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The development and evaluation of virtual reality-based training on performance and rehabilitation outcomes

Study 1- The application of immersive technologies to the rehabilitation outcomes after ACL reconstruction: A systematic review.

Study 2- Validity of the Azure Kinect against the Gold standard motion capture system called Qualisys

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Abstract

Sports injuries are types of injuries that usually occur during sports, training, or exercise. Sports injuries often result from poor training methods, inappropriate equipment, lack of fitness, insufficient warm-up, and trauma (Salerno, 2009). Knee injuries are considered one of the most common injuries in athletes and include a large part of the cost of medical care for sports injuries (Loes et al., 2000; Sancheti et al., 2010). The ACL is the most common knee ligament injury in rugby, soccer, ski, volleyball, gymnastics, and basketball players due to quick deceleration movements such as landing, pivoting, cutting, and changing direction in these sports. Despite increased knowledge of ACL injury mechanisms, rehabilitation programmes and surgical techniques, the rates of return-to-sport (RTS) and the subsequent ACL re-injury after ACL reconstruction (ACLR) are not optimal (Buckthorpe, 2019).

Therefore, rehabilitation plays a significant role in helping athletes return to sports activities, and inappropriate rehabilitation can even devastate a satisfactory ACLR (Wright et al., 2015). This dissertation consists of two studies, including a systematic review in Chapter 2 that explores the research conducted on the application of immersive technologies for improving the outcome of the rehabilitation phases after ACL reconstruction and examines the correlation between virtual reality, rehabilitation, exercise therapy, and sport-related ACL injuries in patients. The second study in Chapter 3 validates the Microsoft Azure Kinect camera for body tracking of dynamic movements against the gold standard Qualisys system.

The findings indicated that VR-based systems could be a considerable alternative to real-world training to improve certain aspects of athletic performance because immersive technologies effectively offer a tool to control virtual environmental features. Finally, immersive technologies and VR-based systems are still in their infancy and will need considerable improvements in the future. Therefore, further research needs to be conducted in a theoretical frame to acknowledge the profitability of VR interventions in sports performance and rehabilitation programmes. The triple Azure Kinect system provides a consistent track of the joint centres' displacements with good to excellent agreement in the vertical and AP direction during the squat exercise in all joints except the ankles, particularly in upper joints such elbow and shoulder. However, future investigations must be conducted

to acknowledge the Azure Kinect's profitability in the assessment of abnormal clinical conditions and the limits of Kinect's accuracy in various movements and planes of motion.

In conclusion, the markerless triple Azure Kinect motion capture system may be a considerable alternative to a gold standard Qualisys marker-based system for specific applications such as human activities in the frontal plane. However, future investigations must be conducted to acknowledge the Azure Kinect's profitability in the assessment of abnormal clinical conditions and the limits of Kinect's accuracy in various movements and planes of motion.

Chapter One: Introduction

1.1 Injury in Sports

Sports activities can improve cardiovascular health, reduce the risk of various diseases, and be associated with a better quality of life (Arija et al., 2018). They also result in physical, psychological and social benefits for involved athletes (Shanmgam & Maffulli, 2008). However, participating in sports competitions or training can also increase the risk of injuries in athletes (Erlandson et al., 2008). It is believed that the development of the musculoskeletal system throughout life, from childhood to the elderly, and anatomical differences between various genders change the characteristics of injuries and cause various presentations of sports injuries at different ages and genders (Gross, 2004). For instance, there is a lower rate of sports injuries in children under 12 than those at the junior high school level due to the slower pace and intensity of their activity and more flexibility of their musculoskeletal system (Gross, 2004). Also, an increased rate of anterior cruciate ligament injuries (ACL) in girls due to their anatomical structures and lower strength of the musculoskeletal system shows that gender can play a significant role in the presentation of various sports injuries (Gross, 2004). Moreover, some sports injuries result from preventable training errors because some sports programmes conducted either in schools or by youth teams are not appropriate for the development level of strength, skills and technique at their age (Salerno, 2009). Injuries to the lower extremities are most common in sports activities and can cause more consequences later in life (Emery and Tyreman, 2009). For instance, knee and ankle injuries may increase the risk of developing osteoarthritis and motor control changes (Conn et al.,2003; Doherty et al., 2014). Knee injuries are considered one of the most common injuries in athletes, accounting for 15–50% of all sports injuries, and include a large part of the cost of medical care for sports injuries (Loes et al., 2000; Sancheti et al., 2010). Accordingly, the ACL is the most common knee ligament injury in rugby, soccer, ski, volleyball, gymnastics, and basketball players due to quick deceleration movements such as landing, pivoting, cutting, and changing direction in these sports (Evans et al., 2020; Otsuki et al., 2014; Kobayashi et al., 2010; Griffin et al., 2006).

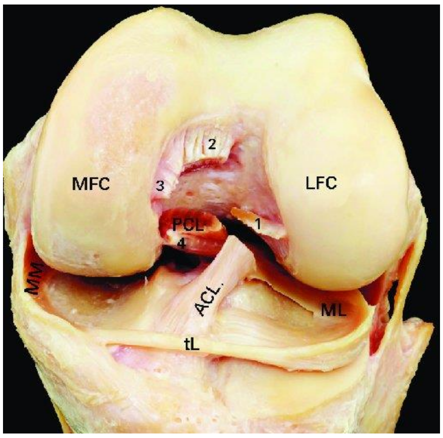
In the United States, there are approximately 100,000 ACL injuries per year (approximately 1 in 3,000 individuals), with an estimated annual surgical cost of nearly $ 1 billion. (Griffin et al., 2000; Agel et al., 2005). Renström (2013) and Samuelsson(2012) reported that over 2 million ACL injuries occur each year worldwide. In addition, a survey conducted by the National College Athletic Association (NCAA) showed that ACL injury is the second most common injury in the lower extremities (Arndt et al., 1999). Another study in the USA was conducted on soccer and basketball players of the National Collegiate Athletic Association (NCAA) and reported an incidence of 14 and 17 ACL injuries, respectively, per 100,000 athletes per year between 1989 and 2004 (Mihata et al., 2006). Two other studies found an ACL injury prevalence of 7.0% among basketball players in Australia between 2000 and 2004 (Flood et al., 2009) and a prevalence of 10.6% among high school basketball players in Canada in 2004 (Emery et al., 2006). The incidence of ACL tear in the UK is 20 per 100,000 per year (Gillquist et al., 2002). Also, there is an increased rate of ACL injuries in deliberate contact sports (Hootman et al., 2007; Agel et al., 2005).

Indeed, rupture of the ACL is one of the most debilitating injuries among athletes (Montalvo et al., 2019) because there might be altered movement patterns after an ACL injury, and athletes might experience impaired knee function such as instability, re-injury, knee pain and swelling, joint stiffness, and reduced activity in daily life or sports activities (Tengman, 2014). Despite increased knowledge of ACL injury mechanisms, rehabilitation programmes and surgical techniques, the rates of return-to-sport (RTS) and the subsequent ACL re-injury after ACL reconstruction (ACLR) are not optimal (Buckthorpe, 2019). Also, an ACL injury is deemed one of the most prolonged sports injuries due to the requirement for extensive treatment, including surgery (ACL reconstruction) and a long-term rehabilitation programme. Indeed, athletes' treatment goal is to return to their sport with minimum performance loss, whereas for non-athletes, the goal is to return to regular everyday activities without discomfort or pain (Saka, 2014). Consequently, athletes' sports injuries often become a more complicated decision-making process for doctors because it is necessary to consider the nature of the injury (acute or overuse), the type of sport and the athletes' regular training schedules (De Araújo et al., 2019). Indeed, rehabilitation after a sports injury is crucial to preventing re-injury, providing full recovery, and reducing the period of return to play. Although the role of pharmaceutical requirements and surgical interventions are essential after sports injuries, the rehabilitation team provides major work to help athletes return to play (Dhillon et al., 2017). For instance, ACL injuries induce significant mass and strength loss in the thigh muscles of the injured leg (Lorentzon et al., 1989; Kannus, 1988). Thus, one of the most important aspects of rehabilitation after ACL injuries is restoring the injured leg's skeletal muscle mass and strength to improve the functional level and re-establish the pre-injury activity level (Holm et al., 2006). Therefore, practitioners require clinical evidence about various types of sports-specific profiles and miscellaneous options for athletes' treatments (Buckthorpe, 2019), and experimental studies such as randomised controlled trials (RCTs) typically provide valuable evidence (Smith et al., 2014). For instance, the potential of using virtual reality (VR) as an intervention and alternative route for rehabilitation to improve the recovery process and reduce the rehabilitation cost has been explored recently (Mantovani et al., 2003; Simone et al., 2006).

Indeed, VR is a computer-generated graphical environment that offers opportunities for users to interact with the virtual environment while using real-time performance feedback and interface modification contingency. We will discuss ACL injuries in more detail in the following sections, focusing on risk factors, biomechanical assessment, treatment methods, return to play criteria and usage of virtual reality technologies for ACL injury assessment and rehabilitation.

1.2 Anatomy and Biomechanics of ACL

The ACL is one of the knee ligaments, connecting the anterior of the tibial intercondylar area to the posteromedial side of the lateral condyle of the femur. This ligament is the primary restraint for the anterior translation of the tibia on the femur (Fukubayashi et al., 1982) and a secondary restraint for internal rotations of the tibia (Masouros et al., 2010). The middle geniculate artery is the main blood supply of the ACL, while a branch of the tibial nerve innervates it (Brown et al., 2004). Although ACL functions as a single ligament, it contains anteromedial and posterolateral bundles, which are rigid in flexion and extension, respectively (Guoan et al., 2004). It is believed that the ACL improves dynamic control with proprioceptive feedback. In 1992, Pitman et al. showed evidence of proprioceptive receptors within the fibres of the intact ACL. Two studies have reported continued proprioceptive deficits in the knee even after ACL reconstruction (Lephart et al., 1997; Barrack et al., 1989). In addition, the ACL enhances static stability in the knee by restricting the anterior translation of the tibia on the femur (Laskowski, 2014) and controlling excessive medial-lateral translations of the tibia on the femur to prevent the knee from giving way (Smith et al., 1993). Also, the ACL provides up to 86 % of the total force to resist the anterior draw (Markatos et



Cadaver specimen of the left knee joint, frontal view, anterior cruciate ligament (ACL), posterior cruciate ligament (PCL) and anterior menisco-femoral ligament (aMFL) is cut off. Notice flat structure on the cross section of the ACL (1), PCL (2) and aMFL (3).

al., 2013). The anterior drawer test involves the patient lying down with a bent knee, applying anterior and posterior translation stress to the proximal tibia. Displacement of more than 6mm comparing the opposite side with a soft endpoint offers ACL injury (Makhmalbaf et al., 2013). Accordingly, a significant increase in ACL load during sidestepping and crossover cutting manoeuvres was associated with an increased risk of ACL injury in a variety of sports (Hewett et al., 2005; Besier et al., 2001)

1.3 Risk Factors of ACL Injury

ACL injuries are multifactorial and are thought to be caused by various internal and external risk factors. External factors include shoe-surface interaction, type of sport, footwear, and environmental conditions such as climate or sports surface irregularities, which may result in musculoskeletal injuries (Brophy et al., 2010). However, limited information about the influence of external factors makes this area suitable for further investigation (Griffin et al. 2006; Renstrom et al. 2008). Internal factors include hormonal, anatomical, biomechanical and development of the musculoskeletal structure. For example, females preferentially have higher activations of the quadriceps muscles compared to the hamstring muscles with increased landing intensities (Ford et al., 2011). These neuromuscular differences may increase frontal plane knee movements and loads during activities in females (Shultz et al., 2007; Ahmad et al., 2006; Quatman et al., 2006).

Another example is the differences in landing technique due to various alignments of the lower limb, limb dominance, location of the centre of gravity, and muscle strength (Barber-

Westin, 2009; Bedo et al., 2022). The risk factors of ACL injury can also be divided into non-modifiable risk factors such as anatomical, genetic, gender and previous ACL injuries, and modifiable risk factors (Bisciotti et al., 2019). Healthcare providers should recognise the modifiable risk factors for ACL injury and attempt to address these risk factors before re-injury (Wetters et al., 2016). Indeed, multiple modifiable risk factors contribute to an ACL injury, such as external factors (shoe-surface interaction, footwear, environmental conditions), biomechanical and neuromuscular factors, such as excessive frontal plane movement with dynamic valgus forces at the knee, lower-extremity muscle strength (quadriceps-to-hamstring ratio), hyperextension of the knee and improper landing or cutting techniques (Uhorchak et al., 2003; Wetters et al., 2016). In the following sections, the biomechanical risk factors for ACL injuries will be discussed in more detail because they are believed to be significant modifiable risk factors.

1.3.1 Biomechanical risk factors

Based on considerable evidence, biomechanical risk factors are thought to be associated with non-contact ACL injuries (Griffin et al., 2000; Shimokochi & Shultz, 2008; Wall et al., 2012; Hughes, 2014). Non-contact ACL injuries are described when there is no physical contact with other players at the time of the injury (Alentorn-Geli et al., 2009). The rate of non-contact ACL injuries is high among all ACL tears in female and male athletes, ranging from 70 to 84% (Boden et al., 2000; Feagin et al., 1985; McNair et al., 1990; Noyes et al., 1983). These injuries are produced by sudden deceleration while changing direction during running or landing (Shimokochi & Shultz, 2008). Koga et al. (2011) analysed actual injury events, demonstrating that rapid knee abduction and internal rotation in the early weight-bearing phase occur at the time of injury. Most ACL injuries are believed to result from knee abduction combined with internal knee rotation, anterior tibial translation, and increased tibial compression (Levine et al., 2013). Also, peak ACL strain may be increased with larger ground reaction forces and decreased hip angles during a simulated single-legged landing (Bakker et al., 2016). Furthermore, Ireland (1999) reported that hip forward flexion, hip adduction and internal rotation, knee extension, knee external rotation and knee valgus may increase the risk of ACL ruptures. Hewett et al. (2005) reported an increased peak external hip flexion moment in injured ACL of female soccer, basketball, and volleyball players. However, it was not found to be a significant predictor of ACL injury. Also, it was reported that female soccer players exhibited lower external hip flexion moment and hip flexion angle during spontaneous side-cut and running (Landry et al., 2007). Correspondingly, Zazulak et al. (2005) demonstrated reduced gluteus maximus activity and increased quadriceps activity in females during single-leg landings, which might contribute to the increased risk of noncontact ACL injuries in female athletes. It is postulated that the more joints are flexed during landing, the more energy is absorbed, and the less impact is transferred to the knee. Thus, knee flexion is protective against ACL damage (Alentorn-Geli et al., 2009), and a less erected posture during landing was related to a reduced ACL injury risk (Hewett, 2000; Griffin et al., 2000; Kirkendall & Garrett, 2000). Indeed, decreased hip and knee flexion angles at landing induce a greater risk of ACL injury because a higher peak landing force is conveyed to the knee (Hewett et al., 1996). The ACL has a greater elevation angle near knee extension, and it is more perpendicular to the tibial plateau (Alentorn-Geli et al., 2009). Conversely, the ACL is nearly parallel to the tibial plateau when knee flexion passes 90° (Li et al., 2006). This modification in the ligament direction affects the load on the ACL and leads to sustaining elastic deformation without injury (Blackburn & Padua, 2008). Therefore, the ACL elevation angle is maximised while the knee progresses into extension, and with this configuration, the anterior tibial shear force, generated by the quadriceps/patellar tendon, increases (Alentorn-Geli et al., 2009). Hip angles during landing can be important determinants of impact force at the knee (Aizawa et al., 2016).

Coronal plane knee biomechanics are also related to ACL injury. Hewett et al.(2005) conducted a prospective study where 205 female athletes participating in the high-risk sports of soccer, basketball, and volleyball were measured for neuromuscular control using three-dimensional kinematics (joint angles) and joint loads using kinetics (joint moments) during a jump-landing task. Nine athletes had a confirmed ACL injury. Knee abduction angle at landing was 8° significantly greater in ACL-injured athletes compared to uninjured athletes. In addition, ACL-injured subjects had 2.5 times greater knee abduction moment and 20% higher ground reaction force compared to uninjured subjects. Also, women have exhibited greater valgus moments than men during the landing phase of each stop-jump task (Chappell et al., 2002). Additionally, increased motion, force, and moments occurred more quickly in the injured compared to uninjured athletes (Hewett et al., 2005). For cutting manoeuvres, Ford et al. (2010) demonstrated that females exhibited greater knee abduction (valgus) angles compared with males.

Besier et al. (2001) showed that varus/valgus and internal/external rotation moments of the knee during sidestepping and crossover cutting were more significant than those measured during regular running. Also, they found that cutting manoeuvres may increase the risk of non-contact knee ligament injury due to an increased varus/valgus and internal/external rotation moments applied to the knee (Besier et al., 2001).

Therefore, clinicians and sports trainers need to expand their knowledge about ACL risk factors to identify which athletes are at risk of injury, design prevention sessions, and assess the effectiveness of rehabilitation programmes. The following paragraph will critically analyse the existing biomechanical assessment methods for ACL risk factors.

1.4 Biomechanical Assessment of ACL risk factors

A biomechanical assessment is performed to measure the functional parameters of knee movement for various reasons, such as diagnosis of injury, monitoring progression during rehabilitation or exploring performance after training (McClelland et al., 2007). These measurements were typically analysed in the past by visual observation of movement and posture. For instance, video-based motion acquisition was used to obtain player movements with primitive but effective techniques (Erdmann, 1992). Indeed, one of the key factors in the diagnosis and treatment of ACL injuries is the assessment of knee stability, which would provide helpful information regarding a safe time for a return to play in athletes due to the instability of the knee after an ACL injury (Kiefer et al., 2017). There are various tests to assess knee stability, such as:

- The Lachman test is widely used in clinical settings to evaluate knee instability (Gurtler et al., 1987). It has a reliability of 87% to 97% and a validity of 91% to 97%. (Graham et al., 1991; Wiertsema et al., 2008; Torg et al., 1976).
- The anterior drawer test evaluates the knee's anterior stability more specifically (Jonsson et al., 1982). There is an agreement in the literature on its effectiveness (Mitsou et al., 1988; Scholten et al., 2003), with a sensitivity of 0.18–0.92 and a specificity of 0.78–0.98.
- The pivot shift test is a clinical diagnostic tool for assessing ACL injury. It has a sensitivity of 32% to 81.8 % and a specificity of 83% to 98.4%. (Katz, J.W. & Fingerothet, 1986; Prins, 2006; Kurosaka et al., 1999; Huang et al., 2016). The sensitivity and specificity of this test can vary based on multiple factors, including the practitioner's

skill level, the patient's level of relaxation, and the severity and chronicity of the injury.

- Also, the KT-1000 knee ligament arthrometer (MEDmetric Corp, San Diego, CA, USA) is a commonly used device to measure anterior-posterior translation of the tibia on the femur in millimetres (Küpper et al., 2007), with a sensitivity of 0.50 to 0.97 and specificity of 0.70 to 0.93 (Bach et al., 1990; Van Eck et al., 1989)

Regarding biomechanical assessments of the knee, Gwynne et al. (2014) reported moderate-to-excellent correlations (r = 0.64–0.78) between 2D and 3D analyses in the frontal plane of the knee during the single-leg squat. Figueroa Ayala et al. (2013) found similar results during the drop vertical jump (r = 0.82–0.97) between 2D and 3D analyses in the same plane. However, there are some limitations that impede the conduct of sport-specific measurements. For instance, laboratory assessments can provide highly accurate results, but they cannot fully replicate the realistic experience of playing sports (Svensson & Drust, 2005). For example, assessments are performed in the field for soccer fitness, such as the aerobic and anaerobic fitness tests, may provide greater specificity of the assessments while reducing the accuracy of the tests (Balsom, 1994; MacDougall & Wenger, 1991). Accordingly, transferring the measurement tools to the sports field can generate issues such as data inaccuracy due to the impact of the weather, device calibration, and the inability to fully control tasks that result in uncontrollable variability in outcome assessment (Bonnechère et al., 2014; Kiefer et al., 2017).

Typically, 3D motion analysis is the gold standard for assessing kinematics and kinetics of the lower limb due to providing information regarding the multi-planar biomechanics of joints (Schurr et al., 2017). Most motion capture systems are marker-based, and they include a set of infrared cameras for tracking markers, such as the Qualisys motion capture system, which is a gold-standard method that has been used in some studies to isolate biomechanical movement patterns with a skeletal representation of the subject on a computer display. For instance, Baskwill et al. (2017) used an eight-camera Qualisys motion capture system in a gait assessment module and compared it to the traditional gait assessment module. Also, Harato et al. (2021) used an eight-camera Qualisys motion capture system with forty-six retroreflective markers to examine the effects of fatigue and recovery on the knee biomechanics of the drop vertical jump in females. They reported that the impact of fatigue on drop vertical jump were more significant in female recreational athletes than in female collegiate athletes (Harato et al., 2021). Thus, these marker-based motion capture systems are suitable for full body motion capture and high-speed tasks due to having a larger capture volume and higher capture framerates. However, these systems are not practical in clinical settings and cannot used widely due to considerable setup costs and space requirements (Whittle, 2007; Mentiplay et al., 2015). Furthermore, marker tracking error can result into to poor approximations of the joints kinematics (Ackland et al. 2011). Recently, markerless motion capture systems such as the Microsoft Kinect (Microsoft, Redmond, US) has gained popularity in the biomechanics studies due to being less expensive and resource-intensive than marker-based systems. One of the markerless motion capture systems is the Azure Kinect (Figure 1), which was announced by Microsoft in 2019 to provide a portable and less expensive alternative for the accessibility of kinematic data (https://azure.microsoft.com/en-us/services/kinect-dk).

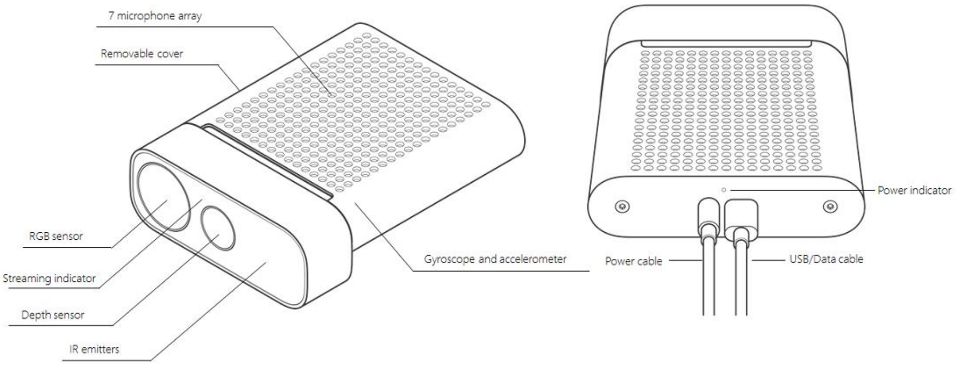


Figure 1. Azure Kinect (https://learn.microsoft.com/en-us/azure/kinect-dk/set-up-azure-kinect-dk)

The Azure Kinect sensor is capable of capturing human motion in real time without using any markers. It includes an RB camera and infrared (IR)- based depth sensor, which may represent a feasible alternative to more complex and expensive 3D camera setups (Brown Kramer et al., 2020). These cameras are capable of producing 3D images by capturing RGB colour images enriched with depth data at each pixel so they can be used to track real-time human motion (Napoli et al., 2017). Kinect V1 and V2 were the previous models of Microsoft Kinect, which were released in 2010 and 2014, respectively. Kinect V2 brought some upgrades compared to V1, such as higher accuracy in the depth map and decreased body detection distance between the player and the sensor from 2.4 m in Kinect V1 to 1.37 m. However, the body tracking of the Azure Kinect (the newest model) is more potent than the Kinect V2. The Azure

Kinect can detect any number of people on the scene, even with high occlusions, whereas Kinect V2 can only detect up to six people in front of the device when most of their bodies are visible.

Figure 2. From up to down Azure Kinect, Kinect v2, and Kinect v1 (Tölgyessy et al., 2021)

However, markerless systems have potential limitations. They might not be as accurate as marker-based systems, especially when tracking small or subtle movements, which can be a significant issue in applications that require high precision, such as sports performance analysis or surgical training. Also, markerless systems rely on computer vision algorithms to track movement, which can be more easily affected by occlusion, where one body part obscures another, causing inaccuracies in the movement data and requiring additional post-processing for correction. Moreover, the accuracy of a markerless system can be affected by environmental factors such as lighting, shadows, or reflections (Armitano-Lago et al., 2022; Colyer et al., 2018). These factors can interfere with the system's ability to detect and track movement accurately. In Chapter 3, the validity of the markerless Azure Kinect system against the marker-based Qualisys system, which is one of the gold standard motion capture systems, will be discussed.

1.5 Treatment and Rehabilitation of ACL Injuries

ACL reconstruction (ACLR) is considered a standard surgical approach for injured ACLs to restore knee stability after ACL injuries in athletes who aim to return to high-level activities (Marx et al., 2003). However, many studies showed asymmetries in multi-dimensional knee biomechanics (kinematics and kinetics) and impaired neuromuscular control after ACLR through daily activities (Arnason et al., 2014; Cordeiro et al., 2014; Gokeler et al., 2103). In fact, it is believed that the mechanical stability of the knee joint does not return to the same level as a normal knee, even with a successful ACLR (Gardinier ES et al., 2012). There are several sensory deficits after ACLR, such as impaired proprioception and postural control, which might be induced by disruption of mechanoreceptors and associated neuromuscular systems within the ACL, and they may increase the risk of re-injury (Courtney et al., 2004). According to Wiggins et al. (2016), the overall risk of re-injury following ACLR is around 15%, but the chance of ACL re-injury can also be increased to 30% within the first two years after returning to sports in younger athletes (Paterno et al., 2014). Therefore, while surgical aspects are critical for treating ACL injuries, post-surgery rehabilitation also plays a significant role in helping athletes return to play, and inappropriate rehabilitation can ruin the best surgically reconstructed ACL (Wright et al., 2015). However, conventional rehabilitation programmes following ACLR may not effectively address these deficits related to the initial injury, and a comprehensive rehabilitation programme is crucial for patients to achieve full recovery after ACL injuries (Lee et al., 2009). In fact, conventional rehabilitation programmes consist of primarily structured and repetitive exercises, which are often considered a tedious method for treatment and may elicit a loss of motivation due to being time-consuming (Karakoç et al., 2019). Conventional ACL rehabilitation usually involves repetitive exercises, starting with prone hanging exercises to achieve full knee extension, closed kinetic chain flexion exercises to accomplish flexion and isometric training to improve quadriceps control, followed with many resistive knee exercises and jogging, which were allowed weeks after to 6–8 months after surgery. (Baltaci et al. 2013, Cooper et al. 2005, Yosmaoglu et al. ,2011). Most patients do not participate in such conventional rehabilitation programmes for an extended period, which makes these programmes ineffective in the long run, and only a low rate of functional improvement is achieved as they are considered a pointless waste of time by patients. Indeed, the specificity or intensity of the exercises in the rehabilitation programme is not usually the same as the athletes do in their specific sports and often is insufficient for provoking a response (Indorato et al., 2016). Thus, an alternative approach and a different strategy should be implemented to overcome the issues often found in traditional rehabilitation programmes. Accordingly, the gap between motor learning concepts and conventional rehabilitation induced researchers to employ advanced technologies to imitate the altered movement patterns of real-life conditions, provide accurate measurement of physical activities and improving the effectiveness of treatments after ACLR (Gokeler et al., 2013). A systematic review has been conducted in Chapter Two and showed the effect of immersive technology and virtual reality-based treatment on the improvement of rehabilitation outcomes, such as the range of motion (ROM), proprioception, balance, and functional status.

1.6 Return to play

There is a significant issue among athletes following a prolonged sports injury, which is a quick return to play, and it needs to be settled by the appropriate collaboration of the athlete and clinicians in order to develop a competent rehabilitation strategy for the improvement of the athlete's motor functions (De Araújo et al., 2019). Therefore, the adverse effects of a prolonged absence of athletes from training must be considered alongside providing appropriate rehabilitation for the athletes (Bianco et al., 1999). In 2015, the annual cost of ACL reconstruction to the NHS was between £63-£85 million. Besides, rehabilitation had a cost burden on the NHS (Beard et al., 2022). Many athletes never return to the same performance level, while re-injury and osteoarthritis rates remain high (Connell et al., 2019). The return-to-play outcomes after ACLR is unacceptable because 35–45% of patients cannot return to sport following ACLR (Ardern et al., 2011). Even in professional athletes, the rate of returning to sport is 20–25% (Lai et al., 2018). One reason is an increased risk of re-injury following ACLR (Grindem et al., 2016). The overall risk of re-injury following ACLR is around 15% (Wiggins et al., 2016). However, the chance of ACL re-injury can be increased to 30% within the first two years after returning to sports in younger athletes (Paterno et al., 2014). Accordingly, it is assumed that current rehabilitation approaches are not comprehensive and specific enough to fully prepare athletes for their sport (Buckthorpe, 2019). Indeed, returning an athlete to the sport after ACLR is challenging and requires a bio-psycho-social approach (Ardern et al., 2016). Therefore, the criteria for return to play after ACLR and functional recovery programmes need to be improved. The criteria for evaluating RTS readiness are mainly based on subjective opinions, and the importance of each of these criteria may depend on the individual (Dingenen & Gokeler, 2017). Barber-Westin and Noyes (2011) conducted a systematic review of studies published between April 2001 and April 2011 in which 40% of studies provided no criteria for RTS after ACLR, 60% used time after ACLR as one of the RTS criteria, and 32% used time postoperatively as the only criterion. Furthermore, Burgi et al. (2019) conducted a systematic review and categorised RTS criteria into six domains, including time, muscle strength, clinical examination, hop testing, patient report and performance-based criteria. In this systematic review, time was used in 85% of included studies and was the only RTS criterion in 42% of papers. Strength tests were used in 41%. Hop tests were reported in 15% of studies. Also, Clinical examination in 26%, patient reports in 12% and performance-based criteria in 20% of studies were reported. Therefore, time after ACLR is the most used RTS criterion (Dingenen&Gokeler, 2017; and Burgi et al., 2019). However, there is still no consensus on the ideal time frame for RTS postoperatively. Dingenen & Gokele (2017) showed that returning to sport before finishing nine months after ACLR could increase the risk of ACL re-injury. Accordingly, Gokeler et al. (2016) indicated altered movement patterns in patients after ACLR, even after they were cleared for RTS. Furthermore, they revealed that immersive technologies such as virtual reality could assist in assessing realistic movement patterns in patients postoperatively and enhance rehabilitation programme to meet the criteria of RTS. Gokeler et al. (2016) also reported that using clinically feasible technology in rehabilitation programmes may enhance the assessment and rehabilitation of motor learning capabilities to decrease the risk factors for second ACL injury.

In the section below, an overview of immersive technologies and virtual reality is explained, and later in chapter three, the validity of one type of immersive technologies against the gold standard method for motion capture and tracking body movements will be explained. Also, the effect of immersive interventions on the biomechanics of sports movement and performance has been discussed in a systematic review in chapter two.

1.7 Immersive technologies

One of the most promising technologies used to assess joint movement is immersive technologies such as virtual reality (VR), augmented reality (AR) and extended reality (ER). Immersive technology can create an interactive three-dimensional environment similar to real life. It can use visual, auditory, and somatosensory stimuli to help patients interact with an artificial virtual environment while enabling health professionals to monitor and evaluate their progress (Kizony et al., 2005; Bohil et al., 2011).

1.7.1 Definition and Types of Immersive Technology

Immersive technologies combine the physical world with digital or simulated reality to develop distinct experiences. The two main immersive technologies are augmented reality (AR) and virtual reality (VR). The difference between these technologies is that AR blends computer-generated information into the user's real environment, while VR uses computer-generated information to provide a full immersion sense. Indeed, AR combines the real world and virtual computer-generated objects to provide a hybrid form of visualisation (Choi, 2016, Kamphuis et al., 2014). In the following section, VR technologies will be discussed in detail because they seem to be preferable to AR interventions in rehabilitation studies due to some reasons, such as the high costs of AR glasses, the low level of performance in most AR devices, and the requirement for more free space while using the AR-based rehabilitation. Accordingly, augmented reality uses the current and real environment to overlay information and virtual objects, unlike virtual reality, which creates an entirely artificial environment (Chavan, 2016).

1.7.2 Virtual Reality

VR systems use head-mounted displays (HMD) to provide a sense of immersion. Immersion levels are categorised by the number of senses excited by the system to create a sense of reality in a computer-generated environment. HMD cover the user's field of view to display computer-generated content and allows the user to interact with the virtual environment. Based on levels of immersion, VR systems have three types: non-immersive, semi-immersive and immersive. Non-immersive technology only stimulates the limited senses of users, and the user can maintain awareness of the physical environment outside of the virtual reality, and usually, the interaction with the virtual environment occurs with a monitor, keyboard and mouse. Finally, in a fully immersive VR technology, the patients are fully engaged in the virtual environment by the application of an HMD to project an entire visual scene that covers all aspects of a patient's visual fields in order to generate an interactive three-dimensional environment for the patients (Baus and Bouchard, 2014). The immersion in virtual reality can range from 3D computer games to a fully immersed experience using head-mounted displays. In the full-immersive environment, the user is presented as an avatar, and this 3D image of the player acts in the VR environment (Ogourtsova et al., 2017). Also, VR applications are even available in smartphones and have become more affordable and available these days (Lohse et al., 2014; Ogourtsova et al., 2017). In 2005, Kizony et al. used virtual reality technologies to create an interactive three-dimensional environment (similar to real-life situations) for balance training in patients with paraplegic spinal cord injuries, and found correlations between performance in a VR environment and static balance ability. Indeed, VR is composed of a head-mounted display and a tracking system in which every change of the head or body position generates a corresponding movement in the virtual setting (Yeo et al., 2019). Recently, various types of immersive technologies have been applied for training and rehabilitation purposes due to their ability to enable patients to achieve experiences that are hazardous in real and physical environments (Cao, 2016). Also, it is believed that VR-based rehabilitation has some benefits in comparison to conventional rehabilitation, such as enhanced motivation, increased dynamic engagement, and a more comprehensive range of exercises that can be designed for patients in the VR environment (Dimbwadyo-Terrer et al., 2016). Indeed, entertaining activities such as video games are more attractive to patients than structured and repetitive activities in exercise therapy, which are usually considered boring. Therefore, VR-based rehabilitation, combining video games and exercise therapy, can improve physical activity behaviour (Qian et al., 2020), and it can be an effective method for developing motor and cognitive therapy in adults and children (O'Neil et al., 2013). Also, VR-based training has provided a new approach for increasing long-term adherence to exercise to promote the psychological benefits of exercise (Mestre et al., 2011). Immersive technology can replicate sensory experiences with visual, auditory, and touch stimuli to help users control the objects within a virtual environment (Pasco, 2013).

However, VR systems have potential limitations and challenges, such as restricted accessibility to high-quality hardware and software due to their high costs, the requirement for a safe physical space, and several health concerns, including motion sickness, eye strain, fatigue and social isolation associated with prolonged usage (Baniasadi et al., 2020). Many studies have explored the impact of VR-based exercise on physiological, psychological, or rehabilitative outcomes of patients with neurological conditions, whereas few studies exist on sports-related injuries. (Lee et al., 2016). Therefore, it is noteworthy to study the potential of using immersive technologies in the performance and rehabilitation outcomes of patients with sports injuries to explore whether immersive technology can be adopted as a motivating technique for improving rehabilitation and performance. (Lee et al., 2016).

1.8 Summary and Conclusion

Although anterior cruciate ligament reconstruction (ACLR) remains the standard treatment for ACL injuries in athletes who seek to return to competitive sports (Marx et al., 2003), it is not equal to the restoration of normal knee function (Gardinier et al., 2012). Indeed, asymmetries in neuromuscular control during daily tasks and multidimensional knee biomechanics are repeatedly reported after ACLR (Castanharo et al., 2011; Arnason et al., 2014; Cordeiro et al., 2014; Gokeler et al., 2103). Therefore, rehabilitation plays a significant role in helping athletes return to sports activities, and inappropriate rehabilitation can even devastate a satisfactory ACLR (Wright et al., 2015). However, conventional rehabilitation programmes may not effectively address these deficits because conventional rehabilitation programmes consist primarily of structured and repetitive exercises, which are considered a tedious method for treatment and may elicit a loss of motivation for patients (Lee et al., 2009). Thus, an alternative strategy should be implemented to overcome the issues often found in traditional rehabilitation programmes. Virtual reality can offer a controlled laboratory environment with a simulation of real-world contexts to assess biomechanics and performance more rigorously to reduce risk factors for a second injury (Kiefer et al. 2017; Gokeler et al. 2016). In 2016, Gokeler et al. found that knee joint biomechanics in patients with ACLR are more significantly affected by the VR environment compared to the control healthy group. Further, DiCesare et al. (2019) assessed biomechanical deficits for lower-limb injury in a sport-specific context created by VR technology and offered a promising approach for future injury prevention. This dissertation consists of two studies, including a systematic review in Chapter 2 that explores the research conducted on the application of immersive technologies for improving the outcome of the rehabilitation phases after ACL reconstruction and examines the correlation between virtual reality, rehabilitation, exercise therapy, and sport-related ACL injuries in patients. The second study in Chapter 3 validates the Microsoft Azure Kinect camera for body tracking of dynamic movements against the gold standard Qualisys system. Finally, Chapter 4 summarises the findings and conclusions of these two studies.

1.9 Aim and Research Questions

1.9.1 . Aim

This research aims to explore the extent to which immersive technologies, including virtual reality and augmented reality, can improve performance, biomechanical assessment, and rehabilitation outcomes in patients with ACL reconstruction.

1.9.2 Research questions

- How are immersive technologies being applied in assessing and monitoring the lower limbs' biomechanics and performance?

- How do immersive technologies, such as virtual reality (VR) and augmented reality (AR), influence the post-operative performance levels of patients who have undergone ACL reconstruction?

- How do immersive technologies and virtual-based rehabilitation affect rehabilitation outcomes in people after ACL reconstruction?

- Can we identify a novel approach to improve the performance, biomechanical assessment and rehabilitation outcome through virtual reality technologies?

1.9.3 Objectives

1- To Conduct a systematic review to evaluate current evidence and the research methods conducted on the application of immersive technologies to performance and rehabilitation outcomes in patients with ACL reconstruction.

2- To conduct an experiment to investigate the validity of the Azure Kinect against the gold standard motion capture system called Qualisys

Chapter Two:

The application of immersive technologies to the rehabilitation outcomes after ACL reconstruction: a systematic review

2.1 Introduction

Anterior cruciate ligament (ACL) injuries are multifactorial and are thought to be caused by a combination of various intrinsic and extrinsic risk factors such as environmental, biomechanical, anatomical, age, genetic variants, hormonal factors, and history of previous injuries (Silvers HJ et al., 2007). Among the modifiable ones, neuromuscular and biomechanical factors such as proprioception, muscular strength, knee and hip flexion, knee abduction and adduction, ankle stability, rotation of the hip and the tibia, neuromuscular control and core strength have been widely studied and may be significant components of the mechanisms which lead to the increased rate of ACL injuries and reinjuries (Hewett et al., 2005; Bisciotti et al., 2019; Wetters et al., 2016). Other studies indicate that prevention programs focused on muscle strengthening, plyometrics, and neuromuscular training (improving jumping and landing technique) could significantly reduce ACL re-injury rates (FR Noyes and SD Barber-Westin, 2011). Anterior cruciate ligament reconstruction (ACLR) continues to be the standard surgical treatment to restore stability of the knee for ACL injuries in athletes who aim to return to high-level activities (Marx et al., 2003). However, restoration of the mechanical stability of the knee joint does not remain the same as the normal knee even after successful ACLR (Gardinier ES et al., 2012). Many studies report asymmetries in multi-dimensional knee biomechanics (kinematics and kinetics) and neuromuscular control after ACLR through daily activities (Arnason et al., 2014; Cordeiro et al., 2014; Gokeler et al., 2103). Also, a few studies report the biomechanical risk factors for ACL injuries and indicate that sagittal plane factors contribute to the mechanism of ACL injury. For instance, Alentorn-Geli et al. (2009) indicated that higher joint flexion of the lower extremities during landing could cause greater absorption of energy in muscles, transmitting less energy to passive components of the knee. Besides that, Hashemi et al. (2011) indicated the probability of a significant ACL loading mechanism after a high external hip flexion moment in the transverse plane. Furthermore, Leppänen et al. (2017) stated that higher peak external knee flexion moment and decreased hip flexion during landing could increase the risk of ACL injury among young female sports players. Also, it is suggested that hip abductors might help facilitate control of hip flexion during the landing after ACLR (Tate et al., 2017). After ACLR, there are several sensory deficits such as impaired proprioception and postural control, which might be induced by disruption of mechanoreceptors within the ACL and associated neuromuscular systems, which may increase the risk of reinjury (Courtney et al., 2004; Howell, 2011).

Traditional rehabilitation programmes after ACLR may not be optimally effective in addressing deficits related to the initial injury (Lee et al., 2009). There is a gap between motor learning concepts and conventional rehabilitation Gokeler et al. (2013), due to lack of appropriate measurement technology to understand altered movement patterns in real-life situations. One of the most promising technologies to achieve this are immersive technologies such as virtual reality and augmented reality which can utilise visual, auditory, and somatosensory stimuli to assist the patients in moving and interacting with a virtual environment while enabling the health professionals to monitor and evaluate progress. Immersive technology can create an interactive three-dimensional environment that is similar to real-life situations (Kizony et al., 2005). It is composed of a head-mounted display and a tracking system in which every change of the head or body position generates a corresponding movement in the virtual setting (Yeo et al., 2019). Therefore, this technology, such as virtual reality (VR), can promote balance control and gait recovery in tailored contexts after complicated injuries (Chen et al., 2009). Recently, it has been indicated that VR technology can be applied for training and rehabilitation purposes due to support patients to achieve ecologically valid experiences (Cao, 2016). Accordingly, Dimbwadyo-Terrer et al. (2016) revealed that VR-based rehabilitation has some advantages over conventional rehabilitation, including enhanced motivation, increased engagement and the wide range of exercises that can be implemented for the patients in the VR environment. Although the high cost of these VR systems restricted their accessibility to the public before, the development of technology has led to more affordable systems for measuring and developing rehabilitation interventions. For instance, the release of the Microsoft Kinect camera and Software Development Kit (SDK) introduced a low-cost method for capturing a 3D skeletal model of an individual and the joints' positions without the need for wearable reflective markers. Numerous papers studied the accuracy of both the Kinect sensor camera and the characteristics of the skeletal model by using different tasks in a variety of fields. For instance, Stone and Skubic in 2011 used the Kinect to measure gait parameters, including walking speed, stride time and length for fall risk assessment and in-home gait monitoring. Also, another study evaluated the Kinect skeletal model to capture four biomechanical measures during the Drop Vertical Jump (DVJ) task, which were useful in screening for future ACL injuries (Stone et al., 2013). In recent years, the literature about VR technology as a new rehabilitation method has also expanded because the VR environment can produce real-time feedback and more sensory stimulation during specific motor tasks (Adamovich et al., 2009). Indeed, training and exercise therapy in a VR environment is the initial stage of the journey to retrain the coordination and balance abilities of the patients (Burdea and Coiffet, 1994). However, VR can be considered as a complementary treatment to traditional rehabilitation therapies in the future (Adamovich et al., 2009).

This systematic review sets out to pull research together conducted on the application of immersive technologies as interventions for improving biomechanical factors associated with ACL injury and the outcome of rehabilitation after ACL reconstruction. The primary outcome of this systematic review is to describe the extent of the evidence of the effect of immersive technologies such as VR as an intervention on lower limb biomechanics and performance. The secondary outcome is to describe the evidence of the effect of immersive technologies as an intervention on rehabilitation outcomes in adults and young people after ACLR (Anterior cruciate ligament reconstruction).

2.2 Method

This study explored the literature in 5 databases, including PubMed, SPORTDiscus, Web of Knowledge, the Cochrane Library, and CINAHL. The search of these electronic databases was performed by search terms shown in Table 1, and the search was updated in November 2021. The search strategy was built around the relationship between immersive technologies, including virtual reality, augmented reality, mixed reality, extended reality, 360 video and anterior cruciate ligament rehabilitation after ACL reconstruction. Five researchers were involved in this study. Two researchers independently screened the papers' titles and abstracts, and a third reviewer checked and resolved any issues while any discrepancies happened. Finally, the full text of the studies that met the eligibility criteria was reviewed by the same procedure. This study was conducted following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, a standard reporting guideline initially developed in 2009 to improve the transparency and quality of reporting in systematic reviews and meta-analyses. By providing a structured format for researchers to follow, PRISMA assists in reducing bias, increasing transparency, and enhancing the effectiveness of the reported research findings. Also, PRISMA provides an evidence-based approach to assess the advantages and disadvantages of a healthcare intervention (Liberati et al., 2009). The protocol of this study was registered with PROSPERO. [CRD42020198834].

Table 1. Search terms for Identified Keywords

Keywords	Search Terms
Immersive technologies	virtual realit* OR augmented realit* OR mixed realit* OR extended realit* OR "360 video" OR "computer simulation" OR video game OR exergame OR virtual environment OR serious game OR immersive environment OR "Xbox Kinect" OR Wii OR Nintendo OR “VR” OR “AR” OR “gaming”.
Intervention	Neuromuscular train* OR “NMT” OR “balance” OR propriocept* OR “functional performance” OR “physical performance” OR “outcome” OR assess* OR measure* OR kinematic* OR biomechanic* OR “biofeedback” OR postural control* OR rehab* OR therap* OR treatment* OR prevent*, OR walking* OR motion* OR movement* OR weight-bearing* OR train* OR exercise* OR “performance” OR physical activity* OR “activity”.
Sport-related	sports injur* OR contact injur* OR competit* OR sports trauma OR sport* OR athlete* OR athletic
ACL	“anterior cruciate ligament” OR “ACL” OR “cruciate ligament” OR “ACLR” OR “ACL reconstruction” OR knee ligament*.

2.2.1 Eligibility Criteria

There was a set of conditions that must be met to acknowledge the literature to be included in the study (Fineout Overholt et al., 2011). The studies that measured the effect of immersive technologies such as VR, AR, Kinect camera, and Nintendo Wii on performance and rehabilitation outcomes after ACL reconstruction in adult and young participants with first-time injuries were included. Also, Searches were restricted to journal publications on humans, but there was no restriction for age, and only literature published in the English language was included due to time limitations for this study and constraints for the translation of the studies. These criteria were derived from the literature review and the consensus opinion of experts. The following inclusion criteria were used to perform a relevant and rigorous search strategy in this paper: Interventional studies, Peer-reviewed journal articles, English language articles, Studies including at least one of the immersive technologies, and Observational research including Cohort studies, Randomised Control trials, descriptive laboratory studies, case-control studies, and cross-sectional studies. Also, any article which did not meet the inclusion criteria was excluded from the study. Reviews and conferences were also excluded.

2.2.2 Data Extraction

Two independent reviewers (AA and SL) collected data using a customised Excel® spreadsheet to create a standardised data extraction form to record information about the papers, including the name of the first author, the country where the study was conducted, year of publication, method of recruitment, sample size, comparability of groups, age (mean and range), sex, characteristics of the immersive technologies, study design and settings, type of clinical study, primary and secondary aims, intervention and control groups, primary and secondary outcomes, data analysis, conclusion, and results for each study. To create the VR guidelines, the following characteristics of immersive technologies and VR were collected: type of VR (immersive or non-immersive), type of the VR device (commercial or developed by authors), number of sessions, the positive or negative effects of VR interventions based on statistical significance when $p < 0.05$. The structure of interventions for VR and the control group was elaborated with details in the "Method of Study / Intervention" section, and the specific virtual environments used, the duration and frequency of exposure, and any accompanying procedures or tasks within the VR environment, such as cognitive tasks or physical exercises, were outlined. Additionally, the nature of the control group activities and the duration and frequency of these activities were comprehensively described. This detailed structure provided a clear comparison between the VR and control groups. Furthermore, the "Measurement tools" section highlighted the technical aspects, specifying the types of VR hardware and software utilized in the study to ensure a clear understanding of the technological backbone supporting the VR interventions.

2.2.3 Risk of Bias

The risk of bias and the quality of included studies was assessed by the JBI (Joanna Briggs Institute) critical appraisal checklist. A set of questions collects information about characteristics of the clinical trial studies that are relevant to the risk of bias. For the overall assessment of the risk of bias in each study, the risk of bias was classified as “high,” “low,” or “moderate” based on sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, selective outcome reporting, and other bias (Table 3). Selected studies were assessed for methodological validity prior to inclusion in the review using standardised critical appraisal tools (Critical Appraisal Checklist for Randomized Control Trial) from JBI (Joanna Briggs Institute, 2014. The JBI tool for Randomized Control Trial (RCT) is composed of 13 questions regarding the study design, with the option to answer ‘yes’, indicating higher quality; ‘no’, indicating poor quality; or ‘unclear’. Accordingly, high quality (low Risk of Bias) When a study earns more than 70% of “yes” scores, Moderate quality When a study reached from 50 to 69%, and Low quality (High Risk of Bias) When a study earns less than 49% of “yes” scores. Any discrepancies in judgments regarding scores were resolved through discussion with the authors. The results of the appraisal process are indicated in Table 3.

2.2.4 Data Synthesis and Analysis

A descriptive synthesis of the findings was performed for this systematic review, and an extraction table was constructed from the included studies. The collected data from the tables were used to compare the study details, analyse, and summarise the results. Two researchers independently went through the studies from the beginning, and any discrepancies were resolved by a third reviewer and any discrepancy resolved through discussions at a group meeting. The extracted data from the articles for meta-analysis were analysed by a forest plot using mean differences (MD) and standard deviation (SD) in the ESCI software (Exploratory Software for Confidence Intervals). ESCI is a set of tools for exploring statistical concepts and using the estimation approach to analyse data (https://thenewstatistics.com/itns/esci/).

2.3 Results

2.3.1 Selection of Studies

The initial search procedure retrieved 2179 studies. Then, 77 duplicate papers were removed, and 2102 articles remained. Following a search on Google Scholar, an additional 23 studies were identified, which were reduced to 4 after duplicate removal. Thus, 2016 papers remained for screening. Following title and abstract screening, 2056 papers were excluded on the basis of title, 10 papers were excluded based on abstract screening, and 40 articles remained. Also, another ten studies required third-reviewer judgment; one was deemed eligible, and nine were excluded. Therefore, 2075 studies were totally removed, and 31 articles remained to be reviewed through the full text to determine eligibility for inclusion. In the full-text review, one paper was excluded because the full text was not found, and 15 other articles were excluded because they were either not interventional or not related to ACL. Finally, fifteen studies that met the inclusion criteria were included in the quality assessment and qualitative synthesis (Figure 1).

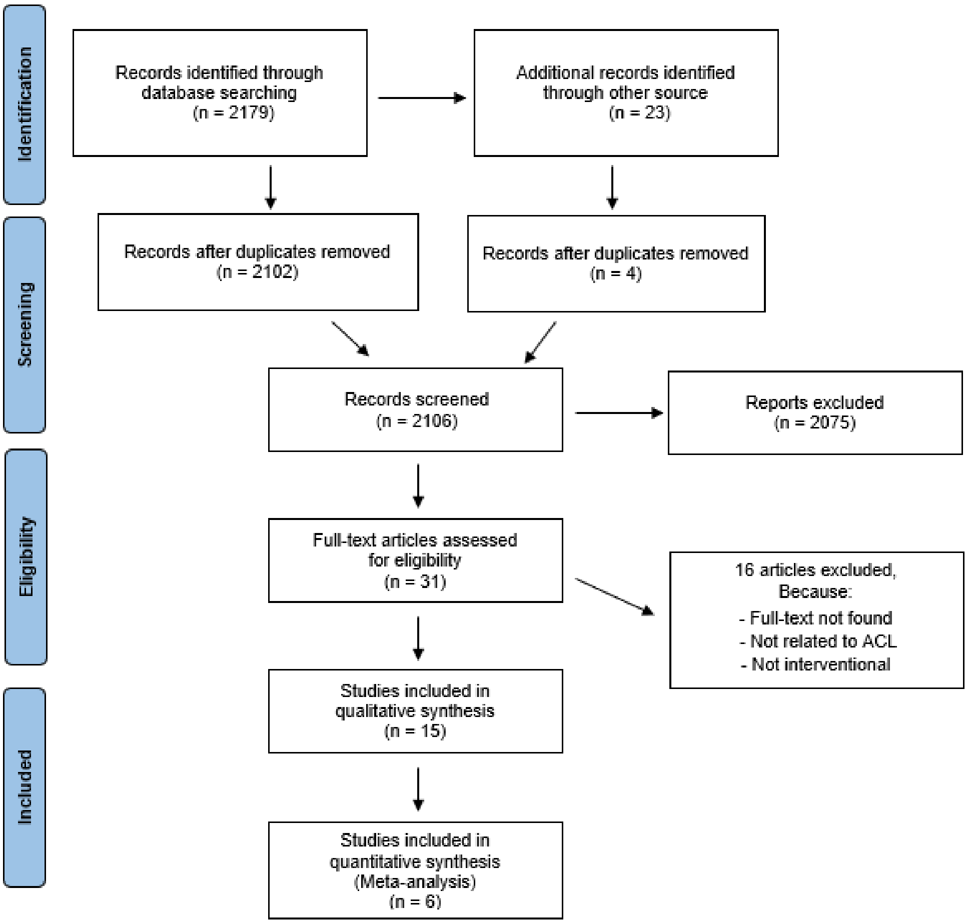


Figure 1. A flow diagram showing article selection, screening, and exclusion**.**

2.3.2 Characteristics of Included Studies

The Characteristics of included studies are presented in Table 2 below. The studies that measured the effect of immersive technologies on biomechanical factors and performance (six studies) and rehabilitation outcomes (nine studies) after ACL reconstruction in adult and young patients with first-time injuries were included. In terms of the type of study, all fifteen studies were RCT (Randomised Controlled Trials). Regarding the type of immersive technologies, one paper applied Microsoft Kinect (Shah et al., 2015); four studies used Nintendo Wii (Baltaci et al., 2013; Karakoc et al., 2019; Lee et al., 2016; McGough et al., 2012), one article used augmented reality (Adams et al., 2020), one employed semi-immersive technology with 3d-TV (Ford e et al., 2017), and eight applied VR headsets as a type of technology (Aydogdu et al., 2017; DiCesare et al., 2019; Gokeler et al., 2014; Gokeler et al., 2016; Kiefer et al., 2019; Prvu Bettger et al., 2020; Thomas et al., 2016; Thomas et al., 2016). The countries of the studies in descending order were: six in the USA, two in the Netherlands and Australia, three in Turkey, and one paper in India and South Korea.

Based on available demographic data, the total number of participants in these studies was 645, with 47.7 % men and 52.2 % women. Unfortunately, the number of participants was not available for one study (Shah et al., 2015). The sample sizes in the included studies ranged from 12 to 306, with an average of 46 participants. There was a diversity in the comparison groups, and it occasionally was not clearly described. However, most of the studies compared conventional rehabilitation and measurement methods after ACL reconstruction with immersive technologies-based rehabilitation and measurements. Also, preparation for the intervention and procedure such as informative videos, verbal briefings and familiarisation techniques were different. A comprehensive description of the studies is provided in Table 2.

Some of the reviewed studies measured numerous biomechanical factors such as Peak Patellar Tendon Force (Adams et al., 2020), Vertical Ground Reaction Force (Gokeler et al., 2014 and 2016), Knee Moment (Adams et al., 2020; Gokeler et al., 2014 and 2016), Ankle Dorsi/Plantar Flexion (Thomas et al., 2016), Knee abduction and adduction (Kiefer et al., 2019). Also, nine studies looked at Knee flexion, two papers measured Hip abduction and adduction, five studies looked at Hip flexion, one paper examined the Center of Gravity (COG), and two studies looked at the Centre of Mass (CoM). There were other studies that measured Lower Extremity Functional Score (LEFS), Balance Score, Star Excursion Balance Test (SEBT), Knee flexor and extensor muscle strength, Response time, Active Range of Motion, Coordination and Proprioception test, Mean Mass Difference (MMD), Absolute and relative symmetry Index (SI), Hip extensor moment, and International Knee Documentation Committee Score (IKDC).

Table 2. Characteristics of studies

Author	Type of Technology	Measurement tools	Participants	Method of Study / Intervention	Results	Outcome
Adams et al., 2020	Augmented reality (immersive)	- Microsoft HoloLens smart glasses - 14-camera Vicon Motion Analysis System (Oxford Metrics Ltd, Oxford, UK). - 600x900mm force plates (9287BA; Kistler Instrumente, Winterthur, Switzerland)	M: 12 Mean age: 18.8 ± 3.21	The laboratory testing area included a net to provide visualisation for landing positioning and a hanging ball used to hit the two testing conditions with AR and without AR. The 30 reflective markers were used on the participants' lower limbs.	- Statistical differences in peak jump height when comparing drop landing with the hop jump (P < 0.001, Cohen’s d = 0.46), spike jump (P < 0.001, Cohen’s d = 0.22), and AR spike (P < 0.001, Cohen’s d = 0.18). - Differences in Peak knee moment presented when comparing the drop landing condition with the hop jump (P = 0.003, Cohen’s d = 2.73), spike jump (P = 0.001, Cohen’s d = 1.49), and AR spike (P = 0.005, Cohen’s d = 1.79). Large statistical differences in ankle angle at the start of the landing phase when comparing the hop jump with drop landing (P < 0.001, Cohen’s d = 1.45), spike jump (P < 0.001, Cohen’s d = 2.19), and AR spike (P < 0.001, Cohen’s d = 2.26). - Differences in hip flexion when comparing the drop landing with AR spike (P = 0.022, Cohen’s d = 1.59).	AR can replicate biomechanical outcomes designed to be task representative because there were no differences in landing forces between the spike jump and the AR spike jump.
Aydogdu et al., 2017	Virtual reality (immersive)	Virtual rehabilitation system known as MarVAJED device	M:13 / F:2 Mean age: 23.36 ± 6.76	A virtual rehabilitation treatment was applied to 15 ACLR patients with visual and auditory stimulus for a total of 8 weeks. Visual and auditory stimuli were applied via the MarVAJED® system, and pain intensity, proprioception, ROM (range of motion), and knee swelling were measured before and after intervention	Significant improvements in measures of - Knee Proprioception (Degree, mean ± SD) in pre-treatment and post-treatment were 6.64 ± 2.48 and 3.29 ± 1.75. (P1: 0.001), - Range of Motion (Flexion Degree, mean ± SD) in pre-treatment and post-treatment were 118 ± 7.94 and 130.02 ± 3.66 respectively.(P1: 0.001) - Pain Intensity (Cm, mean ± SD) in pre-treatment and post-treatment were 4.53 ± 1.79 and 2.56 ± 0.39 respectively.(P1: 0.001) - Knee Swelling (Cm, mean ± SD) in pre-treatment and post-treatment were 2.63 ± 1.51 and 0.93 ± 0.24 .(P1: 0.001)	New VR system (MarVAJED) effectively treated ACL patients by improvements in measures of proprioception, range of motion, pain intensity, and knee swelling between pre– and post-treatment

Baltaci et al., 2013	Nintendo Wii (Semi-immersive)	- Hardware: Nintendo Wii Fit system and Balance Board - Software: 4 Nintendo Wii games with having potential to influence various subject outcomes such as physical and functional movement, cognitive functioning was chosen and included bowling, skiing, Boxing and Football	M: 30 Wii Fit Rehab: 15 mean age: 29 ± 7- Conventional Rehab: 15 Mean age: 29 ± 6	30 volunteer who underwent ACLR with hamstring tendon graft by the same surgeon, were enrolled in either Wii Fit or conventional rehabilitation programmes from the 1st week up to 12th weeks after the operation. Coordination, response time, proprioception, knee muscle strength and SEBT (star excursion balance test) were evaluated at first week, 8th and 12th weeks of rehabilitation.	Significant differences reported in the - Anterior division of SEBT between 1st and 8th weeks (Wii: p=0.004, Conventional: p=0.039) and between 1st and 12th weeks (Wii: p=0.019, Con: p=0.016). - Posteromedial division of SEBT between 1st and 8th weeks (Wii: p=0.004, Con: p=0.005) and between 1st and 12th weeks (Wii: p=0.006, Con: p=0.02). - Proprioception first movement deviation deficit (PFMDD) between the 1st and 12th weeks (Wii: p=0.032, Conventional: p=0.012). - coordination test between 1st and 8th weeks in the Wii group (p=0.017)	There was no significant difference between Wii Fit and conventional group in terms of isokinetic knee strength, dynamic balance, coordination, proprioception, and response time at first, 8th and 12th weeks of the rehabilitation
DiCesare et al., 2019	Virtual Reality (immersive)	Hardware: VR System and HMD Software: VR-based, soccer-specific corner kick Game	F: 22 Mean age: 16.0 ± 1.4	a VR-based soccer-specific corner-kick scenario for the athletes jump to head a virtual soccer ball and land. The landing performance was analysed for a drop vertical jump task.	There are statistically significant reduced hip flexion and abduction, ankle dorsiflexion and inversion, , and frontal plane ankle excursion during landing in realistic sport scenario compared with the standard drop vertical jump task.	Hip, knee, and ankle joint kinematic differences in the frontal and sagittal planes.
Ford e et al., 2017	Virtual reality (semi-immersive)	Hardware: Two oversized force platforms 14 digital high-resolution cameras (Raptor-12, Motion Analysis Corporation Software: M10 Virtual overhead Goal by 3D motion analysis system	F: 14 Mean age: 18.8 ± 1.1	43 retroreflective markers placed directly on the subjects. Each subject performed vertical jumps to define the target jump height during the Deep Vertical Jump trials (DVJ). Subject performed 3 trials of the DVJ with a randomized a physical overhead goal (POG) and virtual overhead goal (VOG).	Maximum jump height during DVJ were similar between the VOG and POG conditions (P = .733, effect size 0.018). The centre of mass (COM) displacement from standing to maximum vertical displacement was 40.8 ± 5.7 and 40.7 ± 5.6 cm during VOG and POG Peak hip extensor moment and hip joint moment impulse were significantly greater with the virtual target. (P < 0.001, effect size 0.457 and P = .004*, effect size 0.313) Increased hip flexion at initial contact was found during VOG. (P = .014, effect size 0.268). Hip energy absorption, Knee kinetic variables and Maximum hip flexion angle were not statistically different.	A virtual target can optimize jump height and promote increased hip moments and trunk flexion
Gokeler et al., 2014	Virtual Reality (immersive)	Hardware: VR System and HMD Software: Virtual reality environment	ACLR subjects:20 M:10 / F: 10 mean age: 23.5 ± 4.3. Control:20 M:10 / F: 10 mean age: 22.7 ± 2.3	Each participant was fitted with 11 retroreflective markers and underwent motion analysis during a step-down task from a 20 cm high box onto two force plates in both a non-VR environment and in a VR environment to measure Knee joint biomechanics during each single leg landing.	- Significant main effect was found for environment for knee flexion excursion (P = 0.031). - Significant interactions differences between environment and groups for vertical ground reaction force (GRF) (P = 0.004), knee moment (P < 0.001), knee angle at peak GRF (P = 0.011) and knee flexion excursion (P = 0.032). - In virtual reality environment knee biomechanics of patients after ACLR increased more than those of controls.	Knee joint biomechanics for ACLR Patients after immersion in a virtual reality environment resemble the control group.

Gokeler et al., 2016	Virtual Reality (immersive)	Hardware: VR System and HMD Software: Virtual reality environment	Total: 40 ACLR subjects:20 M:10 / F: 10 mean age: 23.5 ± 4.3 Control subjects:20 M:10 / F: 10 mean age: 22.7 ± 2.3	Each participant was fitted with 11 retroreflective markers and underwent motion analysis during a step-down task from a 20 cm high box onto two force plates in both a non-VR environment and in a VR environment to display a pedestrian traffic scene. The 3D marker positions were captured by the Vicon motion analysis system including 12 cameras to measure kinematics and kinetics during a step-down task	- Significant main effect was found for environment for knee flexion excursion (P =0.03). - Significant interaction differences were found between environment and groups for vGRF (P = 0.004), knee moment, (P < 0.001), knee angle at peak vGRF (P = 0.01) and knee flexion excursion (P = 0.03). There was larger effect of virtual reality environment on knee biomechanics in patients after ACLR compared with controls. - GFR in ACLR group for NVR and VR: 1.4 ± 0.3 , 1.5 ± 0.3 - Knee moment in ACLR group for NVR and VR: 1 ± 0.5, 1.2 ± 0.5 - Knee angle at peak vGRF in ACLR group for NVR and VR: 27 ± 8.7 , 28.1 ± 7.6 - Knee flexion excursion n ACLR group for NVR and VR: 12.6 ± 4.8 , 12.8 ± 4	virtual reality environment distracts patients after ACLR from conscious motor control and may aid in current rehabilitation programmes to target altered movement patterns after ACLR.
Karakoc et al., 2019	Nintendo Wii balance board (Semi immersive)	Software: LabVIEW 8.5 software Hardware: 2 of Nintendo Wii Balance Boards	M: 22 with ACLR Nintendo group: 14 Control group: 8	Participants divided into Nintendo and control groups and both groups received 6-week accelerated rehabilitation. The Nintendo Wii balance games were added to Nintendo group after three weeks for 40 minutes a day, three times a week. pain, functionality, centre of gravity (COG) and balance at the baseline and end of the 3rd and 6th week of rehabilitation program evaluated.	Similar improvements in the pain, functionality, COG and balance scores of the two groups at the end of the treatment program. Pain : Mean change and SD from baseline to week 6 in Nintendo group and control group were 1 ± 2.38 and 0.5 ± 2.35 (p= 0.256) LEFS: Mean change and SD from baseline to week 6 in Nintendo group and control group were 35.50 ± 18.77 and 27.50 ± 16.65. (p= 0.393) COG: Mean change and SD from baseline to week 6 in Nintendo group and control group were 8.3 ± 7.18 and 7.70 ± 15.56 respectively (p= 0.707) Balance score: Mean change and SD from baseline to week 6 in Nintendo group and control group were 4 ± 8.30 and 4 ± 11.23 respectively (p= 1.000)	the Nintendo Wii balance games applied did not change the outcome of the rehabilitation in early period after ACL reconstruction.
Kiefer et al., 2019	Virtual Reality (immersive)	Software: Cortex (Version 6.2, Motion Analysis Corporation) / Visual3D / MATLAB (MathWorks, Inc) Hardware: HMD Hyperion 1300	Total: 38 Female preseason NMT group : 25 Mean age: 15.62 ± 1.38 Normal offseason training group: 13 Mean age: 16.76 ± 0.79	The sport-specific virtual environment streamed through a wireless HMD (Head-Mounted device). Athletes' head position and lower limb angular movement trajectories were tracked with 39 motion capture cameras through 5 markers fixed to the HMD and 31 markers on lower limbs. Athletes performed 4 tasks within the soccer specific virtual environment:	significant difference was observed for hip rotation: - The 25% stance phase, t(4) = 2.76, p = .05, indicating an 87% reduction in internal hip rotation during the loading phase following augmented NMT. - The 60% stance phase, t(4) = 3.81, p = .02, with a 116% reduction in hip internal rotation during the push-off phase post-training compared to pre-training. - A non-significant trend of a 19% reduction in knee abduction was observed (p = .15).	VR sports scenarios showed a significant improvement in the ACL injury risk variables after neuromuscular training interventions.

Lee et al., 2016	Nintendo Wii (Semi-immersive)	Hardware: Nintendo Wii, Balance Board, Plasma display panel monitor Software: Three categories of game content: (1) yoga content (2) strength training content (3) balance games content	M:11 F: 14 Mean age: 36.4 ± 14.8	Participants were introduced to the VR game following pre-treatment assessment, and posttreatment assessment conducted after finishing all sessions. Participants were asked to respond verbally to the open-ended questions of the KUUEQ (Korea University User Experience Questionnaire).	There was no significant correlation between total FSS-2 scores and knee pain severity, physical dysfunction, or age. The total FSS-2 score was significantly higher than the norm value for dance for nondisabled participants (p < 0.001). 24 of the 25 participants (96%) responded “yes.” to the question " Do you think there will be any physical improvement with these exercises?” 18 participants (75%) reported “both in training and game type,” 6 participants (25%) reported “only in training type,” in response to the question: “From what type of program do you expect physical improvement? The majority (96%) of participants said that they would like to use the NWFP (Nintendo Wii Fit Plus) in future rehabilitation treatment.	VR-based games are potentially acceptable as a motivational rehabilitation tool for patients following knee surgery
McGough et al., 2012	Nintendo Wii balanced board (Semi-immersive)	Software: LabView software for analysis Hardware: 2 of Nintendo Wii Balance Boards	M:47 Trained: 15 Mean age: 23.1 ± 2.9 Untrained: 32 Mean age:24.3 ± 4.8	participants were tested for measures of weight bearing asymmetry (WBA) while squatting. The Nintendo Wii Balance Boards (NWBB) provided real time visual feedback of WBA during half of the trials. Participants completed 6 squats at a tempo of 1 repetition per 6 seconds. The feedback was provided at 3-second intervals.	- The MMD (mean mass difference) was reduced significantly (p = 0.028) between the limbs when performing the squatting task, with 14% lower MMD in Visual feedback compared with the no-feedback condition - The SI (symmetry index) was significantly reduced during the visual feedback condition (p = 0.007), with a decrease of 41% . TFSL (time favouring a single limb) displayed a 26% reduction with visual feedback which was not significant (p = 0.080). Correlation analysis revealed that participants with high levels of WBA had the greatest response to feedback (p , 0.001, r = 0.557).	WBA (weight bearing asymmetry) exists in healthy untrained adults and can be reduced by using real-time visual feedback of an NWBB-based system. Healthy, well-trained professional athletes do not possess the same magnitude of WBA.
Prvu Bettger et al., 2020	Virtual Reality (immersive)	Virtual physiotherapy program the Knee injury and Osteoarthritis Outcome Score (KOOS)	287 completed trials. Virtual PT group: 143 Traditional care group: 144 M:37.5% / F: 62.5% Mean age: 65	The Virtual Exercise Rehabilitation Assistant (VERA; Reflexion Health) system used in this trial which tracked activity, performance, exercise quality, and adherence. The telehealth therapist monitored patient’s progress. Each patient set personal recovery goals and was given a diary to record progress	Virtual PT had lower costs at 12 weeks after discharge. Virtual PT patients had fewer rehospitalizations than the usual care group (12 compared with 30; p = 0.007). Virtual PT was noninferior to usual PT in terms of the KOOS at 6 weeks (difference, 0.77; 90% CI, 21.68 to 3.23) and at 12 weeks (difference, 22.33; 90% CI, 24.98 to 0.31). Virtual PT was noninferior to usual care at 6 weeks in terms of knee extension, knee flexion, and gait speed and at 12 weeks in terms of pain and hospital re-admissions. Falls were reported by 19.4% of virtual PT patients and 14.6% of usual care patients (difference, 4.83%; 90% CI, 22.60 to 12.25).	Total health-care costs for the 12-week post-hospital period which revealed significant lower health-care costs after TKA in telerehabilitation with the similar effectiveness.

Shah et al., 2015	Microsoft Kinect (non-immersive)	Hardware: Microsoft KINECT sensor camera motion capture system (VICON) Software: 3D netball court KINECT software algorithms	Total: Unknown Mean age: 18-35	Participants randomly allocated into Group A (non-immersive virtual reality training) with VR training by Microsoft Kinect Xbox and Group B (conventional rehabilitation) with conventional balance exercises which would include single leg standing on the floor and standing on a wobble board. In group A, progression would be in the form of an. In group B, the participants will be given.	The expected RPE (Rate of Perceived Exertion) in both groups was 3 (moderate) In the initial week, and was 4 In the 2nd week in both group (somewhat hard) followed by 5 (hard) and 7(very hard) in the 3rd and 4th week respectively.	The non-immersive virtual reality training would be effective in improving the balance and the functional status of the patients after ACLR surgery when compared to the conventional balance training program.
Thomas et al., 2016	Virtual Reality (immersive)	Software: Motion Monitor Vicon Tracker Vizard software (World Viz) Hardware: a 10-camera Vicon Bonita system 3DTV HMD	M: 9 / F: 8 Mean age: 18-35	Participants were examined during games of Virtual Dodgeball on a 3D television and a head-mounted display (HMD). They performed reaches to each of 3 targets located in the mid-sagittal plane based on their hip height, trunk length, and arm length. The participant was positioned at the free-throw line on one side of the basketball court, and 4 virtual opponents were placed on the opposite side. The participant attempted to block or avoid the balls launched by each of the 4 opponents. The average lumbar excursions were used to calculate the intended impact height location of the virtual dodgeballs.	There were significantly greater excursions of the knee (P=.003), hip (P<.001), spine (P<.001), shoulder (P=.001), and elbow (P=.026) during HMD versus 3DTV gameplay. There were significant differences in forward (P=.003) and downward (P<.001) displacement of the whole-body centre of mass(COM). There was a significant effect of Display Type on movement time (F1,15=6.72, P=.02), with participants moving more quickly in the 3DTV condition. There were no significant differences noted for mental demand.	Visual display type influences motor behaviour in Virtual Dodgeball. It means that use of the Kinect sensor to track and presents an avatar in a third-person perspective may result in very different motor behaviour when compared to the same tasks being presented from a first-person perspective.
Thomas et al., 2016	Virtual Reality (immersive)	Software: Motion Monitor Vicon Tracker Vizard software (World Viz) Hardware: a 10-camera Vicon Bonita system 3DTV HMD	Total: 17 M: 9 / F: 8 Mean age: 18-35	participation consisted of standardized reaches to static targets in the real world (and a round of virtual dodgeball played in two Virtual Reality Environments (3D-TV, HMD). Each round of dodgeball consisted of 3 levels of difficulty. Between each level, the participant had to reach to static virtual targets presented at the same locations as the corresponding reaches performed in the real world.	- Reaches to virtual targets resulted in significantly greater excursions of the ankle, knee, hip, spine, and shoulder compared with reaches made to real-world targets. - Significant differences in the forward and downward displacements of the whole-body centre of mass between the visual environments.	Findings suggested that environment influences how participants perform full body reaching tasks to static targets. It means that the game systems that track and present avatars from a third-person perspective elicit significantly different motor behaviour when compared with the same tasks being presented from a first-person perspective.

2.3.3 Description of Included Studies

The reviewed studies used various types of interventions such as VR headset, Nintendo Wii, Microsoft Kinect camera, infrared cameras and 3D-TV to assess the lower limb biomechanics and improve rehabilitation outcomes. Also, six studies were included in the meta-analysis, and a total of three meta-analyses were conducted in this study. Finally, a narrative synthesis of findings was undertaken, and findings were categorized in terms of the effect of immersive technologies on rehabilitation outcomes, biomechanical factors and performance in people with ACL reconstruction.

2.3.4 Quality Scores of Included Studies

From selected studies in the review, Two studies were assessed through the JBI critical appraisal checklist tool with high quality/ low risk of bias (Baltaci et al., 2013; Shah et al., 2015), two studies with low quality/high risk of bias (Lee et al., 2016; McGough et al., 2012), and eleven studies were assessed as moderate (Adams et al., 2020; Aydogdu et al., 2017; DiCesare et al., 2019; Ford et al., 201; Gokeler et al., 2014; Gokeler et al., 2016; Karakoc et al., 2019; Kiefer et al., 2019; Prvu Bettger et al., 2020; Thomas et al., 2016; Thomas et al., 2016). Table 3 provides the overall risk of bias scores.

Table 3. JBI Critical Appraisal Checklist for RCT studies.

JBI Critical Appraisal Checklist for Randomized Controlled Trials															
Studies	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**	**Q8**	**Q9**	**Q10**	**Q11**	**Q12**	**Q13**	**Score**	**Overall appraisal**
Adams et al., 2020	Yes 1	No 0	Yes 1	No 0	No 0	No 0	Yes 1	No 0	No 0	Yes 1	Yes 1	Yes 1	Yes 1	7 / 13 (53.8 %)	Moderate
Aydogdu et al., 2017	N/A --	No 0	Yes 1	No 0	No 0	No 0	Yes 1	No 0	Yes 1	Yes 1	N/A --	Yes 1	Yes 1	6 / 11 (54.5 %)	Moderate
Baltaci et al., 2013	Yes 1	Yes 1	Yes 1	Yes 1	Yes 1	Yes 1	Yes 1	No 0	Yes 1	Yes 1	Yes 1	Yes 1	Yes 1	12/13 (92.3 %)	High
DiCesare et al., 2019	Yes 1	No 0	Yes 1	No 0	No 0	No 0	Yes 1	No 0	Yes 1	Yes 1	Yes 1	Yes 1	Yes 1	8 /13 (61.5 %)	Moderate
Ford et al., 2017	No 0	No 0	Yes 1	No 0	No 0	No 0	Yes 1	No 0	Yes 1	Yes 1	Yes 1	Yes 1	Yes 1	7 / 13 (53.8 %)	Moderate
Gokeler et al., 2014	Yes 1	No 0	Yes 1	No 0	No 0	No 0	Yes 1	No 0	Yes 1	Yes 1	Yes 1	Yes 1	Yes 1	8 /13 (61.5 %)	Moderate
Gokeler et al., 2016	Yes 1	No 0	Yes 1	No 0	No 0	No 0	Yes 1	No 0	Yes 1	Yes 1	Yes 1	Yes 1	Yes 1	8 /13 (61.5 %)	Moderate
Karakoc et al., 2019	Yes 1	No 0	Yes 1	No 0	No 0	No 0	Yes 1	No 0	Yes 1	Yes 1	Yes 1	Yes 1	Yes 1	8 /13 (61.5 %)	Moderate
Kiefer et al., 2019	Yes 1	No 0	Yes 1	No 0	No 0	No 0	Yes 1	No 0	Yes 1	Yes 1	Yes 1	Yes 1	Yes 1	8 /13 (61.5 %)	Moderate
Lee et al., 2016	No 0	No 0	Yes 1	No 0	No 0	No 0	No 0	No 0	Yes 1	Yes 1	Yes 1	Yes 1	Yes 1	6 /13 (46.1 %)	Low
McGough et al., 2012	No 0	No 0	Yes 1	No 0	No 0	No 0	No 0	No 0	Yes 1	Yes 1	Yes 1	Yes 1	Yes 1	6 /13 (46.1 %)	Low
Prvu Bettger et al., 2020	Yes 1	No 0	Yes 1	No 0	No 0	No 0	Yes 1	No 0	Yes 1	Yes 1	Yes 1	Yes 1	Yes 1	8 /13 (61.5 %)	Moderate

Shah et al., 2015	Yes 1	Yes 1	Yes 1	Yes 1	No 0	No 0	Yes 1	No 0	Yes 1	Yes 1	Yes 1	Yes 1	Yes 1	10 / 13 (76.9 %)	High
Thomas et al., 2016	Yes 1	No 0	Yes 1	No 0	No 0	No 0	Yes 1	No 0	Yes 1	Yes 1	Yes 1	Yes 1	Yes 1	8 /13 (61.5 %)	Moderate
Thomas et al., 2016	Yes 1	No 0	Yes 1	No 0	No 0	No 0	Yes 1	No 0	Yes 1	Yes 1	Yes 1	Yes 1	Yes 1	8 /13 (61.5 %)	Moderate

Q1 – Q13 indicate questions 1 to 13 based on the JBI risk assessment (Appendix A).

1) Was true randomization used for assignment of participants to treatment groups? **2)** Was allocation to treatment groups concealed?
3) Were treatment groups similar at the baseline? **4)** Were participants blind to treatment assignment?
5) Were those delivering treatment blind to treatment assignment? **6)** Were outcomes assessors blind to treatment assignment?
7) Were treatment groups treated identically other than the intervention of interest? **8)** Was follow up complete and if not, were differences between groups in terms of their follow up adequately described and analysed? **9)** Were participants analysed in the groups to which they were randomized? **10)** Were outcomes measured in the same way for treatment groups? **11)** Were outcomes measured in a reliable way?
12) Was appropriate statistical analysis used? **13**) Was the trial design appropriate, and any deviations from the standard RCT design (individual randomization, parallel groups) accounted for in the conduct and analysis of the trial?

- If the answer is "**Yes**", it is equal to 1; if the answer is "**No**", it is equal to 0

- **High quality (low Risk of Bias)** When a study earns more than 70% of "yes" scores, **Moderate quality** When a study reached from 50 to 69% , and **Low quality (High Risk of Bias)** When a study earns less than 49% of "yes" scores

2.3.5 Rehabilitation outcomes

Immersive technologies and virtual reality interventions were applied for rehabilitation and clinical improvements in six studies (Aydogdu et al., 2017; Baltaci et al., 2013; Karakoc et al., 2019; Prvu Bettger et al., 2020; Lee et al., 2016; Shah et al., 2015) and most of these papers reported positive finding. For instance, Aydogdu et al.(2017) found significant improvements in the range of motion (ROM) and proprioception measures in people with ACL reconstruction (ACLR) after application of virtual rehabilitation treatment for eight weeks and a comparison of pre-treatment and post-treatment values. Baltaci et al.(2013) found similar rehabilitation outcomes between Nintendo Wii and a conventional rehabilitation programme in terms of improvement of coordination, proprioception, and functional mobility. Prvu Bettger et al.(2020) reported that the effectiveness of virtual physical therapy was similar to conventional physical therapy, along with a reduction in rehospitalizations in the 12 weeks after surgery. Shah et al.(2015) showed that four weeks of virtual reality training with MS Kinect, improved the balance and the functional status of the patients after ACLR surgery when compared to the conventional balance training program. Also, Lee et al. examined the perspectives of participants about virtual reality-based rehabilitation with the Nintendo Wii balance board and reported a high rate of expectation of therapeutic effect (96%) and more positive experiences in people with physical dysfunction, which resulted in an increased intention of exercise adherence among the participants and higher levels of flow during VR-based rehabilitation. In contrast, Karakoc et al. used a Nintendo Wii balance board for three weeks as adjuvant therapy in a 6-week accelerated rehabilitation programme and revealed that there were no significant differences in the balance, lower extremity functional scale, and the centre of gravity (COG) between Nintendo Wii and the control group. Based on the included studies in Table 2, Virtual Reality (VR) has demonstrated various potential benefits in physiotherapy and rehabilitation settings, including:

1. **Task-Specific Interventions:** VR interventions are capable of simulating real-world tasks in a controlled and safe environment that mimics daily activities. For instance, Adams et al. (2020) and Aydogdu et al. (2017) used VR to replicate specific tasks and treat patients effectively, while DiCesare et al. (2019) used VR to recreate sport-specific scenarios.
2. **Increased Frequency:** The immersive nature of VR can encourage more frequent use. Baltaci et al. (2013) found that enjoyable activities, such as using the Nintendo Wii Fit, could potentially increase usage frequency.
3. **Improved Adherence:** Studies like the one by Lee et al. (2016) suggest that VR can increase patient adherence to rehabilitation programs by making exercises more engaging.
4. **Distraction:** VR can distract patients from conscious motor control, potentially leading to more natural movements and better recovery outcomes (Gokeler et al., 2016).
5. **Enhanced Biomechanical Outcomes:** VR can lead to improved biomechanical outcomes by allowing for the safe practice of movements that may be risky in a real-world setting (DiCesare et al., 2019; Thomas et al., 2016).
6. **Cost-Effective:** Some studies suggest that VR interventions could be more cost-effective than traditional care while maintaining similar effectiveness (Prvu Bettger et al., 2020).

It's important to note that while the effectiveness of VR interventions seems promising based on these studies, more comprehensive research is needed to fully understand its potential in various rehabilitation settings. Factors such as patient demographics, the specific nature of the injury or condition, and the design of the VR system can all influence the effectiveness of VR-based rehabilitation.

2.3.6 Performance

Immersive technologies were used in nine studies (Adams et al., 2020; DiCesare et al., 2019; Ford et al., 2017; Kiefer et al., 2019; Gokeler et al., 2014; Gokeler et al.,2016; McGough et al., 2012; Thomas et al.,2016; Thomas et al.,2016) to evaluate performance and biomechanical factors. For instance, two studies (Adams et al., 2020 and Ford et al., 2017) showed the benefit of the virtual intervention on jump height and demonstrated the similarity of jump height measures with and without the application of immersive technology in one session measurement. Correspondingly, Adams et al. (2020) reported that there were no differences in landing forces and landing mechanics between the spike jump with an augmented reality (AR) headset and the spike jump without an AR headset. Similarly, Ford et al. (2017) showed no difference in maximum jump height during the drop vertical jump when using a virtual target and compared it with a physical target. Therefore, the immersive intervention has the capability to replicate movement patterns of sport-specific tasks along with having the potential to create more complex scenarios, such as the simulation of a real match without the need for other team players.

In 2019, Kiefer et al. used a sport-specific virtual environment to assess ACL injury risk variables after six weeks of neuromuscular training (NMT) and showed a significant improvement in the ACL injury risk variables, such as a significant reduction in the internal hip rotation during the loading and push-off phases of a soccer-specific cutting task following six weeks of NMT. Indeed, hip internal rotation is associated with the peak knee valgus which is a primary indicator of ACL risk (Lephart et al., 2005). Therefore, modulation of hip posture can be substantial to provide a potentially protective mechanism for the ACL (Zazulak et al., 2005).

In 2012, McGough et al. found an improvement in the weight-bearing asymmetry (WBA) during squats, using real-time visual feedback provided by a Nintendo Wii Balance board (NWBB) based system. Indeed, there are high levels of WBA in individuals who have undergone ACLR (Neitzel et al., 2002), and McGough et al. (2012) showed that participants with high magnitudes of WBA had the most significant response to visual feedback provided by NWBB. Therefore, they concluded that immersive technology such as NWBB could be effective when a high level of WBA was present.

DiCesare et al. (2019) assessed biomechanical deficits for lower-limb injury in a sport-specific context, created by VR technology and offered a promising approach for future injury prevention. They found decreased hip and ankle flexion in the sagittal plane as well as hip abduction and ankle excursion in the frontal plane during landing in a VR-based sports scenario compared to the standard drop vertical jump task.

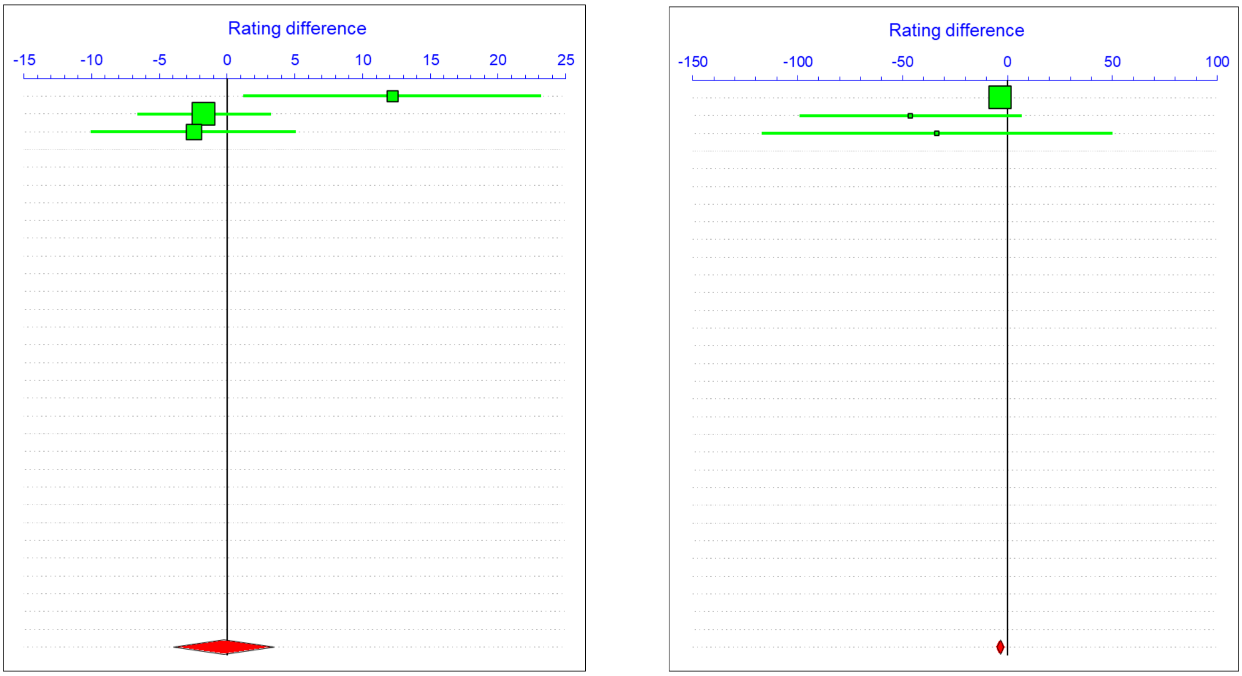
Gokeler et al. (2014 and 2016) found significant differences between environments and groups for knee moment, vertical ground reaction force (vGRF), knee angle at peak vGRF, and knee flexion excursion. Also, they showed a more significant effect of the virtual reality environment on knee biomechanics in patients with ACLR than in the control group.

Another study (Thomas et al.,2016) indicated significantly greater excursions of the knee, hip, and spine on gameplay during head-mounted display (HMD) when compared to 3DTV, resulting in significant differences in the centre of mass displacement. Thomas et al. (2016) reported different motor behaviours with various visual display avatars (first-person and third-person perspective).

2.3.7 Meta-Analysis

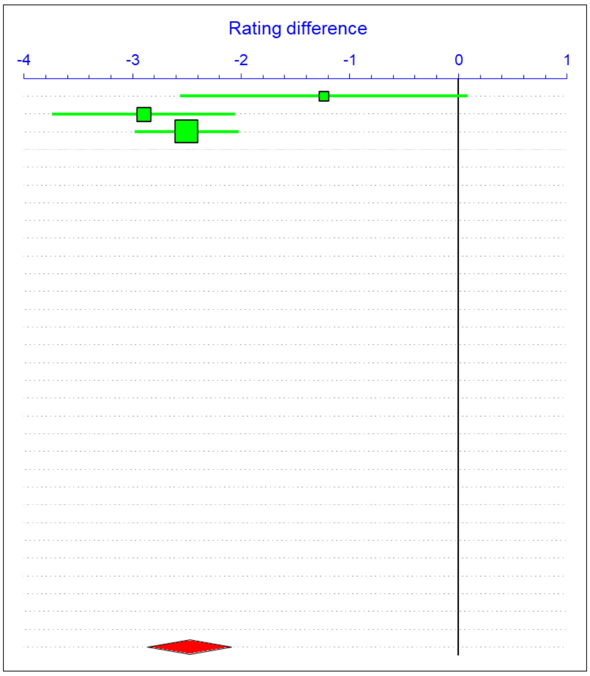
Overall, three meta-analyses were conducted in this study, and a total of six studies were included in these meta-analyses. One meta-analysis was conducted to measure hip flexion after a Drop Vertical Jump (DVJ) in the landing phase, and the other two meta-analyses were conducted for proprioception and pain measures in included studies that focused on rehabilitation.

The first analysis was performed for hip flexion measures after Drop Vertical Jump (DVJ) in the landing phase between a control and virtual reality intervention groups in one single session measurement (Figure 2). Two studies (Ford et al., 2017 and DiCesare et al., 2019) were included in this meta-analysis. Ford et al. (2017) measured hip flexion at initial and maximum contacts (two separate measurements), whereas DiCesare et al. (2019) measured hip flexion at peak knee flexion. This analysis revealed that there was no statistically significant difference between the virtual environment and control group for hip flexion measures in the landing phase of DVJ (95% CI= -3.937, 3.4743; P=0.903; Fixed effect= -0.231; MoE=3.7058). The second meta-analysis was conducted for two studies (Aydogdu et al., 2107; Baltaci et al., 2013) with three measurements of proprioception before and after using immersive technologies in a rehabilitation programme (Figure 2). Aydogdu et al. (2107) used virtual rehabilitation in addition to conventional physiotherapy for eight weeks, while Baltaci et al. (2013) applied immersive rehabilitation for 12 weeks and compared it with conventional physiotherapy in the control group. This analysis showed a statistically significant improvement in proprioception measures after the application of virtual rehabilitation treatment (95% CI= -4.936, -1.8652; P< 0.05; Fixed effect = -3.4; MoE= 1.535). The last meta-analysis was also conducted in three studies (Aydogdu et al., 2107; Karakoc et al., 2019; and Prvu Bettger et al., 2020) to assess pain intensity pre and post-treatment with virtual-based rehabilitation. All three studies added a type of immersive intervention from the 6th to 12th weeks of the treatments to the conventional rehabilitation in the interventional group (Figure 2). This meta-analysis reported a significant reduction of pain intensity after the application of virtual rehabilitation in the intervention group (95% CI= -2.864, -2.085; P< 0.05; Fixed effect = -2.475; MoE= 0.3893).



A: Hip flexion in the landing phase of the DVJ.

B: Proprioception after VR



C: Pain after VR

Figure 2. Three Meta-Analyses for A: Hip flexion, B: Proprioception, C: Pain reduction

2.4. Discussion

This study aimed to explore the effect of immersive technologies on the rehabilitation outcome, performance and biomechanical assessment of the lower limbs following ACL injury. Of 2179 studies found by the literature search, 15 studies met the study inclusion criteria and were included in this review. One of the main findings of this study was the effect of VR-based treatment on improving rehabilitation outcomes such as improvement in the range of motion (ROM), proprioception, balance and functional status, which indicated by five studies (Aydogdu et al., 2017; Baltaci et a, 2013; Prvu Bettger et al., 2020; Lee et al., 2016; Shah et al., 2015). Another main finding was the effect of immersive technology interventions on the biomechanics of sports movement and performance which was indicated in the nine studies (Adams et al., 2020; DiCesare et al, 2019; Ford et al., 2017; Kiefer et al, 2019; Gokeler et al., 2014; Gokeler et al.,2016; McGough et al, 2012; Thomas et al.,2016; Thomas et al.,2012), and was discussed in detail in the following section. Finally, a total of six studies were included in three meta-analyses, from which two meta-analyses showed significant improvement in the rehabilitation outcomes including proprioception and pain, while another meta-analysis showed was no significant difference between the virtual environment and control group for hip flexion measures in the landing phase of DVJ. In the following sections, the validity and reliability of immersive technology against standard method were discussed.

2.4.1 Effect of immersive technology on rehabilitation outcome

One of the main findings was the impact of virtual reality-based treatment on improving rehabilitation outcomes by comparing pre-treatment and post-treatment values in people with ACL reconstruction (ACLR) after the application of virtual rehabilitation treatment, in comparison with a control group following conventional therapy. For instance, five studies (Aydogdu et al., 2017; Baltaci et a, 2013; Prvu Bettger et al., 2020; Lee et al., 2016; Shah et al., 2015) reported improvement in the range of motion (ROM), proprioception, balance and functional status, whereas only one study (Karakoc et al., 2019) did not report any significant difference for using the virtual reality-based treatment along with conventional therapy. However, it did not observe any adverse effects. A reason for the improvement failure in the early stage of ACL rehabilitation programmes might be the limited time of the study because it lasted only for six weeks and Nintendo Wii balance games were added in the fourth week, whereas the regaining of dynamic joint stability is usually between the 20th and the 32nd weeks after ACLR (Cooper et al., 2005). Also, the small sample size and simple measurement for balance scores assessment could be the other reasons for no change in the rehabilitation outcome .

Two studies (Lee et al., 2018 and Balteci et al., 2018) used the Nintendo Wii Balance Boards (NWBBs) to improve rehabilitation outcomes. They showed significant improvement in dynamic balance and coordination following ACL reconstruction in both VR-based rehabilitation and control groups. Two other studies (Aydogdu et al., 2017, Prvu Bettger et al., 2020) used VR headsets to focus on enhancing rehabilitation outcomes, and they reported improvement in the biomechanical factors such as proprioception, range of motion, dynamic balance along with reducing the risk of ACL injury in the future. Finally, another study (Shah et al., 2015) demonstrated that Microsoft Kinect would improve balance and early return to functional activities after ACL reconstruction compared to the traditional balance training program. Also, two studies conducted a meta-analysis on proprioception measurements before and after using immersive technologies in a rehabilitation programme (Aydogdu et al., 2107; Baltaci et al., 2013), which showed a significant improvement in proprioception measures after the application of virtual rehabilitation treatment. In previous studies, it is believed that virtual-based rehabilitation requires participants to produce appropriate responses to visual signals provided on display (Sadegh et al., 2017), and users can observe the real-time results by obtaining feedback on their movements that can help the patients maintain a greater focus on proprioception to perform efficient movements. Accordingly, this awareness of body positions and movements in the VR environment benefits proprioception. Benjaminse et al. (2017) reported that the athlete could effectively reach a level of high performance and a low chance of injury while using video feedback of whole-body movement during the learning phase. Also, Cho et al. (2014) showed improvement in motor control by using visualized movement feedback during repetitive exercise. Indeed, movement in virtual reality requires cognitive abilities such as spatiotemporal perception to interact with the virtual environment, which cannot be provided by conventional exercise programs (Monteiro-Junior, Vaghetti, Nascimento, Laks, & Deslandes, 2016). In addition, the VR technologies can automate the rehabilitation process by gradually increasing the complexity of tasks while decreasing therapist support and enabling therapists to individualize treatment needs based on the patient’s physical defect, which leads to the achievement of a more significant effect of rehabilitation (Weiss et al., 2004). Further, Lee et al.(2018) reported that the exercise and treatment in VR environments are pleasurable physical activities that can increase the intention of exercise adherence among the participants (96%), and this higher level of flow during VR-based rehabilitation could generate more repetitive movements and joint angle motions, which were able to stimulate muscle mechanoreceptors and enhance proprioception (Ju et al., 2013). Another meta-analysis was conducted on the measurement of pain intensity pre- and post-treatment with immersive technologies, and it showed a significant reduction of pain intensity measures after the application of six to twelve weeks of virtual rehabilitation treatment, which was similar to conventional therapy or even better improvement. However, one of the included studies (Karakoc et al., 2019) used NWBBs for three weeks in a 6-week accelerated rehabilitation programme and showed that the Nintendo Wii balance games did not change the rehabilitation outcomes in the early period after ACL reconstruction surgery, though this study has not observed any adverse effects on outcomes.

2.4.2 effect of immersive technology on performance

The other main finding was the effect of immersive technology interventions on the biomechanics of sports movement and performance. Two studies (Adams et al., 2020; Ford et al., 2017) showed the similarity of jump height measures in virtual and physical environments. Adams et al. (2020) reported that there were no differences in landing forces and mechanics between the vertical jump and hit volleyball's ball with and without an AR headset. The rationale for using AR is that introducing variability in the learning environment enables a task to become more representative (Hodges & Williams, 2012). Further, AR can easily manipulate perceptual information while providing complete control over task variability (Adam et al., 2020). Therefore, AR can be employed in a clinical setting to efficiently replicate data from the competitive environment, and it may be worthwhile to create more effective learning options (Adam et al., 2020). Similarly, Ford et al. (2017) measured the maximum jump height during the drop vertical jump (DVJ) with a virtual target in 3D-TV (non-immersive technology), and with a physical target, which showed no significant difference between these two measurements. Indeed, Ford et al. (2017) used both physical and virtual objects as an external focus for the participants to enable them to receive immediate feedback on their performance. External focus, defined by attention to the task outcome, can improve movement efficiency in jumping tasks, whereas performance remains the same or increases (Wulf et al., 2009). Thus, a virtual object could replace the physical targets to improve performance during biomechanical testing and training conditions. Also, Ford et al. (2017) reported differences in several biomechanical variables at the trunk and hip between the vertical drop jump with a virtual target in 3D-TV and a physical overhead target. For instance, the trunk had more extension posture with a physical overhead goal than a virtual one. Also, a greater peak hip extensor moment was reported during the virtual target condition compared with the physical

target. Therefore, Ford et al. (2017) found that the placement of the physical goal overhead caused the participants to modify their trunk and hip kinematics compared to the virtual goal condition on a screen in front of them. Accordingly, the current review conducted a meta-analysis for hip flexion measures after first landing of the vertical jump, which showed no statistically significant difference between the VR and the control groups for hip flexion measures in the landing phase (figure 2). Therefore, VR-based assessments can provide a sport-specific context to assess biomechanical factors and can be helpful in preventing athletes from injuries.

In 2016, Gokeler et al. found that the ground reaction force (GRF) and peak internal knee moment values for patients with ACL reconstruction increased after immersion in a VR environment and resembled healthy subjects. Gokeler et al. (2016) indicated that virtual reality environments may distract patients with ACL reconstruction from conscious motor control based on a change in patients' attention. Indeed, it is believed that a more conscious type of control may constrain the automatic control processing of the motor system due to an internal focus on one's own movements (Wulf et al., 2010). In contrast, an external focus on the movement effect enhances unconscious or automatic processes that can accelerate the learning process (Wulf et al., 2001). Accordingly, an effective way to promote learning with an external focus of attention is video feedback from an expert model, which enables athletes to compare their movement with the expert model's movement and correct the differences (Benjaminse et al. 2017).

Another study (Thomas et al.,2016) showed the impact of the virtual environment and the visual display on motor behaviour. Thomas et al. (2016) also reported that visual display avatar (first-person and third-person perspective) resulted in various motor behaviour. It means that the game systems introducing avatars from a first-person view elicit significantly different motor behaviour compared to the same functions presented from a third-person perspective (Thomas et al., 2016). Thomas et al. (2017) observed discrepancies in joint excursions between 3D-TV and VR head-mounted displays (HMD), which could result from the presentation view of the avatar. Accordingly, previous studies reported that the sense of actual existence in a virtual environment declined in a third-person view when compared to a first-person perspective. (Slater et al., 2010; Torok et al., 2014). Therefore, it can be concluded that different visual environments might affect participants' ability to reach the full-body tasks.

2.5 Limitation

Some limitations need to be addressed. The included studies were limited, so the results had to be interpreted cautiously. The type of VR technology used in the studies varies significantly, ranging from Augmented Reality (AR) to semi-immersive and immersive VR systems. This variability can make it difficult to compare results across studies and could potentially affect the review's conclusions. Future reviews could attempt to categorize results based on the type of VR technology used. Further, included studies were varied in methodology, intervention, outcomes, and patient groups. The heterogeneity of studies can complicate the result comparisons and conclusions. This could be improved by focusing on more specific research questions or including only studies with similar methodologies. Language bias was another limitation, as this review included only studies published in English. This could be mitigated in future reviews by including studies published in other languages. Some included studies had narrow inclusion criteria, which limits generalizability. Future reviews could include a more diverse range of studies to increase generalizability. There was a limitation related to the various levels of the participants' injuries because they were not investigated separately. Moreover, there was a limit on the quality-assessment tools in VR-based studies because the response to “blind in treatment assignments" was "no" in most of the included studies (see Table 2). Indeed, the nature of VR interventions conflicts with their use by blind participants. So, the modified versions of the quality-assessment tools for VR-based studies need to be designed. Lastly, due to the time-consuming nature of conducting a review, the results of a systematic review might be outdated by the time of publication. Regular updates of systematic reviews can address this issue.

2.6. Conclusion

This study identified papers investigating the application of immersive technologies to the rehabilitation outcome and performance assessment after ACL injury. The findings indicate that VR interventions and immersive technologies may provide a promising approach for improving rehabilitation outcomes such as proprioception and pain management. Also, VR-based systems can be a considerable alternative to real-world training to improve certain aspects of athletic performance because immersive technologies offer a tool to control virtual environmental features effectively. Finally, immersive technologies and VR-based systems are still in their infancy and will need considerable improvements in the future. Therefore, further research needs to be conducted in a theoretical frame to acknowledge the profitability of VR interventions in sports performance and rehabilitation programmes.

Chapter Three:

Validity of the Azure Kinect against the gold standard motion capture system called Qualisys.

3.1 Introduction

In clinical settings, biomechanical assessments of patients are performed to measure functional parameters of movement and evaluate joints' range of motion to monitor progression during rehabilitation or explore performance after training (McClelland et al., 2007). In the past, these measurements were typically performed by visual observation of movements and posture using joint, body segment position and angles without any equipment. This visual inspection yielded less reliable results than those measured by using modern motion capture systems (Mentiplay et al., 2015). Indeed, the introduction of marker-based motion capture technologies, which is the process of tracking the complexities of the movement and processing this information either by recording or in the moment, brought motion analysis to a new level, enabling researchers to gather a wealth of data accurately and rapidly (Mentiplay et al., 2015). Although these marker-based systems have played a significant role in joint pathology and sports performance studies, they cannot be used widely in clinical settings due to various limitations (Pfister et al., 2014). First, being expensive and resource-intensive due to the requirement for multiple cameras, markers, and a large amount of space for stationary equipment and the correct placement of cameras (Mentiplay et al., 2015). In addition, they include time-consuming procedures for system calibration and data processing (Napoli et al., 2017). Also, participants may demonstrate altered performance because of feeling observed due to its marker-based tracking strategies (Van Den Noort et al., 2013). One of the optical marker-based motion capture systems is the Qualisys system. Optical motion capture is considered a gold standard method that has been used in some studies to isolate biomechanical movement patterns with a skeletal representation of the subject on a computer display (Baskwill et al., 2017). However, the Qualisys system also includes the same limitations.

In the past few years, markerless motion capture systems have become available off-the-shelf and are less expensive than marker-based systems. Amongst these systems, the Kinect sensor, based on an RGB (Red, Green, Blue) camera and IR-based (infra-red) depth sensor, produces 3D images by capturing RGB colour images enriched with depth data at each pixel so they can be used to track real-time human motion (Brown Kramer et al., 2020; Napoli et al., 2017). In 2019, the Azure Kinect was announced by Microsoft as a portable and cost-effective alternative to more expensive and complex motion capture systems for the accessibility of kinematic data (https://azure.microsoft.com/en-us/services/kinect-dk/). Its main features include speech and image analysis with significantly higher accuracy and resolution than other commercial alternatives. It provides orientation data for 32 joints. In addition, an integrated inertial measurement unit (IMU) and a 7-microphone array allow the Azure Kinect to extend the range of possible applications for rehabilitation, training, and sport-specific tasks (Albert et al., 2020). These improved features may enhance its clinical feasibility for analysing body motions (Albert et al., 2020; Ma et al., 2020). Ma et al. (2020) stated that the Azure Kinect may have the capability to improve image-sensing technologies. Indeed, the advantage of the Azure Kinect as a portable and cost-effective tool to assess kinematic data outside the laboratory, can be a subject of great interest when compared to current standard methods such as Qualisys (Ma et al., 2020). However, it is crucial to evaluate the validity of any measurement system. Based on international consensus, the COSMIN (COnsensus-based Standards for the selection of health Measurement Instruments) taxonomy of measurement properties is presented in Figure 1, in which three quality domains are observed, including (https://www.cosmin.nl/tools/cosmin-taxonomy-measurement-properties/)

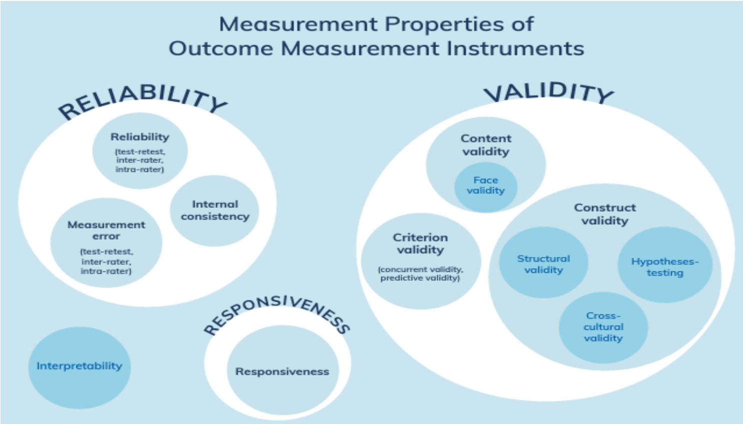


Figure 1. COSMIN taxonomy of measurement properties

https://www.cosmin.nl/tools/cosmin-taxonomy-measurement-properties

reliability, validity, and responsiveness. Also, each domain contains one or more measurement properties. When considering validity, the COSMIN panel has defined *validity* as "the degree to which an instrument measures the construct it purports to measure." (Mokkink et al., 2016), and different types of validity based on the COSMIN panel are:

- Content validity (including face validity).
- Construct validity (including structural validity, hypothesis testing, and cross-cultural validity).
- Criterion validity (including concurrent validity and predictive validity).

Concurrent validity indicates the agreement and correlation between a new assessment and a valid existing test (Murphy & Davidshofer, 1998).

Considering measurement properties, to date, there has been limited validation of the Azure Kinect for measuring lower limb function. Therefore, the Kinect Azure should be explored for validity sensors before it can be used in clinical procedures. To our knowledge, there have been limited studies published on the validity of Azure Kinect. Indeed, most studies evaluated the validity of previous Kinect models, such as Kinect v2, which has significant differences in hardware specifications compared to Azure Kinect (Tölgyessy et al., 2021). For instance, body tracking of the Azure Kinect is more potent than the Kinect V2 because it can detect any number of people on the scene, even with high conclusions from any angle (Terven et al., 2021). Recently, two studies (Clark et al., 2019 and Springer et al., 2016) reported poor accuracy of the older versions of Kinect (V1 and V2) for tracking some kinematic gait variables. Poor validity with single camera systems could be due to occlusions that might happen because the body segments can obstruct each other (Ma et al., 2020). Also, walking aids or other assistive devices in patients with restricted mobility might interfere with the tracking accuracy (Skals et al., 2017). Multiple integrated Kinect cameras could solve this issue by tracking human motion simultaneously and providing better more consistent capture of motion in all planes (Kotsifaki et al., 2018; Ma et al., 2020). For instance, Kotsifaki et al. (2018) showed the validity of dual Kinect v2 cameras configured with the iPi software to assess the sagittal and frontal plane of hip and knee kinematic parameters by reporting excellent agreement for the shin flexion/extension range of motion (ICC=0.854 and 0.886 for right and left respectively) and thigh abduction/adduction (ICC=0.758 and 0.775 for right and left respectively) in a single leg squat test for both legs between a marker-based motion capture system (BTS-SMART 1000, BTS S.p.A., Italy) and dual Kinect v2 cameras.

In addition, Ma et al. (2020) developed a dual Azure Kinect system for gait analysis and compared this system with a standard marker-based motion capture system (Vicon) and a single Kinect V2 system in their previous study. The coefficient of multiple correlations (CMC) and root mean square errors (RMSE, Figure 2) were computed. The CMC is used to report the agreement between Aure Kinect and the reference system (Vicon system). The RMSE was measured to compare the error and accuracy between dual Azure Kinect and a single Kinect V2 system based on the results extracted from their previous study (Ma et al., 2019). As a result, the dual Azure Kinect system revealed a very good similarity in the knee angles with the referential Vicon system (CMC=0.87±0.06) and reported smaller errors when compared with the Kinect V2 in their previous study (RMSE=11.9°±3.4° in the Azure Kinect against RMSE=16.7°±4.2° in the Kinect V2). Thus, Ma et al. (2020) indicated improved precision and validity in assessing knee kinematics in dual Azure Kinect compared to the single Kinect V2 due to better agreement with CMC measurements in their new study (Ma et al., 2020) and higher RMSE reported in their previous study for the single Kinect system (MA et al., 2019).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(f_i - o_i)^2}$$

Figure 2. Root Mean Square Root equation.

∑ : Summation of all values.
f : Predicted value.
o : Observed or actual value.
N : Total sample size.
$(f_i - o_i)^2$: Differences between predicted and observed values and squared.

(https://medium.com/@mygreatlearning/rmse-what-does-it-mean-2d446c0b1d0e)

In this study, a motion capture system with triple Azure Kinect sensors was developed to provide adequate depth images for skeletal tracking, and we aimed to evaluate the concurrent validity of the updated markerless motion capture system (Azure Kinect) against the standard marker-based system (Qualisys) for tracking joints displacement during the squat movement in a healthy population.

3.2 Method

3.2.1 Subjects

Subjects were recruited from students and staff at a British University. All subjects were provided with an informed consent form and a PAR-Q questionnaire for their physical readiness before the test. Inclusion criteria included healthy people aged 18 to 65 without a history of injury, previous surgery, or a long-term illness over the past year that prevented them from participating in the study. This study was approved by the local Ethics Committee with approval number of [201485] and was conducted at the MoRes laboratory (the centre of movement, occupational, rehabilitation, and exercise sciences). The data were collected between November 2021 and February 2022.

3.2.2 Procedure

Participants were invited to attend the lab on one occasion. Prior to participation, participants completed an informed consent form and a physical activity readiness questionnaire (PAR-Q). The PAR-Q questionnaire is a primary screening tool for physical activity or exercise participation (Warburton et al., 2010). In addition, some demographic data, such as age, height, and weight, were measured. Then, the participants were equipped with fifteen reflective markers corresponding to anatomical landmarks, and their movements were recorded by a triple Azure Kinect system and a six-camera Qualisys system simultaneously (Figure 3).

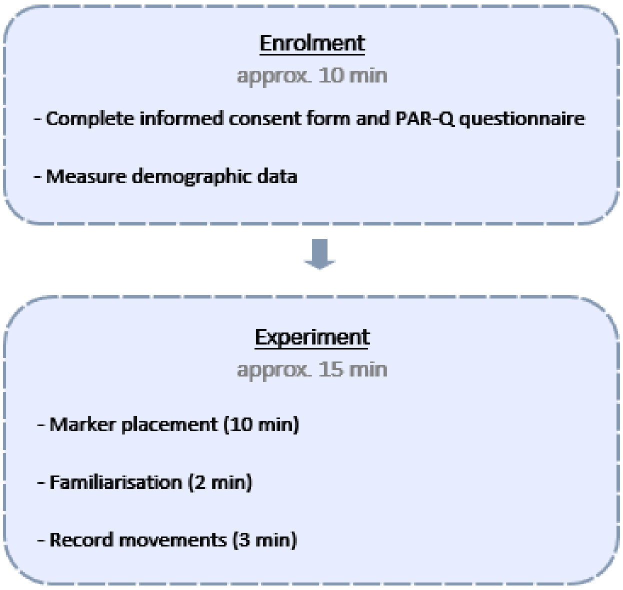


figure 3. procedure of Experiment

3.2.3 Experimental setup

The experimental setup consisted of one gaming laptop (Dell G5 gaming laptop 5500, equipped with a 256GB SSD, 32GB RAM and Windows 10 operating system) and two systems: 1) Maker-based Qualisys system (Qualisys AB, Sweden), including six infrared cameras and 15 reflective markers. 2) Markerless Kinect system composed of three Kinect Azure cameras (Microsoft Corporation, USA) and iPi Mocap Studio software (iPi Soft, LLC, Moscow, Russia) for data fusion and merging the recording videos. Prior to data collection, all participants were equipped with fifteen reflective markers placed on the pelvis and segments of the lower limbs and upper limbs for the Qualysis motion capture system according to the Plug-in-Gait marker set (Kadaba et al., 1990), which corresponded to anatomical landmarks but adjusted to this study's requirements. All movements were recorded by six infrared Qualisys cameras and, at the same time, with three Azure Kinect cameras. These special markers are covered with a retro-reflective material to reflect light, and the Qualisys cameras were adjusted to reveal only the bright reflective markers and ignore the participant's skin and clothes in order to track the markers' trajectories. Also, it was considered that at least two Qualisys cameras should see each marker during the measurement to create 3D data. For achieving this purpose, six cameras were used in the following setup: the two cameras were positioned at the front and back of the measurement volume while the other four cameras were located on the sides. In comparison to the Qualisys system, the Azure Kinect sensor consists of an RGB camera, an IR camera, and an IMU sensor, which could estimate its position in space without using the markers on the body. Six Qualisys infrared cameras were placed two meters apart from the participant's movement area on a hexagon angle, and simultaneously, three Azure Kinect cameras were placed three meters apart from each other on a triangle area with 1.5 meters distance from participants, and one meter elevated from the ground with a tilt angle of -5° to maximize the practical depth range. Finally, both these systems were required to be calibrated to receive 3D data.

3.2.4 Calibration of Qualisys

Calibration is a process that determines the relationship between the marker and anatomical axes. Wand calibration is the most commonly used method for calibrating the Qualisys system, using an L-shaped reference structure and a T-shaped calibration wand. The global coordinate system (GCS) was defined using an L-shaped reference structure where X was forward/backwards, Y was left/right, and Z was considered a vertical gravitational axis (Richards et al., 2008). Besides that, a T-shaped wand is moved and waved through the whole volume to provide a dynamic calibration of the anticipated movements (Triggs et al., 2000). Also, the Qualiysis Track Manager software (QTM) was used to collect data about the position of the cameras in order to perform computations for converting the 2D data into 3D data.

3.2.5 Calibration of Kinect

First, the background was evaluated without moving objects. Then, a dynamic calibration was conducted to detect the orientations and positions of the three Azure Kinect cameras by using a torch. Indeed, an operator held the torch and waved it slowly from the top in a descending spiral motion throughout the measurement volume (Ma et al., 2020). This process was completed when the iPi Mocap Studio software assessed the calibration quality as "Perfect" (Fig. 2).

3.2.6 Experimental protocol and data acquisition

The test was performed twice with all movements, once for familiarisation and once as an actual test. The experiment consisted of performing the following tasks for each participant: two neck bends; two consecutive lateral neck flexions to each side; two squat movements; two hip flexions; two kicks for each leg; walking one step forward and one step backwards; and one shuffle step to each side at a comfortable speed. All these movements were chosen to resemble sports activities and performed at a moderate intensity to prevent any exhaustion and injury. The 3D position and trajectories of the reflective markers were tracked at a frame rate of thirty per second, using a six-camera motion capture Qualysis system during the movements, and all the data processing was conducted with Qualysis track manager software. At the same time, the depth image data of the movements were captured by the triple Azure Kinect system at a sampling rate of 15Hz, and three recorded videos by the Azure Kinect system were merged with iPi Mocap Studio software (iPi Soft, LLC, Moscow, Russia). Locations of the shoulder, elbow, hip, knee, and ankle joints were recorded from both the Kinect skeletal model and the Qualisys motion capture system. However, the research team only analysed the squat movement data due to its greater complexity (involvement of all joints) compared to other movements, and the difficulty of analysis for a massive quantity of data recorded from all activities. It was assumed that the validity data for the squat exercise be representative of other activities with a lower level of complexity.

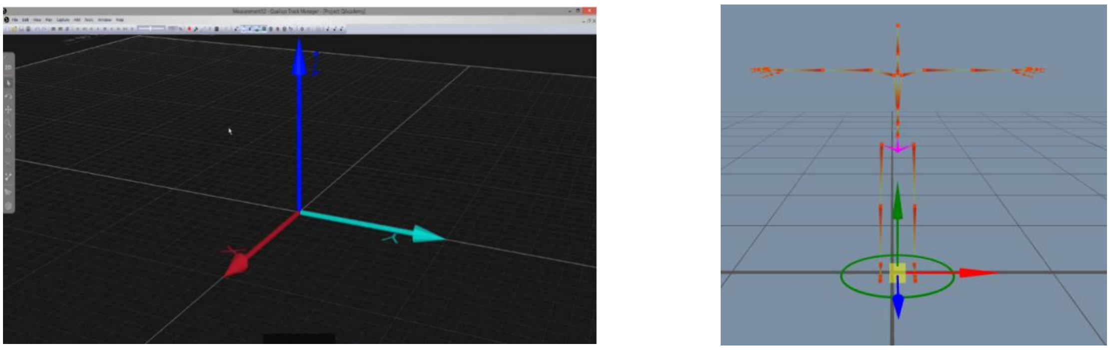
3.2.7 Synchronization of the two systems

It was tried to activate the two systems simultaneously in all tests, but the actual operational start times differed between the Qualisys and triple Azure Kinect systems because two separate computers controlled these two systems. Indeed, the time of starting to record data after sending the command was different between the two systems, which impeded synchronising them. The proposed solution was to ask each participant to stand while performing a T-pose (standing with abducted arms) for five seconds before initiating the movements to fit the generic skeleton (Fig. 3). Then, the two systems were synchronised by adding or cutting the time difference before the start of the first movements. Another issue was that the Qualisys system operated at thirty frames per second (FPS) while Azure Kinect recorded fifteen frames simultaneously. To address this issue, the data for every two consecutive frames of Qualisys was replaced by their average in order to synchronise the frame rate of the two systems.

3.2.8 Data analysis:

To analyse the data, the first frame of the initiation of the squat for each participant was individually determined and considered an original frame. Then, the difference between the coordinates data of consecutive frames and an original frame was calculated to determine the displacement of joints between the first and the end frame of the squat movements in both Azure Kinect and Qualisys in the three axes. Finally, the relative differences of all displacements in every identical frame during squat movement between Azure Kinect and Qualisys were calculated to show the errors of the Kinect when compared to the Qualisys. Also, the following data were used for transformations and equalisation of both Azure Kinect, and Qualisys coordinates systems: 1) Each Kinect joint was matched with the appropriate Qualisys marker. 2) The Azure Kinect X-axis was switched to the Qualisys Y-axis to display the mediolateral direction. 3) The Azure Kinect Y-axis was switched to the Qualisys Z-axis to express the Vertical direction. 4) The Azure Kinect Z-axis was switched to the Qualisys X-axis to represent the anterior-posterior direction. 5) The measurement units of both Azur Kinect and Qualisys measures were converted to centimetres (Figure 4).

Figure 4. Cartesian Coordinate Systems for A: Qualisys and B: Azure Kinect



A: Qualisys

B: Azure Kinect

X Kinect = Y Qual / Y Kinect = Z Qual / Z Kinect = X Qual -----> XYZ Kinect --> YZX Qualisys

3.2.9 Statistical Analysis

All statistical analyses were conducted using the SPSS V28 (IBM Corp., USA) and Excel spreadsheet. As discussed above, only the data for the squat movement was extracted, and 33 different parameters were defined in total. The difference between Azure Kinect and Qualisys data in every identical frame was calculated, which showed the magnitude of error for each joint position. Furthermore, some measures such as the mean, standard deviation (SD), root mean square error (RMSE) and ICC (Intraclass Correlation Coefficients) were calculated for the data set (Koo et al., 2016). Concurrent validity between the triple Azure Kinect and Qualisys systems was evaluated through ICC. The Interpretation of the ICC values was based on the categories for poor (<0.5), moderate (0.5-0.75), good (0.75-0.9), and excellent (>0.9) (Koo & Li, 2016). In addition, standard Bland-Altman plots with 95% limits of agreement while the y-axis was the difference, and the x-axis showed the average score, were used to visually assess the trends and bias in the data (Bland & Altman,2010). Outliers were defined as 95% limits of agreement (mean difference ± 1.96 standard deviation). These assessments compared the results between the Azure Kinect and the Qualisys while both systems were recording the squat exercise simultaneously.

3.3 Results

Sixteen healthy participants have taken part in the study. However, three were removed due to technical issues in capturing their data, and therefore, only thirteen participants remained in the final dataset, including four males and nine females [age = 32.08 ± 10.19, height = 171.49 ± 12.97, and weight = 76.64 kg ± 11.14]. Table 1 shows demographic data for thirteen participants. Overall, thirty-three different parameters were assessed during the squat exercise. Table 2 shows the ICC and RMSE of each parameter that was measured for all participants.

Table 1. Demographic features of participants

Demographic Data	Means ± SD
Age (years)	32.08 ± 10.19
Height (cm)	171.49 ± 12.97
Weight (kg)	76.64 kg ± 11.14

3.3.1 Validity

Our results showed good to excellent consistency between the two systems in the vertical (VR) direction for all joints except the ankles (Table 2). Also, moderate to good consistency was found in anterior-posterior (AP) alignment for all joints ((ICC= 0.645 to 0.884) except the ankles. Regarding the mediolateral (ML) direction, the consistency between the two systems was poor to moderate in most of the joints (ICC= 0.073 to 0.64) except for the shoulder and elbow, which demonstrated moderate to good consistency (ICC= 0.683 to 0.859). Therefore, the ankles were the only joints that showed poor agreement in all directions between the two systems (ICC= 0.022 to 0.128), while upper body joints (shoulder and elbow) showed moderate to excellent agreement in all directions (ICC= 0.683 to 0.954). The rest of the joints, including the knee, hips and sacrum, also showed moderate to excellent agreement in AP and VR direction and poor to moderate agreement in ML direction. The RMSE between the two systems ranged from 1.790 cm to 6.542 cm. The results are shown in Table 2.

Table 2. **RMSE, ICC, Upper and Lower Limit of Agreement (LOA) of 33 measured parameters**

Joints	RMSE	Upper LOA	Lower LOA	ICC
Sacrum AP	4.671	8.273	-9.802	0.695
Sacrum ML	3.970	7.792	-7.782	0.321
Sacrum Ver	4.797	10.101	-8.4279	0.934
Right Shoulder AP	4.670	7.567	-10.078	0.685
Right Shoulder ML	3.019	6.115	-5.698	0.721
Right Shoulder Ver	6.542	12.420	-13.197	0.92
Left Shoulder AP	4.061	7.519	-8.332	0.812
Left Shoulder ML	3.029	6.410	-5.257	0.683
Left Shoulder Ver	5.112	9.488	-10.473	0.953
Right Elbow AP	3.901	8.235	-6.811	0.762
Right Elbow ML	3.414	5.408	-7.401	0.781
Right Elbow Ver	4.570	8.487	-9.360	0.954
Left Elbow AP	3.836	7.630	-7.413	0.79
Left Elbow ML	2.890	6.363	-3.835	0.859
Left Elbow Ver	5.180	9.506	-10.715	0.942

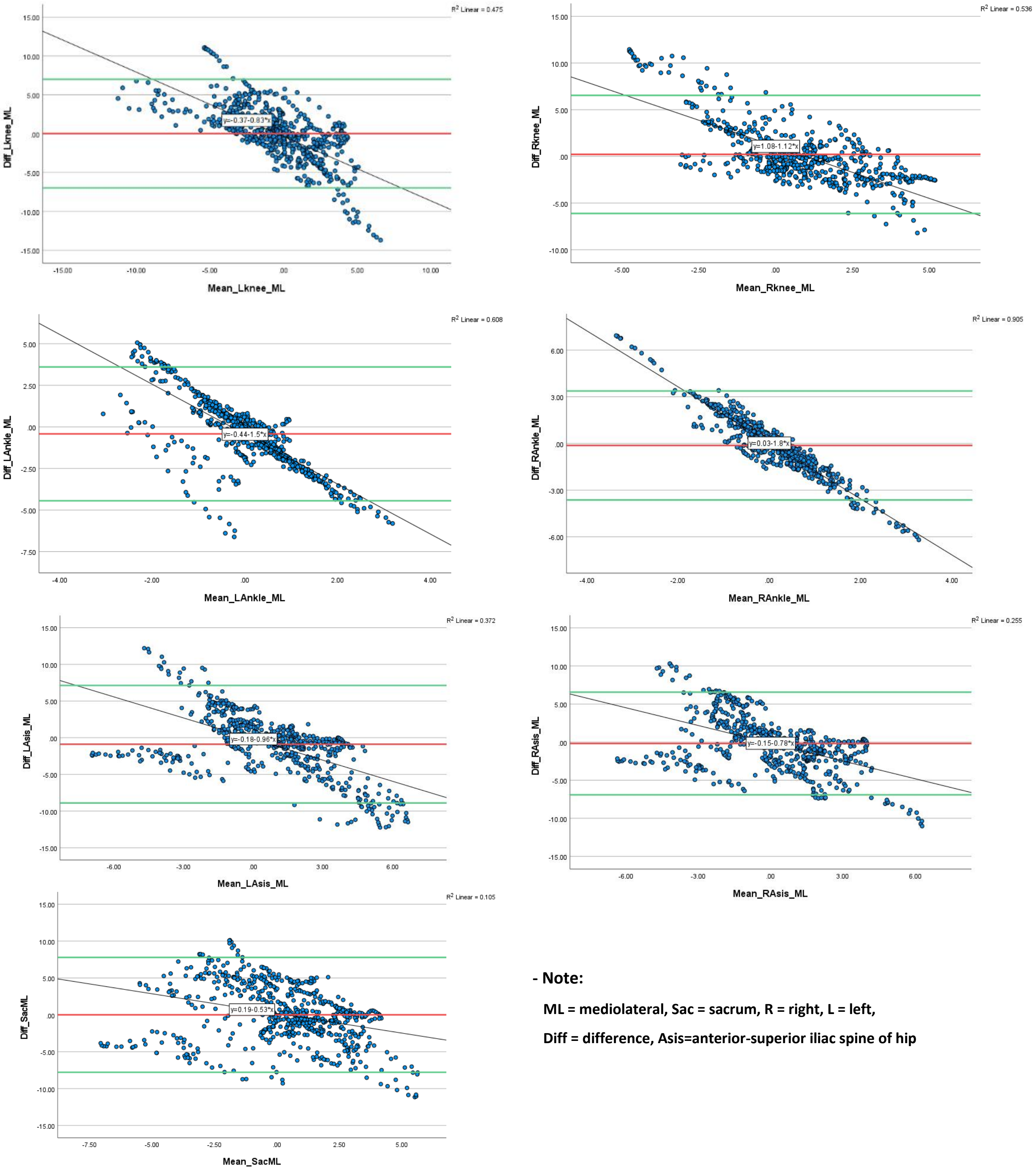
Table 2 **(continue)**

Joints	RMSE	Upper LOA	Lower LOA	ICC
Right Hip AP	5.061	9.057	-10.571	0.645
Right Hip ML	3.442	6.569	-6.914	0.41
Right Hip Ver	4.193	7.820	-8.563	0.952
Left Hip AP	3.694	7.598	-6.811	0.837
Left Hip ML	4.179	7.132	-8.893	0.385
Left Hip Ver	5.399	10.176	-10.948	0.919
Right knee AP	5.309	8.949	-11.344	0.884
Right knee ML	3.232	6.5454	-6.105	0.42
Right knee Ver	4.440	8.463	-8.932	0.862
Left knee AP	6.216	12.507	-11.842	0.817
Left knee ML	3.565	7.008	-6.975	0.64
Left knee Ver	4.555	8.312	-9.424	0.825
Right Ankle AP	3.721	7.188	-7.404	0.046
Right Ankle ML	1.790	3.375	-3.627	0.104
Right Ankle Ver	4.358	8.999	-7.980	0.022
Left Ankle AP	3.403	6.052	-7.129	0.128
Left Ankle ML	2.093	3.603	-4.441	0.073
Left Ankle Ver	3.991	8.444	-6.923	0.101

3.3.2 Bland-Altman plots

The graphs show the range of displacement measured by Kinect was overestimated in the mediolateral (ML) direction as the mean values increased at all joints. Indeed, overestimation is defined when the difference values between Qualisys and Kinect are positive numbers. Figure 5 shows the Bland-Altman plots for ML direction in the sacrum, knees, hips and ankles. Also, overestimation was observed as the mean values increased in the anterior-posterior (AP) direction of the knee (Figure 6), in the vertical (VR) direction of the Hip, and in all directions (AP, ML, VR) for the ankle (Figure 5, 6). Larger magnitudes of errors (differences between the two systems) were observed as the mean values increased in all directions at the elbow and in the AP and VR directions for the sacrum, knee, hips and shoulder joints (Figure 7). Also, there is an increased number of errors that were observed beyond the upper and lower limits of agreement (LOA 95%) as the mean values increased at the elbow, shoulder, and knee joints in the VR direction (Figure 6). A larger magnitude of errors and increased numbers of errors beyond LOA were also observed in the ML direction of the right shoulder as the means increased, when the left shoulder showed a smaller magnitude and reduced number of errors. The magnitude of errors also decreased as means values increased for the hip joints in the AP direction (Figure 8).

Figure 5. **Bland-Altman plot for Medio-lateral direction in the Knee, Ankle, Hip (anterior-posterior iliac spine) and Sacrum.**



- Note:

ML = mediolateral, Sac = sacrum, R = right, L = left,

Diff = difference, Asis=anterior-superior iliac spine of hip

Figure 6. Bland-Altman plot for anterior-posterior (AP) direction in the Knee and Ankle joints.

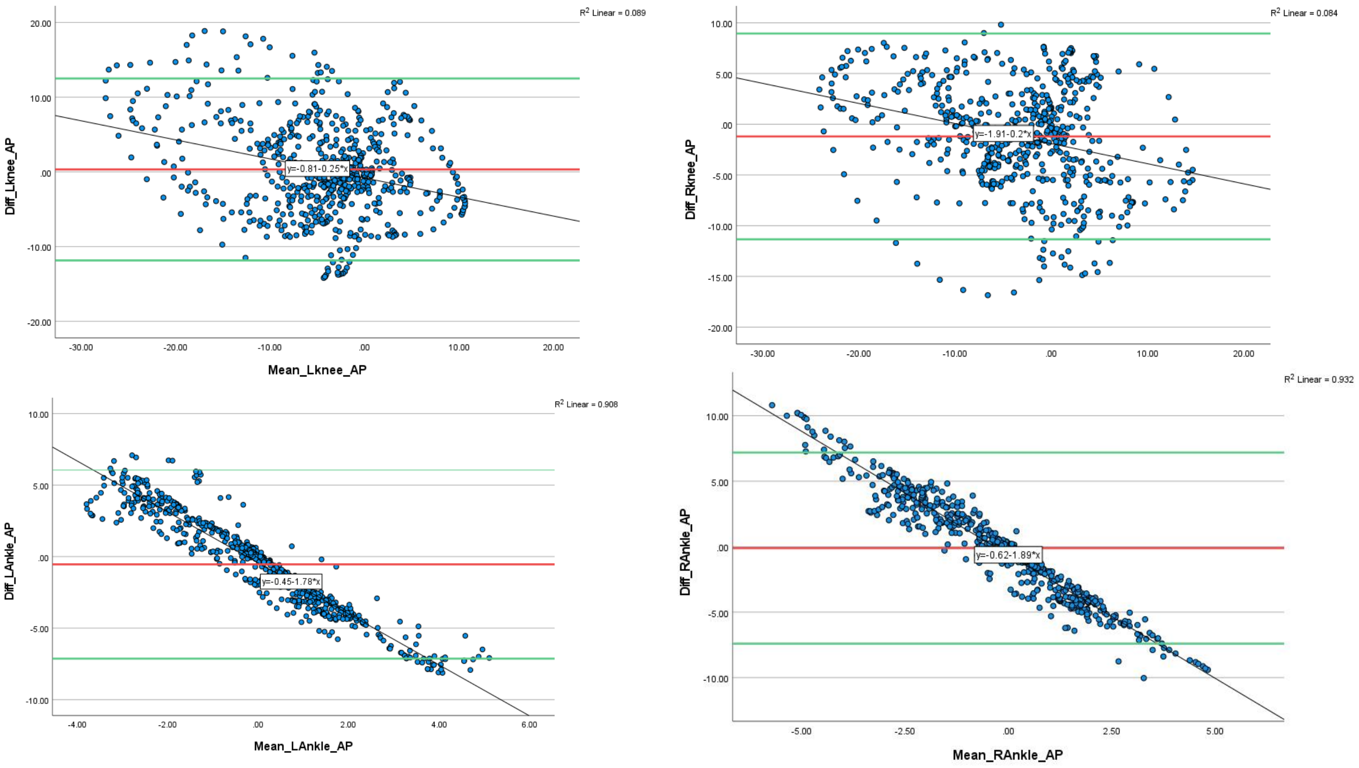


Figure 7. Bland-Altman plots for Vertical (VR) direction in the Elbow, Shoulder, Knee and sacrum joints

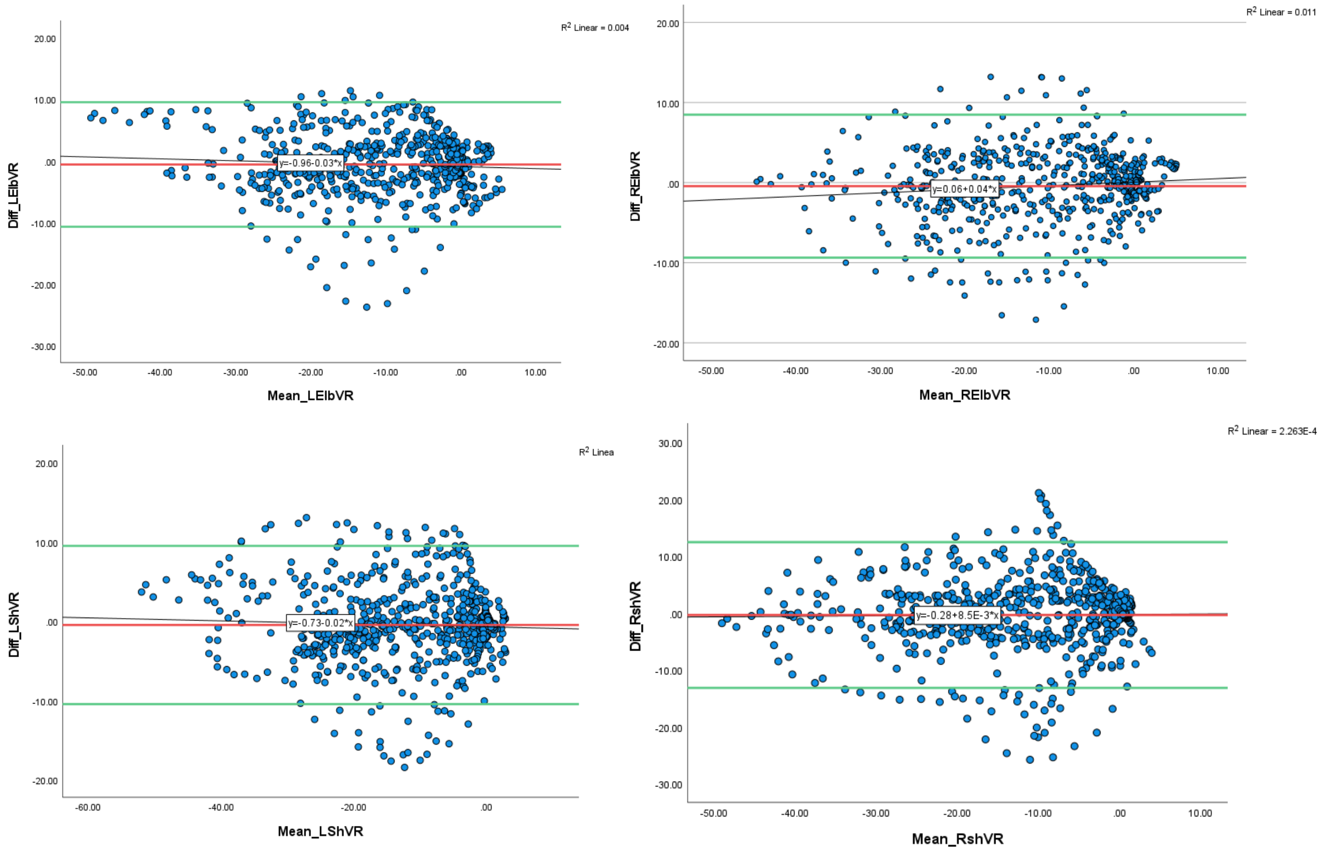
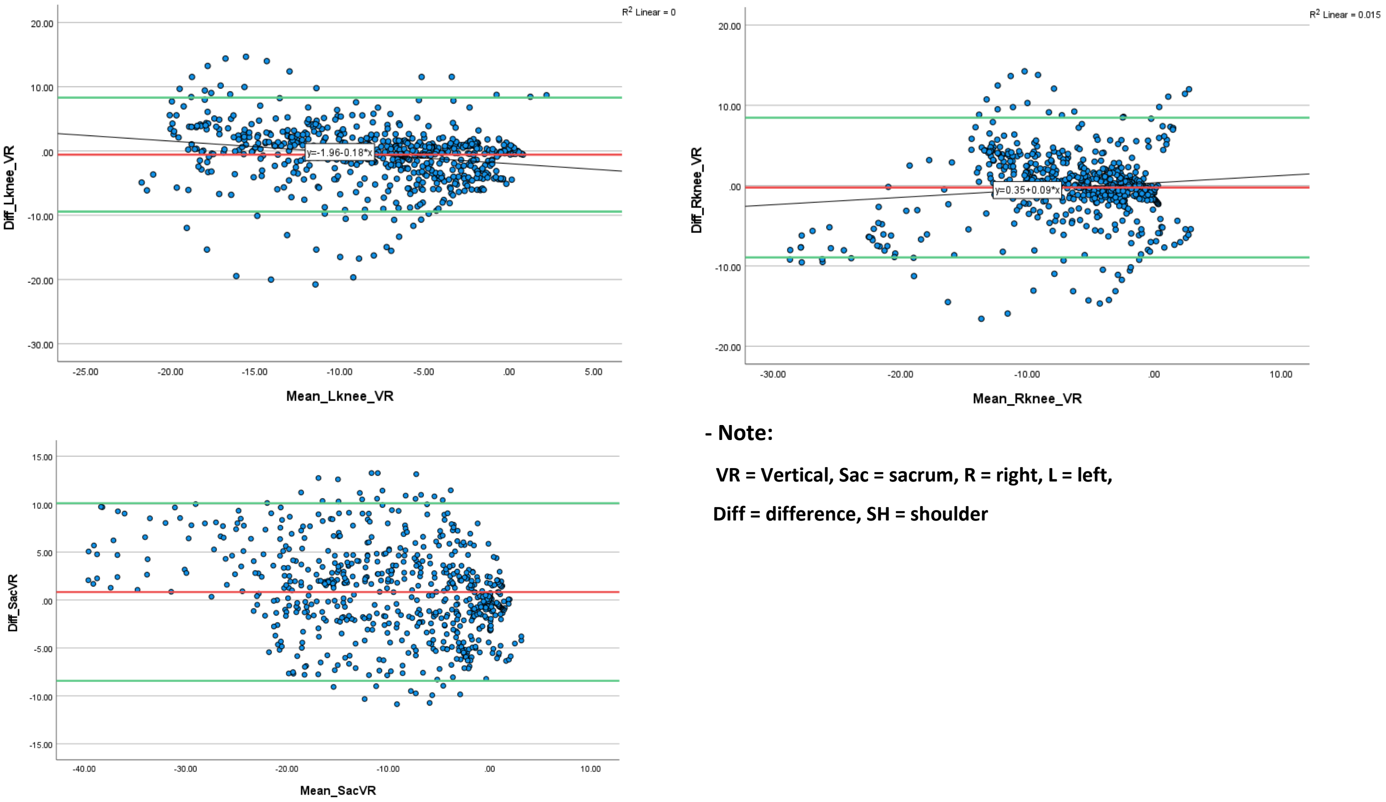


Figure 7. **(Continue)**

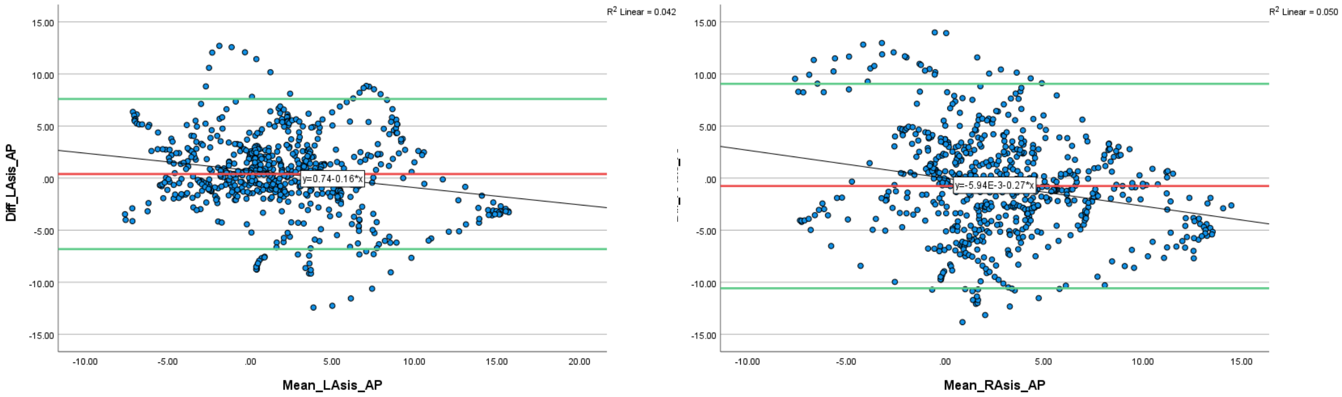


- Note:

VR = Vertical, Sac = sacrum, R = right, L = left,

Diff = difference, SH = shoulder

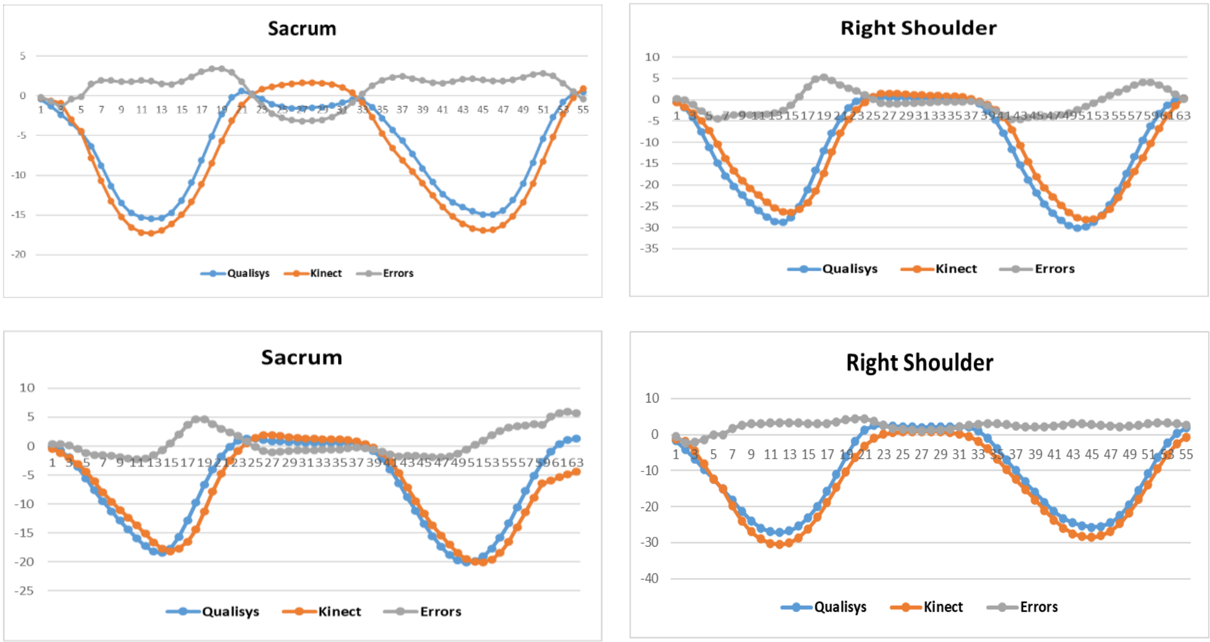
Figure 8. **Bland-Altman plot for anterior-posterior (AP) direction in the hip (anterior-superior iliac spine).**



3.4 Discussion

This study assessed the concurrent validity of the Azure Kinect, a markerless depth sensor, against Qualisys, a gold standard system for kinematic analyses, during the squat exercise. According to the findings of this study, the Azure Kinect revealed excellent consistency and correlation against Qualisys in the vertical direction during the squat exercise in all joints except the ankle. Figure 9 demonstrates the similarity and congruency in the graphs for the vertical displacements of two joints (sacrum and right shoulder) measured by the Azure Kinect and the Qualisys systems in two participants. Also, good consistency was found in the anterior-posterior (AP) direction for all joints except the ankle.

Figure 9. Vertical displacements of the sacrum and right shoulder were measured by Azure Kinect and Qualisys in two participants



The finding of this study indicated that an increased range of motion in the joints might be associated with a higher level of consistency between two measurement systems, suggesting that joint movement can be a factor that affects the agreement and consistency of the measurements. Indeed, the squat exercise is mainly considered a sagittal plane movement with the most significant displacement of joints in the vertical direction. However, there is also limited displacement in a few joints, such as the Knee and shoulder in the AP alignment and usually no displacement in the ML direction during squat exercise (some people may have mild displacement in the ML direction due to a slight postural imbalance while performing the squat exercise). Accordingly, excellent consistency between the two systems in the vertical direction during the squat exercise in all joints was observed. (Except ankles due to having constant position and low magnitude of displacement during squat). Kotsifaki et al. (2018) found similar findings by evaluating the validity of dual Kinect V2 configuration to a marker-based motion capture system (BTS-SMART 1000). They reported an excellent agreement for sagittal plane knee range of motion during the squat (flexion/extension) with ICC= 0.886 and 0854 for left and right knee respectively. In addition, Ma et al. (2020) reported similar findings by measuring the CMC between a dual-Azure Kinect system and the standard Vicon motion capture system. They showed good agreement for knee angles (CMC=0.87±0.06), and moderate agreement for hip angles (CMC=0.60±0.34) in the sagittal plane.

In contrast, our results showed that consistency between the Azure Kinect and Qualisys systems in the ML direction was poor to moderate in most joints, while the ankles were the only joints that showed complete poor agreement in all directions. Indeed, the consistency between the two measurement systems could be significantly influenced by the extent of movement; for example, reduced consistency between the two systems was observed due to the lowest range of motion in the ML direction during squat exercise and poor consistency was reported in the ankles for maintaining steady position throughout the squat. However, some studies have reported different findings. For instance, Kotsifaki et al. (2018) reported an excellent agreement between the two systems for the ankle range of motion in ML direction (abduction/adduction), which contrasted our findings. Also, Ma et al. (2020) found poor agreement between the two systems for the hip frontal angle (ML direction) and ankle movement.

In addition, RMSE for all joints and directions were calculated to indicate the average magnitude of the errors and the difference between the two measurement systems. Surprisingly, higher RMSE was reported in the Joints with larger amplitude displacement despite high ICC and consistency (For example, in the vertical direction for most joints or the knee displacement in the AP direction). This higher RMSE suggested that the measurement system might not be accurately capturing the underlying data. In contrast, lower RMSE was observed in the joints with smaller amplitude of displacement, such as the ankles, due to sustaining the constant position during the squat exercise despite poor consistency (RMSE of 1.790 and 2.093 reported for right and left ankle in ML alignment respectively).

Indeed, the coexistence of a high ICC and a high RMSE during the vertical displacement of squat exercises presented a contradiction because a high ICC indicates a strong consistency between the measurements made by the Kinect and Qualisys systems, while a high RMSE suggests significant differences between the measurements made by the two systems. One plausible explanation for this contradiction is the inherent nature of the RMSE calculation. RMSE is sensitive to the magnitude of the error, and its value increases exponentially due to the squared nature of the RMSE calculation. Therefore, although the Kinect and Qualisys systems demonstrate consistency in the direction and relative magnitude of the vertical displacement, larger displacements can lead to more substantial absolute differences between the two measurements, and slight differences in larger displacements result in significantly higher RMSE values, even when there is a strong consistency as indicated by the ICC. This means that as the vertical displacement increases, the RMSE can disproportionately increase due to its square nature, even if the relative difference between the two systems remains consistent. Another potential reason is that the Kinect system uses infrared depth sensors and RGB cameras to estimate joint positions, while the Qualisys system uses reflective markers and multiple cameras. The inherent differences in these technologies can lead to discrepancies in measurements. In addition, environmental factors such as lighting conditions, reflective surfaces, or obstructions can also affect the measurements of both systems differently. Further, different sampling rates between Kinect and Qualisys can lead to discrepancies, especially in complex movements such as squat exercises.

Therefore, the highest differences in terms of RMSE were observed in the vertical direction with larger amplitudes of displacement during the squat exercise, and the lowest discrepancies were observed for the ML direction due to having the lowest amplitude displacement. The knees were an exception because the displacement of the knees in the AP alignment is usually more considerable than the vertical displacement during the squat exercise, and thus, higher differences were observed in the AP direction for the knee than the vertical movement. Furthermore, analysis of the Bland-Altman plots demonstrated similar results, in which larger differences between the two systems and an increased number of errors beyond the upper and lower limits of agreement (LOA 95%) were observed as the mean values increased in the VR directions of all joints except for the ankles (Figure 6). Therefore, a higher difference was generally observed with an increased range of motion and larger displacement in a specific direction.

A similar pattern of accuracy for the Kinect systems with a multi-camera setup was found in recent studies. For instance, Albert et al. (2020) showed that the signal accuracy of the foot is significantly higher for the Azure Kinect compared to the previous model of Kinect. Also, Yeung et al. (2014) found that Kinect's performance was dependent on the direction of measurement with more accuracy in the ML direction. Furthermore, Merriaux et al. (2017) reported that a marker-based motion capture system had a lower accuracy for dynamic movements of the markers than the static mechanical setup. In contrast, other studies reported different results using previous Kinect models (Kinect V1 or V2). For instance, Shani et al., 2017 reported that the signal accuracy increased with a larger amplitude of movements. Accordingly, Otte et al. (2016) found the lowest accuracy in signals of the feet and ankles in all dimensions for Kinect V2 due to considerable noise in the movement signals with smaller amplitudes in Kinect V2.

According to our findings, the difference level between the measurements of the Kinect and Qualisys was shown to be both axis-dependent and motion-dependent because the lowest differences were recorded in the mediolateral direction, which contained a more stable position, whereas the largest errors were observed in the larger displacement in the vertical direction. As discussed above, a variety of factors can contribute to higher differences in large amplitude displacement during squat exercise, including 1) Measurement reasons due to the squared nature of the RMSE calculation. 2) Technical reasons, such as inherent differences in the technologies, different sampling rates between Kinect and Qualisys in complex movements, inability to track the joint centres in the Kinect system in large amplitude displacement, and an error in placing the markers for the Qualisys system that might lead to an increase in the discrepancies between the two systems. 3) Factors related to a performed exercise, such as the nature of the squat, a movement with more displacement and high volatility in the vertical direction, or a different pattern of performing the movement in each participant in terms of movement speed and amount of knee flexion. 4) The presence of two Azure Kinect cameras to track the vertical displacements through the sagittal plane and the requirement of merging these cameras' recordings. 5) Environmental factors such as lighting conditions, reflective surfaces, and obstructions can affect the measurements of both systems differently.

Another finding of this study was the overestimation of the Kinect as the mean values of errors increased in most joints based on the Bland-Altman plots. Also, the overestimation was observed in all three axes for the ankles’ measurements and in the ML direction for all joints (Figures 3 and 4). Similar results were found by Yeung et al. (2014), reporting significant overestimations of Kinect in comparison to Vicon for total body centre of mass sway. When comparing joint angles and anatomical positions to a gold standard, it's essential to understand the nature and magnitude of the errors to help interpret the data, inform practical applications, and suggest areas for future research and improvement. In this study, the overestimation of the Kinect was observed as the mean values of errors increased in the ML direction for all joints and all three axes for the ankles' measurements. One explanation is that the instantaneous cartesian system and angular measures of the Azure Kinect are still not accurate enough to avoid creating artificial jerky movements and overestimating. This phenomenon is known as 'jitter', defined as any deviation or displacement of the signal pulses in terms of amplitude, phase timing, or the width of the signal pulse. Indeed, the Jitter phenomenon has an adverse effect on the accuracy of measurements and can lead to overestimating a subject's movements. The Azure Kinect also has several advantages. For instance, it can be set up within a reasonable cost, whereas the marker-based motion tracking systems are considerably more expensive (Özsoy et al., 2022). In addition, calibration of the Azure Kinect before the measurement compared to the Qualisys system is more straightforward and effortless (Bilesan et al., 2019). Furthermore, Kinect Azure has an advanced depth sensor and AI algorithm to identify the joints' midpoints, which is able to monitor and follow the major human joints during exercise without any markers (Uhlár et al., 2021). In contrast, the Azure Kinect has certain restrictions and disadvantages. For example, it is sensitive to the external infrared source (sunlight) and unsuitable for outdoor application. Also, it cannot detect highly reflective objects. Furthermore, the Kinect Azure camera can only measure the outer shape of the human body, and the joint midpoint generated by the Kinect is not an exact anatomical location (Uhlár et al., 2021). Finally, increasing the distance between the Kinect and the subject leads to a depth error that can negatively affect the accuracy (Oh et al., 2014). In conclusion, providing some promising findings, such as the ease of setup and effortless use of a triple Azure Kinect system compared to the Qualisys system, as well as its lower cost, can make it more feasible in the clinical setting. Indeed, our results showed that the triple Azure Kinect system could be suitable for quick and valid assessment of body exercises, mainly through vertical direction based on strong consistency and high ICC reported in the vertical movements. However, there was a limitation in measuring joints' displacements through the sagittal plane due to increasing errors of the Azure Kinect against the Qualisys in the vertical dimension measurements. Therefore, further investigation might be needed to determine the consistency of various movements and to consider the potential limitations and variations in different individuals' movements, as well as the impact of external factors such as environmental conditions or equipment used. Also, setting the Azure Kinect cameras with different recording angles for vertical direction might be helpful to increase the accuracy of measurements when vertical displacement tracking is of interest, or applying a correction factor if a consistent bias is observed between the Kinect and Qualisys systems can be beneficial to reduce the RMSE without affecting the ICC.

3.5 Limitation

This study had several limitations. First, our subjects were healthy and free from injury or functional deficits. Thus, the Azure Kinect's ability to assess abnormal clinical conditions was unclear. The limited sample size might have impacted our findings, especially in sagittal plane measurements, due to the potential for high variability within a small number of participants. Future studies need to be conducted with the involvement of a larger number of participants. In addition, there was a different sample rate between the two systems in this study. Therefore, we downsampled the marker-based motion analysis data to synchronise the two datasets. Also, it is worthwhile to mention that the Qualisys motion capture system had potential sources of errors despite being considered a gold standard for evaluating human motion. For instance, one of the disadvantages was the requirement for at least two cameras at any specific time to track each marker to be perfectly interpolated. Another source of error for Qualisys was the soft tissue artefacts resulting from the movement of markers on the subject's clothes, which no longer led the reflective markers to correspond to the underlying anatomical bone landmarks (Albert et al., 2020). Therefore, adequate Qualisys cameras need to be placed in the clinical setting. Despite these limitations, the results of the current study showed the feasibility of using the Azure Kinect to assess movement, particularly in the ML direction. Indeed, validating the Azure Kinect system can be a valuable resource for other investigators who are testing the novel capabilities of markerless motion capture systems in different research settings.

3.6 Conclusions

The markerless Azure Kinect system provides a consistent track of the joint centres' displacements in the vertical dimension, and it offers comparable data to a marker-based motion analysis system when performing the double-leg squat. Also, the Azure Kinect provides multiple benefits over marker-based motion capture systems for assessing movements, such as not requiring any markers to be attached to the body and a lower cost compared with the gold standard maker-based system, which significantly improves clinical feasibility and reduces testing time. This study indicated that the Azure Kinect achieved moderate to excellent consistency against Qualisys in the vertical (VR) and AP directions for all joints except the ankles, which showed poor agreement in all directions between the two systems. In addition, poor to moderate consistency was reported between the two systems in the ML direction for most of the joints except for the shoulder and elbow, which showed moderate to excellent consistency in all directions. The data presented in this study suggest that the markerless triple Azure Kinect motion capture system has the potential to be an alternative to a gold standard Qualisys marker-based system for specific applications such as human activities, especially in the sagittal plane. However, further investigations must be conducted to determine the consistency of different movements and to calculate for which activities it is possible to perform an accurate enough correction. Also, future studies might be beneficial to explore the Azure Kinect's potential for use in the assessment of specific movements in abnormal clinical conditions and to identify the limitations of Kinect accuracy in various movements and planes of motion.

Finally, the square nature of RMSE makes it sensitive to error magnitude and can increase the values exponentially. This means larger displacements still result in higher RMSE values, even with high ICC and consistent relative measurements. Also, environmental factors and varying sampling rates between the two systems can further contribute to these differences, especially in complex movements like squats. Therefore, this exponential increase in RMSE values due to larger displacements underscores the necessity of accurately measuring and minimising errors to obtain valid results. Additionally, it highlights the importance of carefully considering error magnitude when interpreting RMSE values in relation to ICC and relative measurements because a high RMSE might not necessarily indicate poor validity but might reflect the data's inherent variability or unpredictability.

In conclusion, the main findings of this study were listed in the following: 1) moderate to excellent consistency of the Azure Kinect against Qualisys for vertical and AP direction during the squat exercise in all joints except the ankles (Ankles were reported as the only joints with a poor agreement in all directions), and poor to moderate consistency between the two systems in the ML direction, 2) overestimation of the Kinect in most joint measures during the squat exercise, and finally 3) the differences between Azure Kinect and Qualisys measurements in terms of directional components and extent of displacement, including the higher differences between Azure Kinect and Qualisys systems for vertical direction and the lower differences for mediolateral movements that indicated data's inherent variability or unpredictability.

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Chapter 4

General Discussion and Conclusion

4.1 Summary

ACL reconstruction (ACLR) is the standard treatment for athletes suffering from ACL injuries. However, it does not fully restore knee function, leading to neuromuscular control asymmetries post-ACLR, increased risk of re-injury, and performance decline. Traditional rehabilitation, which mainly involves repetitive exercises, can become monotonous and result in decreased motivation. Game-based rehabilitation systems have shown promise in improving outcomes and increasing motivation. Biomechanical assessments are used to measure knee movement functionality, with most systems being marker-based. Though accurate, these systems are expensive and impractical for clinical settings. Markerless systems, such as the Microsoft Kinect, are more affordable and convenient.

This research consisted of two studies to develop a logical framework and intervention in future to underpin an approach for patients experiencing sports injuries in the rehabilitation programme. The first study (Chapter Two) was a systematic review to evaluate current evidence, and the research methods were conducted on applying immersive technologies to rehabilitation outcomes and performance assessment after ACL reconstruction. The findings indicate that VR interventions and immersive technologies may provide a promising approach for improving rehabilitation outcomes such as proprioception and pain management. Also, VR-based systems can be a considerable alternative to real-world training to improve certain aspects of athletic performance because immersive technologies offer a tool to control virtual environmental features effectively. Finally, immersive technologies and VR-based systems are still in their infancy and will need considerable improvements in the future. Therefore, further research needs to be conducted in a theoretical frame to acknowledge the profitability of VR interventions in sports performance and rehabilitation programmes.

The second study (Chapter Three) was conducted to evaluate the concurrent validity of the updated markerless motion capture system (triple Azure Kinect) against the gold standard marker-based motion capture system (Qualisys). This study found that Azure Kinect showed moderate to excellent consistency against Qualisys in vertical and AP directions but had discrepancies in the vertical direction and larger displacements. Despite some accuracy differences, the Azure Kinect system is a potential alternative to Qualisys for specific applications, especially in the frontal and sagittal planes. Further research is needed to determine its effectiveness in assessing abnormal clinical conditions. In summary, Azure Kinect offers a cost-effective, convenient alternative to traditional marker-based systems, with comparable accuracy in certain movements like double-leg squats.

4.2 Conclusion

This research indicated that virtual reality-based interventions could improve rehabilitation outcomes after ACL reconstruction. Also, immersive technology interventions could affect the performance and biomechanical assessment to reach full-body tasks earlier after ACL injuries. The findings indicated that VR-based systems could be a considerable alternative to real-world training to improve certain aspects of athletic performance because immersive technologies effectively offer a tool to control virtual environmental features. Also, virtual Reality (VR) offers promising advantages in rehabilitation settings, such as simulating real-world tasks in a controlled environment, replicating daily activities and sport-specific scenarios, promoting more frequent use and enhancing patient adherence to rehabilitation programmes due to its immersive nature. Additionally, VR can distract patients, leading to more natural movements and improved recovery, and provide a safe platform for practising potentially risky movements, resulting in better biomechanical outcomes. Finally, immersive technologies and VR-based systems are still in their infancy and will need considerable improvements in the future. Therefore, further research needs to be conducted in a theoretical frame to acknowledge the profitability of VR interventions in sports performance and rehabilitation programmes.

Furthermore, the triple Azure Kinect system provides a consistent track of the joint centres' displacements with moderate to excellent consistency in the vertical and AP direction during the squat exercise in all joints except the ankles, particularly in upper joints such as the elbow and shoulder. Also, lower differences were observed in the joints with lower displacement amplitude, such as the ankles, due to sustaining the stable position during the squat exercise, and higher differences were observed with more significant displacement, such as the vertical direction in most joints. This means a contradiction was observed between ICC and RMSE because a high ICC in the vertical direction showed consistent measurements between the Kinect and Qualisys systems, while a high RMSE indicated significant differences between the two systems in the vertical direction. This paradox resulted from the RMSE's sensitivity to error magnitude and the inherent nature of the RMSE calculation, along with environmental factors and differences in the technologies and sampling rates between the two systems. In addition, the Azure Kinect provides multiple benefits over marker-based motion capture systems for assessing movements, such as not requiring any markers to be attached to the body and a lower cost when compared to the gold standard maker-based system, significantly improving clinical feasibility and reducing testing time. However, the Azure Kinect system showed poor to moderate consistency in the ML directions and completely poor agreement in all directions for the ankles. In conclusion, the markerless triple Azure Kinect motion capture system may be a considerable alternative to a gold standard Qualisys marker-based system for specific applications such as human activities in the sagittal plane. However, future investigations must be conducted to acknowledge the Azure Kinect's profitability in the assessment of abnormal clinical conditions and the limits of Kinect's accuracy in various movements and planes of motion.

Appendices

Appendix 1

OXFORD
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UNIVERSITY

CONSENT FORM

Title of the study

The validity of the Kinect camera for body tracking of dynamic movements.

For any questions, you can contact the research team in the following:

- Dr Ali Aminalshareih Najafi. Centre for Movement, Occupational, and Rehabilitation Sciences (MORES), Oxford Brookes University. Email: 1809423@brookes.ac.uk

- Professor Helen Dawes. Centre for Movement, Occupational, and Rehabilitation Sciences (MORES),OxINMAHR Faculty of Health and Life Sciences, Oxford Health NHS Foundation Trust, Oxford Brookes University. Email: hdawes@brookes.ac.uk

- Dr Maedeh Mansoubi. Centre for Movement, Occupational, and Rehabilitation Sciences (MORES),

OxINMAHR Faculty of Health and Life Sciences, Oxford Brookes University.

email: mmansoubi@brookes.ac.uk

- Dr Anne Delextrat. Centre for Movement, Occupational, and Rehabilitation Sciences (MORES), OxINMAHR Faculty of Health and Life Sciences, Oxford Brookes University.

Email: adelextrat@brookes.ac.uk

- Prof Timothy Denison. Nuffield Department of Clinical eurosciences, Dept of Engineering science, University of Oxford. Email: timothy.denison@eng.ox.ac.uk

Please initial box

	No	**Yes**
1. I confirm that I have read and understand the information sheet for the above study and have had the opportunity to ask questions.	☐	☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving reason.	☐	☐
3. I agree to take part in the above study.	☐	☐
4. I understand that as a part of the study, I will be audio and video recorded.	☐	☐

Please initial box

	Yes	No
5. I agree to the use of anonymised quotes in publications	☐	☐
6. I agree that an anonymised data set, gathered for this study may be stored in a specialist data centre/repository relevant to this subject area for future research	☐	☐

Thank you for your interest in this project. Just to remind you, the data you provide in the course of this project will be treated in the strictest confidence and will be used for research purposes only. Furthermore, as a participant in this research you will never be identified in any outputs (e.g., reports, research articles) that arise from this project and your data will never be identifiable or viewed by any other party outside the research team.

_________________________ _______________ _____________________

Name of Participant Date Signature

_________________________ _______________ _____________________

Name of Researcher Date Signature

Appendix 2

The validity of the Kinect camera for body tracking of dynamic movements.

Invitation paragraph

You are being invited to take part in this PhD research study. Please take time to read the following information carefully and discuss it with others if you wish to understand why the research is being done and what it will involve before you decide to take part. This information sheet will explain more about what would happen if you were involved in this study. *If you would like more information or there is anything that is not clear to you, please do not hesitate to contact us. Thanks for your consideration.*

What is the purpose of the study?

There are several ways to track body movements, and depth cameras are a low-priced alternative to expensive and complex marker-based motion capture systems. Microsoft has recently released Azure Kinect camera with an improved image sensing technology which can track human motions in various motor tasks.

This study aims to indicate that Azure Kinect is valid when compared to the gold standard maker-based system.

Why have I been invited to participate?

You and 29 other participants have been invited because you are aged 18 to 65 years old, free from injury and healthy. You should also meet the following inclusion criteria:

1) Having no existence of injuries
2) Having no surgery over the past year
3) Having no existence of the long-term illness or conditions which prevent you from taking part the study

Do I have to take part?

The participation is entirely voluntary, and you are able to withdraw at any time before placing the markers as well as deleting your data. Having accepted to take part the study, you will be provided with a consent form which will be returned to the researchers and an information sheet which involves the researchers' contact details in order to contact the researchers if you have any further queries about the research. *It is up to you to decide whether or not to take part. Also, your personal or professional relationship with researchers will not be affected if you decide not to take part. For instance,* if you are a student of one of the research members or you are a member of staff from Oxford Brookes University, deciding whether to take part or not will not affect your future studies or career. Finally, *if you do decide to take part, you will be able to keep a copy of this information sheet and you need to indicate your agreement to the consent form.*

What will happen to me if I take part?

Before starting the study, we will check your informed consent and make sure you have filled out a questionnaire. If you decide to take part in the study, the informed consent will be sent to you by email to complete with a digital signature agreeing your consent to take part. Then, you will attend in the Oxford Brookes University movement lab in one session, and you will perform some body movement such as squatting, walking, jumping, side shuffling, bending forward and neck movements. You will be equipped with 16 reflective markers corresponding to anatomical landmarks and marker trajectories will be captured by some cameras. Data will be collected by using these special markers which are covered with a retro-reflective material to reflect light which is generated near the camera lens. The camera can be adjusted to reveal only the bright reflective markers and ignore skin and fabric. All the data processing will be conducted with software, and your data will stay anonymous throughout the study. An avatar will replace you during video recording so that your identity will remain confidential. The expected duration will be 30 minutes and will begin with a 15-minute familiarization, informed consent and questionnaires followed by 10 minutes to place the markers and 5 minutes for performing and recording the movement.

Accumulative Time	Task	Duration	Description
00:00:00 - 00:15:00	Recheck consent Form	2 min	
	Questionnaires	8 min	Physical readiness questionnaire
	Familiarisation	5 min	Elaboration of the equipment, markers and body movements
00:15:00 - 00:25:00	Place the markers	10 min	Reflective, tiny and spherical markers are used for body tracking
00:25:00 - 00:28:00 **(3 minutes)**	Standing	10 sec	
	Neck movement	30 sec	Bending forward, backward and side (2 times for each movement)
	Bending forward	15 sec	
	Bending to sides	30 sec	2 times to the right side and 2 times to the left side
	Squatting	15 sec	2 times
	Hip and knee flexion	15 sec	Bending thigh and knee while standing (2 times for each leg)
	Kick (shoot)	20 sec	2 times for each leg
	Shuffle walking	15 sec	1 step to right side and 1 step to left side
	Gait (walking)	15 sec	2 steps forward and 2 steps backward
	Jumping	15 sec	2 times
00:28:00 - 00:30:00	Removing the markers	2 min	

Enrolment

approx. 10 min

- Complete informed consent form and PAR-Q questionnaire

↓

Experiment

approx. 15 min

- Marker placement (10 min)

What are the possible disadvantages and risks of taking part?

There will be no disadvantages or discomfort for participants in this research and the potential physical harm will be the same as any experienced in everyday life. Also, the first aid support will always be available during the session. You will need to dedicate approximately 30 minutes of your time to complete session at the Oxford Brookes University movement labs.

What are the possible benefits of taking part?

There may or may not be a direct benefit to you from participating in this study. Some people can enjoy taking part in this study. Also, the results of this study will help improve the body tracking systems and represent the impact of virtual reality as an adjuvant therapy to improve the quality of care in the future. It may also be interesting for you to see how scientific research is conducted. You will not be compensated for your participation in this study.

Will what I say in this study be kept confidential?

All the data collected throughout the research will be kept strictly confidential. You will not be able to be identifiable in any reports or publications. Collected information may be shared in an anonymised form to allow reuse by the research team and other third parties. Activities of the Participants will be video recorded, and the video data will only be observed by members of the research team. Data will be stored securely at MOReS lab at Oxford Brookes University, and data files will only be accessible to the research team. Consent forms and demographic forms will be stored separately from the data and saved at a secure location. Also, laptops and other devices should be password protected and Data will be stored in Google Drive, for which the University has a security agreement.

What should I do if I want to take part?

If you decide to take part, you would first have to sign the consent form given to you by a member of the research team. The consent forms and will be stored separately from the data and saved at a secure location. The part of the data which does not breach participants' confidentiality, will be available more widely upon request. Then, you are able to take part in the study after filling in a questionnaire regarding your physical activity readiness (PAR-Q questionnaire) which will be completed after obtaining your consent and checking safety measures of testing performed by the research team.

What will happen to the results of the research study?

Data collected in the course of the research will be kept securely in accordance with the University's policy of Academic Integrity for a period of ten years after completion of the study. The results of this study may be published in professional journals as well as being used in the PhD dissertation. However, you will not be identifiable in any report or publication. Also, if you need to be given a copy of any reports from the research, please do not hesitate to ask us to be offered to you.

Who is organising and funding the research?

This research conducted by Dr Ali Amanialsharieh Najafi as a PhD student at Oxford Brookes University with a partnership involving Prof Helen Dawes, Dr Maedeh Mansoubi and Dr Anne Delextrat of Oxford Brookes University (UK) as well as Prof Timothy Denison of the University of Oxford. This work is supported by Elizabeth Casson Trust (ECT), NIHR Oxford Biomedical Centre (BRC) and the CLEAR trust. Also, Centre for Movement, Occupation and Rehabilitation Sciences (MOReS) and Oxford Brookes University are the organisational affiliations of this project.

Who has reviewed the study?

This research has ethically been approved by the University Research Ethics Committee, Oxford Brookes University.

Contact for Further Information

If you have any concerns about how the study has been conducted, you should contact the Chair of the University Research Ethics Committee: ethics@brookes.ac.uk.

For any questions, you can contact the research team in the following:

- Dr Ali Aminalshareih Najafi. Centre for Movement, Occupational, and Rehabilitation Sciences (MORES), Oxford Brookes University. Email: 1809423@brookes.ac.uk

- Professor Helen Dawes. Centre for Movement, Occupational, and Rehabilitation Sciences (MORES),

OxINMAHR Faculty of Health and Life Sciences, Oxford Health NHS Foundation Trust, Oxford Brookes University. Email: hdawes@brookes.ac.uk

- Dr Maedeh Mansoubi. Centre for Movement, Occupational, and Rehabilitation Sciences (MORES),

OxINMAHR Faculty of Health and Life Sciences, Oxford Brookes University.

email: mmansoubi@brookes.ac.uk

- Dr Anne Delextrat. Centre for Movement, Occupational, and Rehabilitation Sciences (MORES), OxINMAHR

Faculty of Health and Life Sciences, Oxford Brookes University.

Email: adelextrat@brookes.ac.uk

- Prof Timothy Denison. Nuffield Department of Clinical eurosciences, Dept of Engineering science, University of Oxford. Email: timothy.denison@eng.ox.ac.uk

Thank you for considering taking part in this study, and we look forward to hearing from you.

Azure Kinect camera	It is a type of entertainment camera and is not medical device	
Retroreflective Marker	These markers are covered with a retro-reflective material to reflect light which is generated near the camera lens.	

Appendix 3

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Privacy Notice for Research Participants

This Privacy Notice provides information on how Oxford Brookes University (Oxford Brookes) collects and uses participant's personal information when you take part in one of our research projects. Please refer to the research Participant Information Sheet for further details about the study and what information will be collected about you and how it will be used.

Oxford Brookes is the Data Controller of any data that you supply for this research. This means that we are responsible for looking after your information and using it lawfully. We will make the decisions on how your data is used and for what reasons.

Why do we need your data?

We aim to assess the validity of the Kinect camera and virtual reality software for body tracking of dynamic movements and then we will assess a type of exercise called squatting to indicate the effects of the virtual reality technologies on reducing pain intensity during repetitive exercise.

Oxford Brookes' legal basis for collecting this data is:

Personal Data identifies you. Brookes' students carry out research, as we are a centre of learning. Brookes' staff may carry out research for the same reason, or in order to improve our courses, staff experience or to comply with our legal obligations. It is in the legitimate interests of the University to carry out research where commercially oriented research is sanctioned.

Your consent is an ethical requirement.

Oxford Brookes University's legal basis for processing your Personal Data (or information) is as set out in Art 6 UK GDPR.

Special Category Data:

Oxford Brookes may ask you for sensitive data such as: racial or ethnic origin, political opinions, religious or philosophical beliefs, trade-union membership, data concerning health or sexual life, genetic/biometric data. This is defined by law as Special Category Data. If Oxford Brookes requests this data it can only be used because one of the following processing exemptions applies as set out in Art 9 UK GDPR:

- You have given OBU explicit consent to do so; and
- Processing is necessary for scientific or research in the public interest. We need this information to customize our algorithm so the result could be validated across different ethnicity, race, sex and age.

What type of personal data will Oxford Brookes use?

This research will require:

- your name, contact details.
- Demographic details including Age (year of birth), Sex, Height, and Weight.
- Your physical readiness which will be assessed through a questionnaire.
- Data concerning your health.
- Video data recorded during the test only.

You will be allocated a unique participant identification number in order to pseudonymise your data.

Who will Oxford Brookes share your data with?

The study data will be accessible to the research team from Oxford Brookes University and authorised members of Oxford Brookes University if required for monitoring purposes. Moreover, Access to qualitative data will be confined to the researchers working on the project. If it is necessary to transfer data between the research team, files will only be sent via the university's secure file sharing facility including university password-protected Google Drive and official emails. Consent forms and demographic forms will be stored separately from the data and saved at a secure location. Also, laptops and other devices should be password protected and Data will be stored in Google Drive, for which the University has a security agreement. The research will be read within the University, where appropriate among project team members. Where it is intended that it is published, your data may be seen by members of the public.

Your anonymised data set may be stored in a specialist data centre/repository relevant to this subject area for future research. There may be additional information about this in the Participant Information Sheet.

Will OBU transfer my data outside of the UK?

No

What rights do I have regarding my data that Oxford Brookes holds?

- You have the right to be informed about what data will be collected and how this will be used.
- You have the right of access to your data.
- You have the right to correct data if it is wrong.
- You have the right to ask for your data to be deleted.
- You have the right to restrict use of the data we hold about you.
- You have the right to data portability.
- You have the right to object to Oxford Brookes using your data.
- You have rights in relation to using your data in automated decision making and profiling.

Your rights will depend on the legal ground used to process your data.

Where did Oxford Brookes source my data from?

Data of this study will have been provided by yourself.

Are there any consequences of not providing the requested data?

There are no consequences of not providing data for this research. It is purely voluntary. If you like to withdraw part way through the research, the Participant Information Sheet includes this information. It may be that some of the data that you have provided has already been used in the research. If you would like more information about this, you should feel free to contact the research team.

Will there be any automated decision making using my data?

There will be no use of automated decision making in scope of UK Data Protection and Privacy legislation.

How long will Oxford Brookes keep your data?

In line with Oxford Brookes policies, data generated in the course of research will be kept securely in electronic form for at least ten years after the project has ended in accordance with University's policy. After this point, all data files will be permanently deleted.

Who can I contact if I have concerns?

In the event of any questions about the research study, please contact the research team in the first instance. Their contact details are listed on the Participant Information Sheet. If you have any concerns about the way in which the study has been conducted, please contact the Chair of the University Research Ethics Committee at ethics@brookes.ac.uk. For further details about information use contact the Information Security Management team on info.sec@brookes.ac.uk or the Data Protection Officer at brookesdpo@brookes.ac.uk. You can also contact the Information Commissioner's Office via their website ico.org.uk.

Appendix 4

Ethics Approval

Dr Anne Delextrat
Director of Studies
Faculty of Health and Life Sciences
Oxford Brookes University
15th July 2021
Dear Dr Delextrat,

UREC Registration No: 201485
Study title: The development and evaluation of virtual reality-based training on the performance and rehabilitation outcomes

Thank you for the email of 8th July 2021 outlining the response to the points raised in my previous conditional approval letter regarding the PhD study of your research student, Ali Aminalsharieh Najafi and attaching the revised documents. I am pleased to inform you that, on this basis, UREC is happy to grant full approval for this study.

The UREC approval period for the data collection phase of the study is two years from the date of this letter, so until 15th July 2023. If you need the approval to be extended please do contact me nearer the time of expiry.

Should the recruitment, methodology or data storage change from your original plans, or should any study participants experience adverse physical, psychological, social, legal or economic effects from the research, please inform me with full details as soon as possible.

Yours sincerely,
Dr Sarah Quinton
Chair of the University Research Ethics Committee
cc Dr Maedeh Mansoubi, Supervisory Team
Prof Timothy Denison, Supervisory Team
Dr Ali Aminalsharieh Najafi, Research Student
Dr Andrew Mitchelmore, Research Ethics Officer
Dr Robyn Curtis, Research Ethics & Integrity Officer

Appendix 5

PAR-Q questionnaire

Physical activity Readiness Questionnaire (PAR-Q questionnaire)		
Evaluation of participants' readiness to start an exercise program	Yes	No
1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?		
2. Do you feel pain in your chest when you do physical activity?		
3. In the past month, have you had chest pain when you were not doing physical activity?		
4. Do you lose your balance because of dizziness or do you ever lose consciousness?		
5. Do you have a bone or joint problem that could be made worse by a change in your physical activity?		
6. Is your doctor currently prescribing drugs (for example, water pills) for your blood_pressure or heart condition?		
7. Do you know of any other reason why you should not do physical activity?		
If YES, please comment:		

______________________________ ________________ ________________________

Name of Participant Date Signature

______________________________ ________________ ________________________

Name of Researcher Date Signature

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