that in both training groups participants enjoyed noticing progress and their growing confidence during training – a demonstration of competence, as highlighted by Carson and Polman (2017). This supports previous research where there was no significant difference between VR and control groups for perceived competence following balance training (Fitzgerald et al., 2010). This in turn may also have built a trust between the participant, tester and the training, important for the need of relatedness. A lack of engagement, understanding, or trust in the clinican or training process would prevent the need for relatedness to be satisfied, thus hindering the motivation.

The training appears to have successfully created an environment to encourage competence and relatedness for both groups, however satisfaction of autonomy was only referred to by participants subject to the visualisations, suggesting that the No-VIS group may not have experienced this. This was highlighted when responses from the three month feedback addressed autonomous feelings directly in the VIS group, whereas the No-VIS group responses were unrelated when asked the same question. Although speculative, this may suggest that the stability-based training programme with visualisation was more autonomous, and therefore it is believed that the basic psychological needs may not have been satisfied to the same extent in the No-VIS group to develop more intrinsically motivated patients.

Specifically the group identified that when training with visualisation the progression pathway was clearly defined, the feedback allowed for progress to be monitored, and the visualisations created a clearer understanding of the rehabilitation process and to technique, which led to self-reported improvements in quality movement. This participant feedback supports that of the healthcare specialists from a study by Ballinger and colleagues (2016) investigating specifically visualisation in rehabilitative practice. It was reported that healthcare specialists thought that visualisations would promote ownership to satisfy autonomy, and also lead to easier understanding of complex tasks, as was also the finding from the focus groups conducted in Chapter 6. Although speculative, this suggests that the need for the patient to feel involved in the programme and the direction and decisions of the process at every rehabilitative stage has been addressed for this initial stages of learning (Carson and Polman, 2017, Marshall et al., 2012). This has not often been achieved in current practice, as evidenced from the lack of adherence reported in the literature discussed in Chapter 3, and dissatisfaction with previous experience reported in the results of Chapter 8.

However, interestingly none of these factors identified most often in feedback – progression pathway, or clear technical and rehabilitative process understanding – explicitly refer specifically to the gamification of exercises. This suggests that the same outcome could potentially be achieved without visualisation if a more autonomous approach was adopted. Despite this, it is not believed that this could be achieved as easily or safely in the rehabilitative space, or in a way that could continually challenge patients to the appropriate level required to return to activities.

To summarise, the feedback from participant’s suggest that both groups felt the stability-based training they received as part of the study satisfied the needs for competence and relatedness. As a result of the feedback the researcher’s speculate that the visualisations also led to greater satisfication of the psychological need for autonomy, however it should be noted that this was not objectively measured.

9.5 Conclusion

This chapter has reported and discussed participant feedback following the stability-based training intervention. An 88% user satisfaction score inferred that participants were satisfied with the cluster application, calibration procedure and virtual environment, and both the CAI and No-CAI groups enjoyed training. This largely favoured the training with visualisation in both CAI and No-CAI groups.

For the CAI group, when the high enjoyment ratings of the VIS and No-VIS groups are considered collectively with the improved stability scores reported in Chapter 8, the results infer training satisfaction following this short intervention. This is an important finding because prior to the study less than half of the participants who had undergone previous rehabilitation were satisfied with the outcome.

Regarding the visualisation, the results are inconclusive as to the effect of addition of the visualisation on rehabilitative experience. Due to the study being under-powered differences may not have been statistically significant. However, further testing of the stability-based package in a properly powered study may provide supporting evidence.For further development of the package, public and patient involvement should retain an integral role to optimise its implementation into clinical practice.

Chapter 10 – Retrospective analysis of the clinical usability of the system

10.1 Introduction

The system is an integral part of the stability-based training package. By incorporating the optoelectronic cameras, cluster-based model, pointer calibration and visualisation software it was designed and developed to create a clinically appropriate motion analysis system. Further to this, the utility of the system, and user interaction, are important to consider when assessing the feasibility of the package as these may influence participant experience. In turn this may affect training engagement and ultimately rehabilitative outcome. For this reason the system was reviewed to assess the overall functionality and usability for clinical practice. This was completed retrospectively so that the rehabilitation experience in the Ankle Stability Training Application with Visualisation study from Chapter 8 was a true representation of the usability of the system in clinical practice, providing the same patient experience. This may not have been achieved had the duration of training and protocols been a primary focus.

The proceeding sections detail the results of the analysis and discuss the cluster-based biomechanical model and calibration process in more detail relative to the system's use for rehabilitation in clinical practice.

10.2 Method

The variables analysed are defined in Table 10.1.

From the 250 testing and training sessions completed (25 participants x 10 sessions each) Table 10.2 shows how much data was recorded and suitable for analysis. By post-processing the missing data occurred from:

- appointment start time unknown
- calibration files overwritten with new participant
- session data not recorded
- training files not recorded
- first and last training exercise not recorded

Table 10.1 Definitions of calculated times.

	Definition	Start	End
Sessions	25 participants x 10 sessions	n/a	n/a
Session Data	Number of sessions where data was saved	n/a	n/a
Preparation time	Time from appointment start time to calibration completion	Appointment start time	Calibration completion
Calibration time	Time to correctly produce visualisation on screen for session	Time of first anatomical landmark saved	Time of last anatomical landmark saved
Recording time	Number of sessions where the final exercise was recorded	n/a	n/a
Estimated session time	Length of entire session	Appointment start time	Time of final exercise recorded

Table 10.2 Number of data files available for use to calculate the above and analysis.

File Count						
Sessions	**Appt. Start Time**	**Calibration Time**	**Prep Time**	**Session Data**	**Recording Time**	**Estimated Session Time**
250	97	135	72	249	224	97

To compare the calibration time to an alternative method, an analysis of the processing data that contributed to the Meng et al. (2020) study was conducted. The recording times to complete the movements required for the functional calibration method in the study were used to approximate the calibration time.

10.3 Results

The time from the participant’s appointment start time to being ready to undergo assessment or training took, on average, 11 minutes. The variation of the preparation time across participants was due to:

- Type of session – assessment or training?

- Whether start time was adhered to – did participant arrive early or late?
- Session greeting

The preparation time included participant calibration which averaged one minute (Table 10.3). Due to errors this was completed approximately twice per person, but no more than 3 times.

Table 10.3 Average and standard deviations of the calibration and prep time, and estimated session length across all sessions for all participants where the data was available

	Calibration	**Prep**	**Estimated Session Length**
	Time (min)		
Average	1	11	31
SD	0.4	5	6

The calibration time using the functional calibration method in Meng and colleague's (2020) study averaged three minutes (Table 10.4).

Table 10.4 Average and standard deviations of the calibration time for functional calibration

	Time (min)
AVERAGE	3
SD	0.4

10.4 Conclusion

The overall estimated session duration, including the preparation time, was approximately 30 minutes. Researchers are confident that the preparation time could be further reduced for reasons discussed in the next chapter, particularly if this protocol was standard practice in clinics.

Chapter 11 – Discussion and future developments

11.1 Introduction

The aim of this project was to design, develop and assess the feasibility of a stability-based training programme with visualisation for people with CAI. The stability-based programme was designed to be specific to ankle stability and postural balance, and the development of the system and application for visualisation created a hybrid tool appropriate for clinical practice to enhance rehabilitative outcomes and experience using a game-development approach.

This chapter reviews and further discusses the design, development and feasibility testing of the stability-based training package presented in this thesis. The results support the feasibility of the package, however there are some aspects of this package that would benefit from further developments. This is explored in the following sections.

11.2 The clinically appropriate motion analysis system

In Chapters 5 and 6 it was identified that for tracking movement in clinical practice the system requires affordability, accuracy and reliability, ease of use, time efficiency, and ability to produce interpretable results. In support of the previous research, the focus groups in Chapter 6 specifically reported the cost of equipment, lack of time in appointments, and lack of experience which prevent biomechanical techniques being implemented. Therefore, if a new system could not be used appropriately in a time-constrained environment, then the success of its use on rehabilitative outcomes would be questionable.

To allow for objective information to be used to monitor rehabilitation and track progression, which is important to ensure the rehabilitation prescribed is effective, optical motion tracking was selected since it would provide the most accurate and reliable method to tracking movement. Historically 3D optical motion tracking has not been associated with affordability, non-complexity, time efficiency, and producing feedback which is interpretable. However, with the price of the hardware decreasing 10-fold each decade making the technology more cost-appropriate (Tawy, 2018), then the biomechanical model, calibration protocol and software introduced in Chapter 7 aimed to address the complexity and time efficiency to produce a clinically appropriate motion analysis system. This could present the opportunity for a more interdisciplinary approach within practices by providing biomechanical feedback using an understandable approach that would not require expert biomechanical knowledge to interpret. From the focus groups in this thesis a lack of an interdisciplinary approach emerged from the discussion, or awareness or education about the biomechanical techniques available to the healthcare professionals that could be utilised to benefit training and assessment practices. This was surprising considering the technology available and recent popularity of virtual reality for rehabilitation. For this reason, the stability-based package in this thesis was designed to prioritise those who would operate or interact with it, thus the healthcare professionals and patients were central to the development.

In this thesis the development of the clinically appropriate motion analysis system was detailed in Chapter 7, tested to assess feasibility in the RCT outlined in Chapter 8, and then retrospectively reviewed in Chapter 10 to assess time efficiency for clinical practice. The system was successfully used in the feasibility RCT and the results of the retrospective analysis in Chapter 10 suggest the time to prepare and calibrate the participants is feasible for integration of this system into rehabilitative practices. The following sections discuss this in more detail, including how this system could be developed further.

The time-constraint in practice was a primary barrier preventing healthcare professionals using motion capture, as highlighted in both Chapters 5, 6 and 7. Therefore, for motion analysis to be integrated into clinical practice the system and protocol should be time efficient. A number of previous studies reported a session length of 20 minutes (Anguish and Sandrey, 2018; Cruz-Diaz et al., 2018), and Baten and colleagues (2007) reported a limit of 30 minutes if motion analysis was to be used as an outcome measure.

In Chapter 10 an approximation of session lengths was therefore calculated using the available information for retrospective analysis. It should be clear that these times were not available for all participants for the reasons outlined in Section 10.2. As a result estimations from a small data sample were calculated.

This was calculated retrospectively since during the experiment it was important for the session duration not to be monitored as this could have created a bias towards keeping this to a minimum, which would have shifted central attention away from the participant. By doing this patient care would have been affected and may have led to a non-realistic representation of clinical practice.

The estimated average session length for the current study was 31 minutes, just exceeding the 30 minute limit proposed by Baten et al. (2007). Given that the session lengths were estimated the researchers believe this system still to be feasible for clinical practice, and further discussion below addresses how this could be reduced further.

The preparation time in this study, which included cluster application, took approximately one third of the total session duration. This could be realistic for implementation into clinical practice, and would be expected to decrease should this become a routine procedure for patients (Tawy, 2018). When the participants first attended the lab the cluster application and motion capture equipment was a novel experience and new process for participants to understand. However participants became more comfortable and accustomed to the environment and equipment as they progressed through the training. This meant that as soon as the participants entered the lab the clusters were immediately attached while the tester was updated on how they were feeling since the previous session, whereas initially this was done separately as the participants were more hesitant and new to the protocol. In some cases, the participants assisted in the application of the clusters before the researcher checked the positioning and security of them before proceeding. This positively reflects the use of the system as the participants became comfortable using the equipment and suggests that self-application could be possible in the future with an expert check before calibration. Although this suggests that the preparation time had reduced from week 1 to week 10, as was reported in Tawy (2018), the results did not support the hypothesis. It is expected that the lack of time reduction may be related to the inaccuracies of the estimated start time, the calibration time, or the small sample size.

The short calibration time for the pointer calibration in the study is achievable for the clinical environment and acceptable to patients. However, action is needed to improve reliability of a successful first calibration that became apparent during the RCT in Chapter 8 and was retrospeculatively analysed in Chapter 10. This could be achieved two-fold:

1. Optimisation of the capture volume for the specific training programme. As referred to in Chapter 8 the capture volume was not optimal for the specific stability-based training programme in Edinburgh, however this was unable to be changed. The cameras created a large capture volume space in Glasgow and Geelong, however in Edinburgh the camera positions were restricted due to the multipurpose use motion analysis room, as well as a netting. Consequently it was the Edinburgh site where the calibration procedure had to be repeated the most.
2. Adjustments of the marker positions on the pointer to prevent confusion. This would prevent the software switching the markers causing the lead marker to be in the opposite direction.

These are both approaches which could minimise the overall preparation time. Regardless however, the pointer calibration was the most appropriate for the present study as discussed in

Chapter 5. This was faster compared to an alternative calibration method tested – the functional calibration method – as reported in Chapter 10. For the functional calibration method the time to perform only the movements necessary for the participant to be calibrated took the same amount of time, or longer, as the entire calibration process using the pointer. This means that extra time would be needed for post-processing to complete the calibration before data collection could begin. As a result, the pointer calibration was the most appropriate method.

A limitation of the study was not including a professional clinical opinion for the usability of the stabilty-based training package in addition to the participant’s perception. When creating a package for clinical use if it is not usable and practical for its proposed purpose then the clinicians will never use it, thus patients will never use it. A clinical perspective was reported following the focus groups in Chapter 6, however the health care professionals never had the opportunity to try the system for themselves. During the testing and training this was not within the scope of the study, however for future work this should be included. In a previous study Millar (2016) used the same cluster application and calibration process and reported the opinions of 4 assessors following the protocol. All had clinical experience but no experience using 3D motion analysis. The study reported that the clinicians found the cluster application and the calibration process easy. There was a 50/50 split however regarding the quickness of the cluster application or calibration process. This suggests that although the process was easy it still may not be feasible for routine clinical use, although with the variation of responses, limited sample size, and no specific timings reported, no conclusions can be made. Furthermore, we would propose that additional experience of this process, and with routine use in practice, this process would become quicker.

Rigid-body clusters were used in the Strathclyde Cluster Model (SCM) primarily for the ease of application, as discussed in Chapter 7. This enabled the clusters to be easily applied compared to individual markers, and without prior preparation or data labelling or processing required, which also reduced time consumption and allowed for real-time data feedback.

The clusters were designed with a slight curve and secured using Velcro, apart from the foot which was secured using tape. This design created two main problems experienced by the researchers:

1. the clusters falling off during the sessions
2. the pelvic cluster shifting upward

Movement of the clusters from the position to which they are calibrated in will affect the anatomical axes, which in turn affects the accuracy of the segment position and kinematic output (Alexander & Andriacchi, 2001; Benoit et al., 2006).

The clusters that fell down most often were predominantly at the thigh and foot. Although this did not happen often, it is believed to be from not fitting the shape of the participant's anatomy sufficiently. As a result of this when dynamic movements were made the clusters became unattached. The issue with the clusters falling down may be related to the sample population and the type of training in this study, since previous work using the same model has not reported this (Millar, 2016; Tawy, 2018). In this study the training was dynamic and involved movements where the impact on landing was relatively high in comparison to the more commonly analysed activities of walking and static balance. Furthermore, the population included competitive athletes whose musculature of the lower body could have caused a greater strain on the Velcro when landing, as well as being a less suitable shape for the cluster to mould to. The thigh of a person with greater musculature structure is more cone-shaped thus if the cluster moved it is more likely to fall. To address this problem we suggest that future research could apply a compression bandage above the cluster as this may secure it in place.

Secondly, the pelvic cluster should be attached below the PSIS to ensure movement of the pelvic segment is tracked, and not movement of the trunk. However, it became apparent throughout the training that the Velcro did not secure the cluster in position for long periods of time when the participant was moving. This caused the cluster to rise above the PSIS and position itself approximately at the illiac crests. This influenced the hip joint angle which would have been misleading to the participant should it have been used as a method of feedback on the screen. For future use an alternative method for attaching the pelvic cluster would need to be identified, particularly if kinematics of the hip are to be used.

In conclusion, the overall session durations, including the time for preparation and calibration, appear comparable to that of appointment times in previous literature. This positively presents the use of visualisation for clinical practice as the system could be used without requiring additional time with the patient, which is already constrained. The use of clusters has presented a couple of issues to be addressed, and further testing is required to assess the ease of use of the cluster and calibration protocol by clinicians themselves.

11.2.1 Future developments

This thesis has developed a motion analysis system to analyse movement both accurately and reliably in a more time efficient and less complex manner than that previously reported, thus addressing key barriers preventing it from being used in clinical practice (Toro et al., 2003; Baten et al., 2007). However, another important factor to consider is the affordability of the system. Although the price has dropped, as discussed in Chapter 5, 3D motion capture is less affordable than lower cost options. Following this study, the researchers are unsure as to whether the accuracy and reliability of the 3D motion capture is as much an essential requirement as initially believed. Therefore, other methods of motion capture should again be reviewed and tested during further development.

The first that should be reviewed as an alternative hardware to track movement are inertial measurement units (IMUs) should be reviewed as an alternative hardware to track movement. As a less expensive hardware to the cameras used in this study these could create a more affordable package. This could address the issue with the cost of current motion capture which was highlighted in the literature and focus groups in Chapters 5 and 6 as a key barrier to its limited utilisation in clinical practice.

Further to this, the IMUs offer portability which the cameras do not. Although the cameras allow for an adaptable space to be used compared to other equipment such as the Kinect, they do still restrict training and analysis to indoors and within the confined space of the camera volume. IMUs may therefore be more practical for many training environments and do not limits the activities which could be performed. However, compared to optoelectronic cameras the IMUs have shown reduced accuracy and reliability, particularly in the frontal and transverse planes, and when the movement was more dynamic (ie. Squat vs. Jumping) (Al-Amri et al., 2018; Cordillet et al., 2019). For IMUs to be incorporated as the chosen hardware this should be investigated relative to the specific needs of the package, and the needs and preferences of the clinicians who are to use it.

The SCM is currently a lower limb model, tracking movement of the pelvis and lower limbs only. Developing this for full body tracking would be beneficial to allow movement of the whole body to be analysed. Specifically, for the stability-based training package this may provide important insight into balance strategies adopted by participants, as well as a more in-depth analysis of the more dynamic movements such as the lunge and leaping activities.

11.3 Development of the stability-based training using visualisation

Despite much research outlining the development of CAI, as discussed in Chapter 2, the management of CAI is still misunderstood, and rehabilitation lacks congruence and consistency in practice. It is important that this is addressed to prevent the severe long-term consequences that affect physical and mental health, both directly and indirectly.

Stability-based training has been shown to be effective at improving the symptoms of CAI (Kosik et al., 2017). The stability-based training programme in Chapter 4 used the principles of training as guidance to create a framework to design a programme. This ensured the exercise selection was specific and appropriate to the evidence and needs of the study, which were to develop ankle stability and postural control using a functional yet safe approach. A similar framework was then outlined to ensure practice was specific, progressive and varied (ACSM, 2018). The frequency, intensity and method of progression was detailed in Chapter 4. Although previous research has lacked homogeneity, the methods of progression have been consistent across the literature and were utilised in this study for the programme (Chodzko et al., 2009; Dault et al., 2001; Klatt et al., 2015; Muehlbauer et al., 2012). This design was shown to be feasible in the study conducted in Chapters 8 and 9 as it was adhered to and conducted safely. The results from the feasibility study in Chapters 8 and 9 showed the programme was also effective at improving stability in both the CAI and No-CAI population in the SEBT, ML Leap Test, and aspects of the lunge with a main effect of time. This highlights that the programme was specific for ankle stability and postural control, and progression of training was an appropriate intensity for the stage of learning of the participants. This supported the literature reviewed in Chapter 2 and highlighted that stability-based training is an effective method of rehabilitation.

Visualisation presented the opportunity to develop a motivational and educational tool to enhance rehabilitation in clinical practice. By providing a combination of knowledge of performance and knowledge of results, using both visual feedback and biofeedback, it could supplement the verbal feedback provided by the clinician to aid interpretation. This was hypothesised to be beneficial during the early stages of learning since the skill being (re)learned would require an increased reliance on feedback when the movement pattern is not yet understood, and there is a high error rate as the patient lacks movement coordination and awareness (Magill and Anderson, 2017). As a result of this, as introduced in Chapter 3, practice can often be repetitive compared to subsequent stages of learning and the patient does not feel competent (Marshall et al., 2012; Utley and Astill, 2008). This is not conducive to a motivating environment, which in turn affects adherence to rehabilitation thus limiting the programme's success (Argent et al., 2018).

Previous literature has reported that without clear progression pathways, or motivational qualities to engage with the programme, the quality and benefit of the programme becomes redundant (Argent et al., 2018). This was highlighted in this thesis in Chapter 8 where the CAI group reported their dissatisfaction following previous rehabilitation. However, after completing the training intervention all participants in the CAI group, regardless of VIS or No-VIS group, reported to have enjoyed the stability-based training programme (Chapter 9). This suggests that regardless of the addition of the visualisations the participants were satisfied with the training they had received and the improvement in their stability and postural control.

The effect of the addition of the visualisations to training in the CAI population is limited when the VIS and No-VIS groups were compared. The results, that have been primarily discussed in Chapters 8 and 9, may have favoured the VIS group for all the tests following training with medium-large effect sizes, however the study only reached statistical significance for the SEBT and was underpowered due to a small sample size, and so no formal conclusions can be drawn. These results were supported by the feedback of the rehabilitation experience which reported that the visualisations led to increased enjoyment and high levels of motivation that were maintained throughout the four weeks of training, although this was again a non-significant finding compared to the No-VIS group, and as reported above the No-VIS group also enjoyed the training experience.

When we consider the literature from Chapter 3, which identified a lack of adherence to training to be related to boredom and disengagement, the dissatisfaction from previous rehabilitative experiences compared to an enjoyable and perceived successful intervention on a group level, and the underpowered study, the results from this thesis warrant further investigation. How we address this and further progress the package in future research is discussed in the following section.

The inconclusive result as to the impact of the visualisations for the No-CAI group was an interesting finding, as it highlights the importance of pilot testing using the population for whom the package had been designed for. The result is believed to be because the stability training was a new phenomenon for people who have never experienced rehabilitation before, as well as it also being unnecessary for an uninjured population. Since all participants engaged with the training the latter is more likely since stability could not be improved further using the programme in this study. This is understandable since it was designed using the principles of training for a CAI population. Again, this highlighted the importance of piloting the package on both the CAI and No-CAI groups as this has indicated the specificity of the programme for the population for whom it has been designed.

11.3.1 Future developments

This study has demonstrated in Chapters 8 and 9 that the specific application developed for the stability-based training using visualisation may be feasible for rehabilitative practice, although currently inconclusive. However, there are a few key factors to be considered when developing this further, and before implementing into clinical practice.

The remainder of this chapter discusses each of the exercises from the application developed in Chapter 7 and the observations from the feasibility RCT in Chapter 8. Using this information, it then details how each should be developed in the future.

For visualisation as an entirety there are two key factors believed to which development should be centred around. These are:

1. Learning and retention
2. Feedback

Visualisation presents a unique opportunity to devise a package which optimizes learning in rehabilitation. This could be through teaching movement and technique in an understandable way and in a stimulating environment. For this reason, creating an application which optimizes learning should be at the forefront of future developments. For the particular application created for this project the single leg balance and lunge exercise both specifically addressed how the participant was moving to ensure suboptimal technique was not practiced and learned. During the lunge exercise the tester provided verbal feedback to help interpret the visual feedback on the screen. The ability to view the avatar from any angle during the movement made the instructions and feedback easier to present to the participant and for them to understand, as highlighted by the feedback from participants in Chapter 9. This suggests that adopting this third-person perspective using externally focussed augmented feedback would be important for following applications. Further examples of how to incorporate this are addressed in the following sections, specifically for the exercises of the single leg balance.

Following on from this, a large part of how to elicit learning and retention is the type and amount of feedback received. In Chapter 3 this was introduced and discussed as it has been documented that receiving feedback 100% of the time, both concurrently and terminally, is not favourable for learning and retention (Rogers, 2017). There is little research to date which has clearly considered feedback when developing a rehabilitation programme using virtual reality, however Rogers (2017) did report that cognitive overload was greater in a group who received feedback in a VR environment which affected the basic needs of the self-determination theory. Since it is known that these are determinants of motivation it is important to identify the effect of feedback in relation to visualisation. For this the following questions must be addressed:

- Should every aspect of the application have a learning opportunity, or should some be only for repetitive practice through gaming?
- How beneficial is the use of visualisation only for gaming? Is there a translation of the effect?

As presented in Chapter 7 the detailed design of the visualisations, including the visual feedback and backgrounds for all of the exercises, have remained simple so as to not create unnecessary distractions during simple exercises for a basic level of ability and initial stage of learning. This was an important aspect of the design however, as the participants progressed through the training, and they became more advanced, it would have been beneficial to have been able to introduce different visual backgrounds and environments. This may not have just been for added challenge, but to keep the training variable and interesting. Further to this, keeping the visual display the same throughout the 4-week training period maintained a consistency throughout the study which was important for the purpose of the research. However, in preparation for clinical practice it is recognised that these must be advanced and extended with improved professionalism.

11.3.1.1 Single leg balance with leg lift

During the single leg balance in this investigation ensuring quality of movement was important as detailed in Chapters 4 and 7, but the feedback and virtual environment created enabled a high score to be achieved with suboptimal technique. This meant that often the participant had to be reminded by verbal feedback that in order to progress the focus must be first on the stability and technique. Future developments of this exercise using visualisations should consider that the movement cannot result in a score unless the movement is acceptable. An example of this would be the use of hiking the hip, which we referred to in Chapter 4.2.1.2. In Chapter 7 this was originally part of the stability-based application before having to be removed to keep the screen simple with not too much information. However, on reflection after conducting the study, one way to present this information may be to create a line object through the HJCs of the avatar which the participant must keep level throughout the reps. A second aspect related to technique which should be addressed is the strategies which may be used to maintain balance. Although these may not lead to compensatory movements of the body and may help maintain balance these do not develop the skills needed to cope out with this specific environment. Examples of these include fixing concentration and reliance on vision. In the current application from this project this often included concentrating on a point in the room, and in the VIS group often included not looking at the screen at all. An example of how fixed vision was overcome here was by asking the participant to count the number of times the spot on the screen turned green, representing the score out of 10. This was successful at drawing the attention to screen and preventing a fixing strategy. This would be more difficult to incorporate into a future application for the system to recognise if a strategy is in place, and there is no awareness of a solution at this time, thus the clinician present may have to address these.

11.3.1.2 Single leg stand and reach

The single leg stand and reach task was particularly challenging for the participants which flourished into a love-hate relationship. It is a simple idea challenging the participant to react quickly to an unpredicted stimulus and included levels for progression, a score for easy monitoring, and enabled a wobble board to be included for further progression.

There are many possible ways to develop this game in the future. One that was originally considered was making game level progression automatic depending on performance. For example, from whichever starting level was decided upon if a certain score was achieved or a certain number of spots had been collected in a row then the game would automatically increase the level of challenge. Despite this, we would debate its appropriateness here as this could make the game last quite a long time which would be fatiguing for the participant and that is not the aim of this particular application. This is just one example of the next step in developing this game.

11.3.1.3 Lunge

During training the visualisations on the screen provided a vital source of information for the participants which helped participants understand the movement and directions easier, as highlighted from the feedback in Chapter 9.

The addition of the cognitive task added a challenging element however from the results we question as to how difficult the participants found the particular cognitive task when using the visualisations, particularly in relation to the No-VIS groups training. However, without a direct comparison this remains unknown. Therefore, it would be beneficial for future work to assess this, and to compare a cognitive task using visualisation and that with none.

11.3.1.4 Leap Game

The leap game was the most gamified exercise of the stability-based application in this study. Although the design was successful in eliciting both challenge and enjoyment the testers often had to add extra conditions to the task to ensure that stability was targeted and practiced, and that quality of movement was not neglected in order to 'win' the game. If the game were to be developed further this could be addressed. Examples of the problems that arose, cues given, and ideas of how to introduce this into the game in the future include:

- Participant standing still for long periods of time

Although this is not necessarily an issue since it required the ability to maintain a single leg balance this was not the aim of the exercise using this game. To combat this, participants were instructed to have moved at least one time per new object that appeared on the screen. In a new game the levels could start harder, having the objects moving faster.

- Participant moving too quickly and not stopping between leaps

In contrast to the problem identified above here the participant never let the opportunity arise to have to maintain a single leg balance for any length of time. This had to be prevented since the participant was not allowing themselves the opportunity to practice any balancing and so were instructed after landing each leap, and before the next one, they had to touch their knee or perform a calf raise. Through game development a reward system could be brought into place where if the player remained still at any point for a few seconds there would be bonus points awarded. Alternatively, a number of items on the screen could be collected in a row, rather than avoided, which would need the ability to maintain the balance.

- Participant performing small steps rather than leaps

Here only small steps or leaps were made which meant there was little momentum to destabilise the COM when landing the leaps. When this occurred, a condition was put in place that the participant was required to move the avatar from one large box to another, thus not allowed to stay within the same box per leap. This ensured that they did a reasonable size of leap rather than small leaps. To address this the game should optimise the size of the objects to be avoided.

11.3.2 Future applications

The current stability-based training programme with visualisation has been specifically designed for people with CAI, however it did no go unrecognised in the focus groups in

Chapter 6 that the exercises cross over to many other rehabilitation programmes. Examples of which include falls prevention and ACL rehabilitation (Benjaminse et al., 2015; Rostami et al., 2018). This suggests that the scope of the stability-based training programme with visualisation is far wider than ankle rehabilitation. Despite the argument presented in Chapter 2 as to the importance of addressing this, there is a greater health and government focus on these other areas. The most recent national prevention strategy for falls and fractures for 2019-2024 reported by the NHS has highlighted the ambition to build a culture where falls prevention behaviours are the norm and to increase the number of people participating in regular movement, with balance a primary focus (GOV.SCOT, 2019). Here they also discuss encouraging people to take part in physical activity, again highlighting balance, however this needs to be enjoyable and act to build confidence when there may be a fear avoidance strategy. Visualisation again has the potential to address these in the same way as it could for ankle injury rehabilitation and prevention. Thus, as future applications are developed for an ankle population only small changes may need to be made for the ACL and falls communities. It is unknown as to whether one application would be suitable for all since the results here cannot be generalised and the research has not been published regarding this, however it is likely that different applications should be developed for the specific populations. This is primarily since game design studies have highlighted that the age of a population determines what should be prioritised in games and what is enjoyed in a virtual environment (Salmon et al., 2017).

11.3.3 Assessment packages

The priority for future developments using visualisation should be furthering a training package, as highlighted by the focus groups in in Chapter 6. However, since the system can analyse the quality of movement and produce results in real-time there is potential for assessment packages. Early evidence of the feasibility of such applications has been reported by Tawy (2017) who objectively assessed range of motion, gait, and strength. Further to this, if a full body SCM was developed, as suggested above, this could provide more in-depth assessments both in clinical and sports performance, including specific upper body assessments and rehabilitation.

11.4 Conclusions

This chapter has discussed the development of the stability-based training package both as a clinically appropriate motion analysis system and a training application using visualisation.

Following this, the future developments for the stability-based training package were outlined. These aim to further this project and create a package which could implement biomechanics into routine clinical practice protocols and use visualisation as both a motivational and learning tool. If these aspects of the system are addressed, the environments where this could be implemented could be extended within both clinical and performance environments, but also health and wellbeing practices. These include movement screenings, rehabilitation training, and technical practice. Further to this, and most importantly, it would make biomechanical analysis more easily implemented into the multi-disciplinary network so it could become part of routine practice.

Chapter 12 – Conclusion

This thesis has designed, developed and assessed the feasibility of a stability-based training package for people with CAI suitable for clinical practice. To conclude the main findings of this investigation are summarised and the main research questions presented in Chapter 1 are revisited.

- Chronic ankle instability leads to reduced quality of life both physically and mentally.

- Although research shows stability-based training is effective at improving symptoms of chronic ankle instability, current protocols lack clarity, functionality, and motivational qualities which effects adherence.

- Providing feedback is important for motor learning and is an effective means for motivating people, particularly when using virtual reality.

- Visualisation presents the opportunity to combine motion capture and feedback in a VR environment for use in clinical practice.

- Biomechanical techniques are still described as time-consuming and complex, however there is an educational barrier between the current technology available, the research, and current healthcare professionals.

- The stability-based package was designed and developed as a hybrid tool to provide externally focused augmented feedback accurately using motion capture in a virtual environment, to improve and monitor stability, quality of movement, and motivation in rehabilitation.

- The feasibility RCT study showed this could be feasible and warrants further investigation. The study was conducted safely, and the adherence, retention and user satisfaction were high.

- The stability-based training programme was effective at improving objective and subjective stability evidenced by a main effect of time. The perceptions of stability were consistent with current literature which implied that the programme was valid.

- The effect of the addition of visualisation was inconclusive during post-training assessments. There was a significant difference in the star excursion balance test, which was the primary outcome measure due to its reliability and validity. However, the study was underpowered limiting interpretation.

- All participants reported a high level of enjoyment, but it was inconclusive as to the effect following training with the visualisations.

- A retrospective analysis suggests the package could be suitable for implementation into clinical practice.

In conclusion, to answer the main research questions, the stability-based package included a clinically appropriate motion analysis system that was accurate and reliable, time efficient, non-complex, and produced interpretable results. The effect of the visualisation regarding the augmented feedback in the virtual environment did enhance performance and enjoyment with medium to large effect, however the study lacked statistical significance and was underpowered, preventing conclusions from being drawn. Therefore, this thesis has demonstrated that the stability-based can be feasibly used for people with CAI, however further research and appropriately powered studies are required to understand the effect of the visualisation on training outcome and experience.

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Appendix A – Focus Group Discussion Questions and Feedback Forms

<u>Questions for the discussion:</u>

Biomechanical analysis:

- Experiences
- Would it be useful?
- Importance of motion capture if any?

The system and using visualisation:

- Have you worked with anything like this before?
- Could real-time feedback and virtual reality be useful or developed to be useful?

- Could see being worked into clinical practice?
- Would you use this to aid your rehabilitative practice?
- How they believe patients may react/perceive the system and programme with visualisation?
- Understandable and ease of use?

The exercises in the programme:

- Programme represent exercises and progressions in current practice?
- Protocol representative of a training programme in current practice (2x week for 4 weeks)?

Future developments:

- Aspects of the package particularly useful or not useful?
- Influence of cost and accuracy?
- Training or assessment tool?

Focus Group				
Participant Information				
Profession				
Years qualified (please tick)	<2	2-5	5-10	10+
	Comments			
Is the system and/or application feasible for clinical practice?				
Would this system benefit clinical practice?				
Please identify which field in practice you would see this most useful, if anywhere **(ie. Orthopaedics/physio/athlete profiling/neuro rehab)**				
Please identify where in practice you would see this most useful, if anywhere **(ie. Reaction/balance/challenge/assessment)**				
Is there something you wish you could perform/create in practice that cannot be done yet? (ie. Real-world challenging situations/quick objective assessments/games)				
Additional comments				

Focus Group				
Participant Information				
Profession				
Years qualified (please tick)	<2	2-5	5-10	10+
	Comments			
Is the system and/or application feasible for clinical practice?				
Are the exercises and progressions represent current practice and measurement of stability? **(ie. frequency and duration of sessions)**				
How do you believe patients may react/perceive the system and application? **(ie. motivation/ enjoyment/feedback)**				

Appendix B – Comparison of SCM to HBM2 during a dynamic stability task

Introduction

The current utilisation of instrumented motion analysis in clinical practice is prevented by the lack of time in clinical practice for the lengthy protocols (Toro et al., 2003). Adopting a cluster-based model, opposed to applying individual markers, could allow for a quicker and simpler process more appropriate for clinical practice. However, the biomechanical model used must be carefully considered as these can significantly alter the kinematic results. Millar (2018) showed the recently developed Strathclyde Cluster Model (SCM) to be a potential alternative to the commercially available, and gold standard, Plug in Gait model routine used in rehabilitation and visual feedback. The cluster-based model had the ability to produce a meaningful kinematic output, which showed good agreement particularly in the sagittal plane, during gait. The current investigation assessed SCM kinematic output during a dynamic task in comparison to the real-time kinematic output from an individual marker model.

Method

The study recruited healthy, able-bodied individuals with no lower limb impairments for participation (n = 11, age = 26±4 years old). Each participant completed one testing session which took place in the Human Performance Lab of the Clinical Research Facility, Glasgow Royal Infirmary. The study was approved by the Department of Biomedical Engineering, University of Strathclyde (DEC.BioMed.2018 227) and NHS R&D approval for testing on an NHS site (IRAS project ID 246773).

A 16 camera Vicon Bonita camera system was used for the instrumented motion analysis, and a D-Flow application ran the leaping task. This was displayed on an LCD TV screen and required the participant, who appeared as an avatar, to leap from one leg to the other to avoid oncoming objects. The task lasted for 30 seconds. This was repeated eight times under various conditions related to another study (Appendix C) but only one trial was used for analysis.

To enable the avatar to be created for the leaping task the SCM was applied to each participant first and calibrated using pointer calibration. Cluster positions and the pointer calibration are both detailed in Chapter 7.2.1 and 7.2.2, respectively. Once the avatar was on the screen a full body HBM marker set was applied. Participants were asked to wear tight clothing for individual marker placement to be as accurate as possible. The location of all markers applied, and worn during testing, is shown in Figure 1 and Table 1.

Figure 1. Participant prepared for testing wearing HBM and SCM

The skin surface markers were attached using double-sided tape and the clusters attached using Velcro straps. Clusters were secured as tightly as possible to minimise cluster movement for the duration of the testing session but remaining comfortable for the participant.

Data processing and analysis

During the task data was recorded in D-Flow and Tracker (Tracker 3.5.1, Vicon). In D-Flow marker position and joint angle data was recorded for the SCM only. Following data collection, the Tracker trial data was processed in Vicon Nexus (Nexus 2.6, Vicon, UK) using the appropriate HBM2 (Motek Forcelink, The Netherlands) modelling template to output the HBM (van den Bogert et al., 2013) marker positions as a C3D file. This was then run through a custom-designed D-Flow application, where the HBM was calibrated and desired marker positions and joint angles output as TXT files. For analysis in this study only the lower limb and pelvis results were required.

Table 1. Marker positions (and calibration locations) for marker set used.

Segment	Marker Location	Model
Pelvis	RASIS	HBM (SCM calibration only)
	LASIS	HBM (SCM calibration only)
	RPSIS	HBM (SCM calibration only)
	LPSIS	HBM (SCM calibration only)
	Pelvis Cluster	SCM
Thigh	LTHI / RTHI	HBM
	LME / RME	HBM (SCM calibration only)
	LLE / RLE	HBM (SCM calibration only)
	L / R Thigh Cluster	SCM
Shank	LSHA / RSHA	HBM
	LMM / RMM	HBM (SCM calibration only)
	LLM / RLM	HBM (SCM calibration only)
	L / R Shank Cluster	SCM
Foot	L / R Toe	SCM (calibration only)
	L / R MT1	SCM (calibration only)
	L / R MT2	HBM
	L / R MT5	HBM (SCM calibration only)
	L / R HEE	HBM (SCM calibration only)
	L / R Foot Cluster	SCM
Head	T / F / R / L HEAD	HBM
Trunk	C7 / T10 / JN / XYPH	HBM
Upper Limbs	L / R SHO	HBM
	L / R DELT	
	LLE / RLE	
	LME / RME	
	L / R FARM	
	LLW / RLW	
	LMW / RMW	
	L / R FIN	

Once the TXT files were obtained, analysis was performed using a custom-written MATLAB programme (MATLAB ver.2018, Mathworks Inc., USA) to smooth the SCM data using the same 2nd order butterworth filter used automatically by D-Flow for the HBM data, resample the SCM and HBM data to equal frequency of 100Hz, and compare the offset between the models across the trials. Joint angles analysed were matched to those automatically output from D-Flow when using the HBM. These were hip flexion/extension, abduction/adduction, and internal/external rotation, knee flexion/extension, and ankle dorsi/plantarflexion and abduction/adduction.

Results

From the 11 participants who completed the testing five participants could not be calibrated for the HBM in D-Flow due to the system not recognising markers. This meant there was no kinematic output for these participants and so were removed from final analysis (n=6, 26±4 years old).

The average difference between the HBM and SCM for each trial and participant, as well as the variance, are shown in Figures 2 and 3. The average difference across participants does not present a consistent offset between the models. This is evident both within and between each joint angle. The hip flexion and abduction differences and knee flexion show the smallest mean difference of 0.41°, 8.9°, and -3.6°, and a maximum difference of 8.5°, 15.2°, and -15.2°, respectively. Hip rotation, and ankle motion in both planes show greater variability across participants with larger maximum offsets of -24.7°, -20.7°, and 29.1°, respectively. Figure 2 shows the ankle flexion distribution across participants to mirror in the right and left sides.

Within each trial for each participant the offset remained below 3.8° and 4.8° for hip and knee flexion, respectively. The greatest variation within trials was seen in the hip rotation and ankle inversion (6°-10.4° and 5.5°-10.8°, respectively). Figure 3 shows the right and left sides to be comparable here.

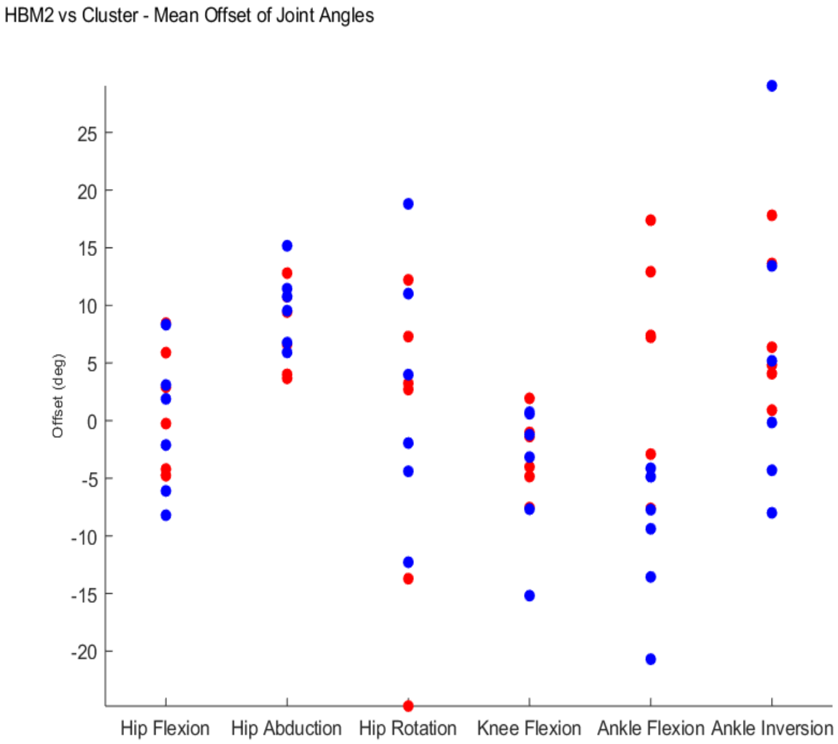

Figure 2. Mean difference between cluster and HBM models for each participant. The offset is the mean difference across the 30 second trial. 12 dots for 6 participants R and L side. Blue = L side and Red = R side.

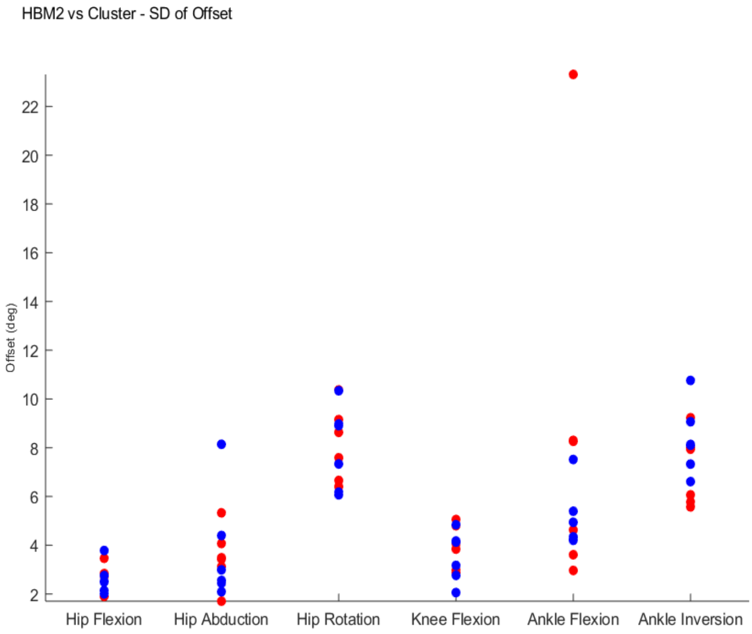

Figure 3. Mean variance of the difference between cluster and HBM within each 30 second trial. 12 dots for 6 participants R and L side. Blue = L side and Red = R side.

Discussion

This is the first study to assess kinematic output from SCM compared to the HBM, with previous work comparing to PiG (Millar, 2018; Papi, 2012). From the results the SCM output is representative of the HBM for the hip and knee movement in the sagittal and frontal planes, however less so for hip rotation and all ankle motion. Currently there are no standards deciphering the threshold for a clinically significant difference between models, however we believe that in the hip and knee joints the offset in this study is acceptable considering the benefits to clinical practice of using the SCM opposed to an individual marker model.

The results of the current study support previous work by Millar (2018) who compared the SCM to the reliable and validated PiG model during overground walking for five and ten participants, respectively. For both studies across all participants the sagittal plane kinematics showed the smallest difference in the hip, knee and ankle, respectively. The hip abduction/adduction and internal/external rotation show less agreement reporting a larger difference across all participants, as did ankle dorsi/plantarflexion. Millar et al. (2018) reported in the hip transverse plane and ankle sagittal plane there was greater variability within the trials for each participant, thus there was not a constant offset to follow the same movement pattern as the PiG. The current study supported these results where hip kinematics in the frontal and transverse planes showed the largest difference across the whole trial, but also within each trial. Kinematic output in the transverse plane has often been reported a highly variable and the results of this study reflect this. Rotation in particular has been shown to be subject to soft tissue artefact. This has been shown to affect individual marker models to a greater extent than cluster-based models thus this may account for the difference between the SCM and PiG model (Duffel et al., 2014).

This study furthers that of previous work as the leap game conducted is a more dynamic task than that of walking, thus requiring greater excursion of each joint which would be assumed to closer approach maximum ROM compared to walking. Limitations of this study include the simplicity of the HBM, which models the knee as a hinge joint thus eliminating knee movement in the frontal and transverse planes. This limits the applicability of the HBM for clinical practice and has prevented comparison between the SCM and HBM in these respective planes. Furthermore, only a small sample size was recruited.

In conclusion the results support the findings of previous research which state that the SCM presents an alternative kinematic analysis which could more suitably be used for rehabilitation and visual feedback than individual marker models.

Appendix C – Assessing Task Difficulty using Visualisation during a leaping game

Introduction

For rehabilitative programmes to be successful the principles of training should be applied. These ensure that the training is specific and progressive, and that practice is varied (ACSM, 2018). When using virtual reality, the level of difficulty must be carefully monitored to ensure the challenge is constantly situated on the boundary of player ability, while maintaining player engagement and desire to re-play (Revyse et al., 2016).

Hawkins et al. (2008) studied the relationship between performance and difficulty by altering game velocity and surface perturbations in a virtual game environment. Performance deteriorates as game difficulty increases by altering game velocity and surface perturbations. Adjustment of both game velocity and the introduction of surface perturbations independently appear to be simple and effective methods of customizing task difficulty as a function of patients' motor ability during rehabilitation. However, there is no other research noted to assess the difference in performance under different task manipulations. This study aimed to address this in order to inform the researchers of optimal game progression in the leap game within the STA, as well as future game development within rehabilitation. A secondary aim for this study was to analyse whether the actual level of game difficulty aligned to the participants' perception of level of difficulty level, and the effect of this on enjoyment of playing.

Method

This study was part of the study detailed in Appendix B, using the same participants and protocol (DEC.BioMed.2018.227).

Participants performed the leaping game for 30 seconds. The objective of the game was to leap between limbs to avoid the oncoming objects on the screen, of which there were 29 in total each appearing on screen one second apart. Each time the centre of the ankle joint of either leg collided with an object this is counted towards the player's score and the aim was keep the score as low as possible. Participants remained blind to the score. An example of the leap game and the participant's screen is shown in Figure 1.

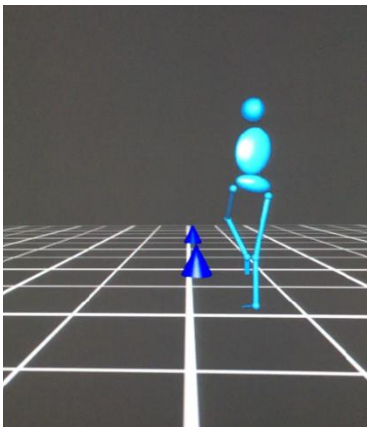

Figure 1. Leap game as seen by participants.

The game was repeated under 8 different conditions. Each condition manipulated either the speed or size of the moving object, or the distance at which it appeared on the screen compared to where the individual was (Table 1). Each variable had two levels – speed: slower/faster, size: smaller/larger, distance: further away/closer. The conditions were performed in a random order decided using a random number order generator (RANDOM.ORG). This was to avoid practice of the game being a confounding factor during testing. Adequate rest was given between the conditions tested.

Following each trial participants were asked to rate the perceived difficulty and enjoyment of the trial just completed from 1-5. Once the game had been performed under all eight conditions, the participant was questioned as to the variable they deemed the most difficult and enjoyable during the leaping game and invited to report any additional comments.

Table 1. Leap Game difficulty levels. Speed, distance and object size all have 2 levels (written either 1 or 2), with each condition a unique combination of the levels of the speed, object size and distance.

EXERCISE	**CONDITION**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
LEAP GAME	Speed:	1	1	1	1	2	2	2	2
	Distance:	1	2	1	2	1	2	1	2
	Object size:	1	1	2	2	1	1	2	2

Data Analysis

The D-Flow software displayed participants' game scores during, and following completion of, each trial on the tester's control panel on the computer. The scores of each condition tested, and the participants' ratings of difficulty and enjoyment, were recorded and compared. All statistical tests were performed in Minitab. ANOVAs were conducted to calculate the statistical difference between each condition for each participant ($p<0.05$).

Results

Game Scores

Conditions 3, 4 and 8 resulted in significantly more objects hit throughout the 30 second game ($p<0.05$) (Figure 2). For condition 3 45% of participants scored more than 50% hit rate, which led it to be the most difficult condition. The variability was greatest in conditions 3 and 4 where the most objects were hit (±29.7% and ±23.8%, respectively).

The scores for conditions 1, 2, 5 and 6 resulted in less than 15% of objects hit, on average. The speed and distance varied across these conditions, but the object size remained smaller at level 1.

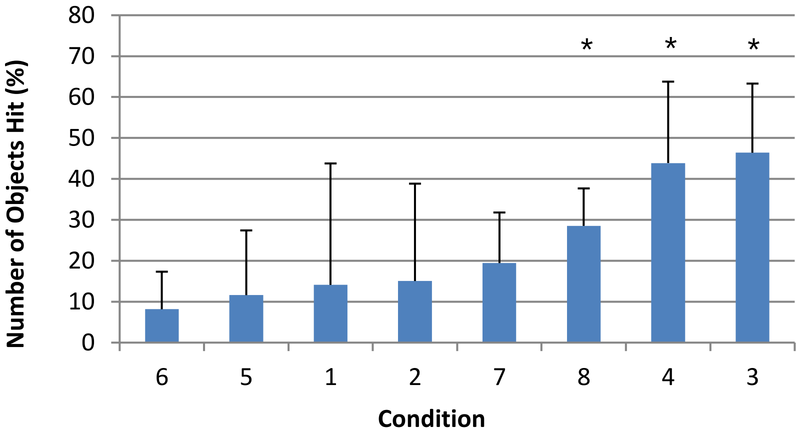

Figure 2. Mean percentage of objects hit for each condition.

Difficulty and enjoyment ratings

The participant's perception of the difficulty overall was 3/5 (±0.5), on average. There was little variation in the perceptions of difficulty across each condition. Table 2 shows conditions

3, 4 and 8 to be perceived the most difficult scoring 3.55 (±1.2), 3.55 (±0.8) and 3.73 (±1.0) out of 5, respectively, significantly differing from other results (*p*=0.009).

Enjoyment scores over the eight conditions remained slightly higher than neutral at 3.5/5, and inter-condition variation was small (±0.1, *p*=0.961). Participants reported conditions 6, 4 and 1 as the most enjoyable (Table 2), scoring on average 3.73 (±0.8), 3.64 (±0.8) and 3.64 (±0.8) out of 5, respectively. This did not correlate with any particular aspect regarding the object speed, size or distance the object appears on screen relative to the avatar.

Table 2. Order of the 8 conditions. Number represents the condition which are detailed in table 1. *condition significantly differs from other conditions (*p*<0.05).

	GAME SCORE	**PERCEIVED DIFFICULTY**	**PERCEIVED ENJOYMENT**
LEAST	6	1	2
	5	2	7
	1	5	8
	2	7	3
	7	6	5
	8 *	3 *	1
	4 *	4 *	4
MOST	3 *	8 *	6

Participant Comments

All participants stated an interest in the use of visualisation in rehabilitation or training after completing all eight conditions. Increasing the size of the object was reported by 54.5% of participants the most difficult and enjoyable variable in the leap game. The remainder were equally split between speed and distance, with one reporting no opinion. An increased speed was found to be the most enjoyable aspect in 72.7% of participants. One participant reported the game to be more enjoyable when the objects appeared on screen further away, one when the objects were smaller, and two had no opinion.

Discussion

When using games to aid rehabilitation it is important that the participant is appropriately challenged to maintain consistent progresses, however this must be enjoyable as well to ensure motivation and adherence. Overall, the highest game scores, showing the most difficulty for participants, were also perceived to be the most difficult however this difficulty did not appear to correlate with the enjoyment of each condition. Following analysis, it was clear that object size was a key influence on final game scores and perceived difficulty. Results suggest larger objects make the game more difficult. This was unsurprising as when the objects were larger not only did this require a greater lateral displacement for each leap to avoid objects, but also there was less time between each object appearing in front of the participant as more space on the screen was filled. Interestingly, the speed for the two highest scoring conditions remained at level one (slower). Results showed two thirds of the participants reported increased enjoyment when the objects moved faster. This suggests that speed is an important variable and should be maintained at a faster speed for participant enjoyment, especially since the slower speed did not appear to affect the performance or perceived performance of the participants.

As a small pilot study, the sample size and homogeneity of the group did not limit the study. However, young and healthy people may perceive game enjoyment and difficulty differently to the patient population for which the game has been designed. A second limitation is use of a five-point Likert scale. Although this is a commonly used method which easily constructs an understanding of people's attitudes (Subedi, 2016), the scale can be perceived very differently which in this study has resulted in an almost neutral conclusion. Researchers attempted to negate this by allowing participants to change any previous result if in a later condition it was felt the perceived score given for a previous condition was, in hindsight, not accurate following completion of following conditions.

In conclusion, this study has successfully identified key variables to satisfy the balance of challenge and engagement. These will be used to guide the development of the leap game within the stability-based training package to inform the progressions from level to level and optimise rehabilitation in a virtual environment.

Appendix D – Inclusion and Exclusion Criteria

Inclusion criteria for previous ankle injury group:

1. History of at least 1 significant ankle sprain

   – the initial sprain must have occurred at least 12 months prior to the study

   – was associated with inflammatory symptoms (pain, swelling, etc.)

   – created at least 1 interrupted day of desired physical activity

2. The most recent injury must have occurred more than 3 months prior to the study.
3. A history of the previously reported injured ankle joint ‘giving way’, and/or recurrent sprain and/or ‘feelings of instability’
4. Report a score of <24 in the Cumberland Ankle Instability Tool (issued with PIS. Please complete if interested in being part of the study. Eligibility for inclusion in the study will be dependent on the result).
5. Self-reported 20/20 vision (with or without visual aid)
6. Able to perform static/dynamic tasks for 1-minute intervals

Inclusion criteria for no previous ankle injury group:

1. No history of ankle sprains
2. Report a score of >90 in the Cumberland Ankle Instability Tool (issued with PIS. Please complete if interested in being part of the study)
3. Self-reported 20/20 vision (with or without visual aid)
4. Able to perform static/dynamic tasks for 1-minute intervals

Exclusion criteria for both groups:

1. A history of previous surgeries to the musculoskeletal structure in either lower extremity.
2. A history of a fracture in either lower extremity requiring realignment
3. Acute injury to the musculoskeletal structures of other joints of the lower extremity in the previous 3 months, which impacted joint integrity and function (ie. Sprain) resulting in at least 1 interrupted day of desired physical activity.
4. Pregnancy or thought to be pregnant

Appendix E – The CAIT questionnaire

Initials		**Date**			

Please tick 1 box per question for each ankle.

	LEFT	RIGHT	Score
1. I have pain in my ankle			
Never	☐	☐	
During sport	☐	☐	
Running on uneven surfaces	☐	☐	
Running on level surfaces	☐	☐	
Walking on uneven surfaces	☐	☐	
Walking on level surfaces	☐	☐	
2. My ankle feels UNSTABLE			
Never	☐	☐	
Sometimes during sport (not every time)	☐	☐	
Frequently during sport (every time)	☐	☐	
Sometimes during daily activity	☐	☐	
Frequently during daily activity	☐	☐	
3. When I make SHARP turns, my ankle feels UNSTABLE			
Never	☐	☐	
Sometimes when running	☐	☐	
Often when running	☐	☐	
When walking	☐	☐	
4. When going down the stairs, my ankle feels UNSTABLE			
Never	☐	☐	
If I go fast	☐	☐	
Occasionally	☐	☐	
Always	☐	☐	
5. My ankle feels UNSTABLE when standing on ONE leg			
Never	☐	☐	
On the ball of my foot	☐	☐	
With my foot flat	☐	☐	
6. My ankle feels UNSTABLE when			
Never	☐	☐	
I hop from side to side	☐	☐	
I hop on the spot	☐	☐	
When I jump	☐	☐	
7. My ankle feels UNSTABLE when			
Never	☐	☐	
I run on uneven surfaces	☐	☐	
I jog on uneven surfaces	☐	☐	
I walk on uneven surfaces	☐	☐	
I walk on a flat surface	☐	☐	
8. TYPICALLY, when I start to roll over (or “twist”) on my ankle, I can stop it			
Immediately	☐	☐	
Often	☐	☐	
Sometimes	☐	☐	
Never	☐	☐	

I have never rolled over on my ankle	☐	☐	
9. After a TYPICAL incident of my ankle rolling over, my ankle returns to "normal"			
Almost immediately	☐	☐	
Less than one day	☐	☐	
1–2 days	☐	☐	
More than 2 days	☐	☐	
I have never rolled over on my ankle	☐	☐	
	TOTAL SCORE		

Appendix F – Participant Enjoyment and Engagement Questionnaire (PACES-8 & USEQ)

Participant no.		**Strongly Disagree**	**Disagree**	**Neither**	**Agree**	**Strongly Agree**
PACES-8						
I find it pleasurable						
It's a lot of fun						
It's very pleasant						
It's very invigorating						
It's very gratifying						
It's very exhilarating						
It's not at all stimulating						
It's very refreshing						
USEQ						
I enjoyed my experience with the system						
I was successful with the system						
The information provided by the system was clear						
I felt discomfort during my experience with the system						
I think this system will be helpful for rehabilitation						
TOTAL SCORE						
Comments						
Ie. Feelings of ankle instability, motivation levels, rehab experience, most/least enjoyable, rehab process.						

Appendix G – Three-month follow up questions

CAI/VIS GROUP

1. Did you feel motivated during the training sessions or before you came into the training sessions?
2. Did you feel appropriately challenged during the training sessions (ie. Were they too hard/easy)?
3. What was your favourite aspect of your training?
4. Did having the visualisations affect the effort you put in?
5. Did having the visualisations affect how involved you felt in you training programme?
6. Did the visualisations add anything else to your experience?
7. How many ankle sprains have you experienced since testing? Is this more/less than usual?
8. Have you noticed any more/less feelings of ankle instability after completing the training?
9. How was your confidence in your overall balance ability after completing the training?
10. Did you continue any stability training following your 4 weeks, or did/has it influenced your current training?
11. How did this balance training compare to the rehab you have experienced/done in the past?
12. Any other comments for development…

CAI/NO-VIS GROUP

1. Did you feel motivated during the training sessions or before you came into the training sessions?
2. Did you feel appropriately challenged during the training sessions (ie. Were they too hard/easy)?
3. What was your favourite aspect of your training?
4. Did not having the visualisations affect the effort you put in?

5. Did not having the visualisations affect how involved you felt in you training programme?
6. Do you think not having the visualisations affected your experience?
7. How many ankle sprains have you experienced since testing? Is this more/less than usual?
8. Have you noticed any more/less feelings of ankle instability after completing the training?
9. How was your confidence in your overall balance ability after completing the training?
10. Did you continue any stability training following your 4 weeks, or did/has it influenced your current training?
11. How did this balance training compare to the rehab you have experienced/done in the past?
12. Any other comments for development…