UNIVERSITY OF TWENTE.

Faculty of Science and Technology
Faculty of Electrical Engineering, Mathematics & Computer Science

Towards the Development of an Objective Movement Analysis Method within a Sport-Specific Context for the Improvement of RTS Decision-Making during ACL Rehabilitation

Marie-Laure Snijders

MSc Biomedical Engineering / MSc Interaction Technology

August 2023

Supervisors:
Dr. ir. D. Reidsma, *Human Media Interaction*
Dr. J. Reenalda, *Biomedical Signals and Systems*
R.P. van Middelaar, *Biomedical Signals and Systems*
Dr. A. Gokeler

Biomedical Signals and Systems
Human Media Interaction
University of Twente
Enschede, The Netherlands

ABSTRACT

Within the current post-operative rehabilitation practice of anterior cruciate ligament (ACL) ruptures, the functional movement evaluation for the return to sports (RTS) is performed through the use of standardised tests and interpreted based on the expertise of the physiotherapist. Central to this key evaluation is the frequently-used horizontal single-leg jump, in which jumping performance is considered based on ill-defined qualitative aspects as well as the limb symmetry index (LSI) that quantifies leg performance based on a jumping distance comparison. This method of evaluation does not adequately identify risk factors in the movement functionality nor does it provide an objective insight into the performance of a patient, leading to high re-injury and discrepancies between physiotherapist clinics. To improve the current decision-making during the RTS evaluation of ACL patients, this work proposes a combination of sensor technology for objective movement evaluation within a rich perceptual-cognitive virtual environment. Within the design, IMU sensors (Xsens MVN) were integrated into a Virtual Reality (VR) setup that triggered study participants to make single-leg jumps at pre-determined intervals of 20, 40, 60, and 80% of their maximum single-leg jumping distance (as measured within the VR condition). In addition, perceptual-cognitive pressure was increased by including an unpredictable dual-task for the jump, sensory stimulation and motivating external focus in the jump task. The system was evaluated with a user study of $n = 18$ healthy participants who were externally perturbed on their non-dominant leg to simulate the ACL-affected jumping movement behaviours. Based on this proof-of-concept evaluation, we were able to show the effectiveness of using VR as a more ecologically valid and high-potential method for increasing sport-specificity in ACL-affected functional movement tests. The use of such a gamified system was found to be engaging and challenging while participants were still able to safely and comfortably perform all movements required of them. With the current methodology, the kinematic data allowed for identifying discriminatory features between the perturbed and non-perturbed leg, which gives hope for exploring similar features that can evaluate the functional movement performance of the ACL-affected leg at the RTS decision. In addition, as differences in jumping performance were also identified for the smaller-distance jumps, this study motivates the use of more single-leg jumps at targeted shorter distances using sensor measurement rather than relying on maximum single-leg jumps for LSI evaluation, to provide a deeper and more reliable consideration of knee functionality.

Keywords
Anterior cruciate ligament — Knee rehabilitation — Return to sports — Diagnostic measurement — Kinematic movement sensing — IMU sensors — Sports interaction technology — Virtual Reality

PREFACE

My thesis work has been a great experience for me to write. As the capstone to my studies at the University of Twente, I was very excited to bring my two Master's studies together in this work. From the moment I chose my Masters, I was amazed at how well my separate study fields fit together. On the one side, Biomedical Engineering builds toward medical devices, practices and analyses that can affect patients within every branch of healthcare. On the other, Interaction Technology provides the tools to bring such medical interventions to the end user in a way that they can meaningfully use them. Both fields are needed for true innovation within the topic of healthcare, and I have seen them complement one another throughout my studies. Within my thesis topic, I was able to integrate these two sides within my own project. As I was preparing for my thesis to start, I knew I wanted to work on rehabilitation. It is such an exciting and innovative medical field, which fits so well with the human-centredness of interaction technology. It was the perfect fit for me to explore for myself how well these two fields could work together.

With a double degree, the trajectory of this work was long, but I am still as excited (or perhaps even more) about this topic as I was at the start. I was able to shape the topic to my interests and allow myself to learn new skills, programmes, coding languages and methodologies along the way. But aside from the long days of programming, analysing data and writing, my main takeaway from this project is in bringing specialists from different fields together on a topic. As both a biomedical engineer and interaction technologist, I see my future work as being someone who can translate input from one field to another. With the different specialists I got to involve in this project, I received new insights and viewpoints that let me see my research objectives in a new light. This made my thesis a multidisciplinary endeavour far beyond my own study combination, and a challenging one at that.

The end result of my thesis has become quite an extensive work. While inherent to the task I set out to achieve and the combination of fields I had to make, this was also partly to blame by my own enthusiasm. An almost central part of my supervisor meetings entailed me being pulled away from adding even more ideas or possible focus points to my thesis. Such are the dangers of an engaging topic! In this, I am very grateful to my supervisors for their endless support in helping me shape and structure my project and their willingness to still give me the space to explore the high potential of this study.

I am especially grateful for my main supervisors Dennis Reidsma and Jasper Reenalda. Dennis, I have immensely enjoyed our bi-weekly talks in which you shared my excitement for the study and its outcomes. You have helped me to shape and structure the work and could always - even with only a few short words - make me think deeper about the choices I was making along the way. Jasper, thank you for all the insights you have given me; for helping me shape the context of this work to bring it to an engaging research topic and for helping me find the clinically relevant focus points within the numbers. To my other supervisors, Alli Gokeler and Robbert van Middelaar, I am immensely grateful for your input and feed-

back on this work, for providing me with fresh ideas and new literature, for asking critical questions and for being there every time I needed you.

There are a lot of others without whom this work would not have been as complete or enjoyable as it has been now and who helped me learn and understand more about this topic and the research process than I could have imagined at the start of my thesis. First, I am very grateful to Bert-Jan van Beijnum, for helping me find my way in this topic and being so supportive throughout my Master's trajectory; to Dees Postma, who helped me to navigate the statistical aspects of this work with more than a whole course worth of knowledge and insights, and to Daniel Davison, who got me started with making my own VR environment and who shared my excitement in making the final interaction a (virtual) reality. Second, to the experts at OCON: Roy Ziel, Arno Kruims, Rens Hoogenraad, Roy Hoogeslag and especially Jan Paalman for their fantastic ideas and input and for their help in organising the focus groups, measurement sessions and observational moments with their colleagues. Third, to all my participants who gave me incredible ideas and were always so eager to help out with my thesis, your input has been incredible to me (and it has been a delight watching you jump around in VR)! Third, the research team of Sports, Data & Interaction and the IMMUnity group that I got to take part in to see how research was being shaped and executed at my two thesis departments; as well as the Interaction Lab and the BMSLab, who helped not only provide the tools for this study but also gave an engaging space to work and share ideas. Finally, all the people who lent an ear for specific questions, such as Marcel Weusthof, Pieter Heuvelmans, Ina Janssen, Leon Schippers, Steven Schurink en Maria João Cabral. And of course a special thanks to my family, friends and colleagues for their support throughout my studies! Thank you all!

To you as a reader: I hope you will enjoy reading my thesis as much as I have enjoyed writing it!

CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Borg	Method of self-estimating one's exertion, using a modified scale between 0-10.
Compensatory movement	A movement deployed to achieve or assist a functional motor task when the normal movement pattern is unavailable, e.g. torso flexion or arm movements to assist knee and hip flexion in slowing down and maintaining balance during a jump landing.
Cybersickness	A feeling of nausea, headache, or discomfort due to (prolonged) VR usage, often the result of latencies or unsharp visualisations.
Dual-task	A practice in motor learning; the addition of a secondary task to a primary task to increase the perceptual-cognitive pressure of performing the primary task.
Ecological validity	Referring to the extent to which a motor-learning task relates in its nature to the higher goal of sports performance, taking the sport-specific contexts and task constraints into account.
Fear of movement	The discomfort a rehabilitation patient may have in trusting their affected body segment during movements out of fear of worsening or re-injuring it.
Fidelity	The degree to which a virtual environment represents a real-world system.
Flight phase	Phase between the moment of toe-off of the jumping leg and the initial contact of landing.
Functional movement assessment	Evaluation of the movement performance relating to a specific task.
Immersion	Measure of how strong the virtual scenario is able to draw a user into that world.
Inside-out tracking	HMD functionality in which sensors are integrated into the HMD to track the head movement rather than using external sensors.
Jump type	Specific distance interval for the single-leg jump of a leg; in this study differentiating between 20, 40, 60 and 80% of the maximum (based on the single-leg jump distance in the VR condition of that leg), the single-leg jump in the real-world condition (SL-RW) and the single-leg jump in the VR condition (SL-VR).
Kinematic data parameter	Specific joint parameter evaluated within the kinematic data of this study (in this study relating to knee, hip and torso).
Landing phase	Final phase of a jump between the initial contact of the jumping leg and the completion of the jump.

MVN avatar	Virtual avatar animating a user's movements in the VR environment.
MVN data	Kinematic data gathered with the Movella MVN IMU sensors.
Pass-through	Functionality of an HMD to allow the user to view the physical world from within the HMD.
Perturbation	External (mechanical) alteration made to the body of a participant to influence their movement behaviour (in this study relating to Leukotape P sports tape attached to the non-dominant knee).
Playspace	The physical space available for the virtual interaction.
Single-leg jump	Jumping task in which a person balances, jumps and lands on one leg (indicated as the jumping leg), while the other moves along in the air (indicated as the swinging leg).
Starting phase	First phase of a jump until the moment of toe-off of the jumping leg.
Virtual guardian	Wall-like demarcation of the playspace shown inside the HMD to safeguard the user from interacting with real-world objects.

ACRONYMS

ACL Anterior Cruciate Ligament.

ACLr Anterior Cruciate Ligament reconstruction surgery.

AIC Akaike Information Criterion, *method of determining whether the model complexity can be justified by its explained variance*.

AR Augmented Reality.

AV Augmented Virtually.

EMG Electromyography.

ER Extended Reality.

FoV Field of View.

GRF Ground Reaction Force.

HMD Head-Mounted Device, *also known as VR goggles*.

ICF International Classification of Functioning, Disability, and Health.

IMU Inertial Measurement Unit.

KNGF Royal Dutch Physiotherapy Society.

KOOS Knee injury and Osteoarthritis Outcome Score.

LME Linear Mixed Effects model, *statistical regression model combining fixed and random effects for a specified dependent*.

LSI Limb Symmetry Index, *a measure of single-leg jump performance determined by dividing the maximum jumping distance of the affected leg by that of the unaffected leg*.

MoCap Motion Capture.

MR Mixed Reality.

MRI Magnetic Resonance Imaging.

PCL Posterior Cruciate Ligament.

PROMs Patient-Reported Outcome Measure.

RoF Range of Flexion, *determined by the difference in flexion of a body segment between two specified moments in the jump movement*

RoM Range of Motion.

RTS Return To Sports, *a moment of evaluating the functional movement performance during ACL rehabilitation to determine whether a patient can (slowly) return to playing their sports again; in literature sometimes also referred to as return to play*.

RW Real-World, *measurement condition*.

SL Single-Leg jump.

VR Virtual Reality.

1
INTRODUCTION

Of all sport-related knee injuries, 20% involve the anterior cruciate ligament (ACL) [1]. When this ligament is ruptured, a reconstruction followed by a lengthy rehabilitation is often needed. Throughout such a rehabilitation, a patient's progress is evaluated based on their dynamic stability, strength and range of motion (RoM) in the knee. For athletes recovering from an ACL injury, a key moment in their rehabilitation is the 'return to sports' (RTS) evaluation, in which they are approved by their physiotherapist to (gradually) return to perform (competitive) sport once more. Currently, the RTS evaluation of the knee is based on standardised tests, which do not provide sufficient objective insights into the movement functionality of the patient and do not consider the complex sports context in which they will return after RTS. To address these deficits (elaborated further below), we present in this paper a gamified system with integrated sensor measurement for the improvement of the objectiveness and sport-specificity of the RTS functional movement evaluations during ACL rehabilitation. Within this proof-of-concept, the combined use of gamified Virtual Reality (VR) and kinematic data analysis of targeted jump tasks was shown to trigger more sport-specific and diagnostically relevant jumping behaviours, of which the gathered data could be used to quantifiably differentiate between a perturbed and non-perturbed leg and be meaningfully utilised by physiotherapists within their RTS decision-making.

1.1 STUDY MOTIVATION AND PROBLEM STATEMENT

During ACL rehabilitation (further elaborated upon in Chapter 2), the movement performance of the ACL-affected leg is monitored at specific intervals by functional movement tests. One of the most frequently utilised jumping tasks in these evaluations is the single-leg jump test. Within the current practice of ACL rehabilitation, there is a high risk of re-injury after RTS. As a functional movement test, the RTS evaluation does not typically result in a binary diagnostic outcome (either "yes" or "no" to return to field training). Instead, it requires a higher dimensionality in its interpretation by a sports therapist to accurately evaluate the risks of letting a patient return to playing their sport and the possible gains that could stem from continued rehabilitation. The topic of this study was motivated by improving this interpretation of the RTS evaluation by addressing the objectiveness and sport-specificity of the tests used.

For this first point, the current method of the RTS evaluation utilises standardised jumping exercises to provide insights into the movement, but objective data regarding the kinematic movement characteristics of the individual body segments that can indicate risks for ACL re-injury is often not gathered or considered in the evaluation. The subjectiveness of RTS evaluations leads to discrepancies in the rehabilitation duration and the accepted movement performance level at RTS and has been a concern also addressed by the Royal Dutch Physiotherapist Society (KNGF) [2]). The addition of objective data, either as a complement or (partial) replacement of the current RTS evaluation, has the potential to provide rich insights to the physiotherapist on the movement performance of that patient. The second objection is that the use of standardised training exercises and functional movement tests generalises the rehabilitation process of patients rather than providing an evaluation based on the sport-specific context they are rehabilitating to return to. As a patient returns to their pre-injury sports performance level, they are required to make movements within a more complex context than what was evaluated during standardised tests in a laboratory-type setting. At the heart of this sport-specific context lies the need for patients to be able to and trust that they can make movements while paying attention and adapting to the (uncontrolled) elements within their sport (such as opponents or balls to which the patient must react). To determine whether RTS is possible, movement performance should, therefore, be evaluated under a similar perceptual-cognitive load as their sport encompasses.

Taking these two objections together, the current RTS functional movement test does not encompass an objective movement measurement and lacks a rich sport-specific context. As a result, athletes may return to their sport too early in their rehabilitation process or be too unprepared for perceptual-cognitive pressure and can be subjected to re-injury. While some studies have applied sensing technology or tried to increase a patient's perceptual-cognitive load during evaluations, we hypothesise that by combining objective evaluation of movement performance through sensing with interaction technology to create a meaningful and controlled evaluation context, we can effectively address these two objections.

1.2 MAIN RESEARCH QUESTION

Given the motivation described above, there seems to be a need for a system that can provide objective and meaningful insights for the RTS evaluation of an ACL patient. Given this need, the following research question was identified for this thesis.

Research question

"*What is a design for a meaningful functional movement evaluation system based on* ***objective measurement*** *and utilising a* ***sports-specific context*** *that supports RTS decision-making in patients during an* ***anterior cruciate ligament*** *rupture rehabilitation?*"

This question proposes the design of a system that combines sensor and interaction technology to create a meaningful diagnostic setting that provides insights to a physiotherapist for the RTS evaluation of an ACL patient. Based on this, two main objectives of the research question are presented below.

Research objectives

- **Objective 1**: to objectively evaluate the movement performance of a simulated ACL-affected leg compared to the unaffected leg in a single-leg jumping task to aid the diagnostics of physiotherapists during the RTS decision.
- **Objective 2**: to provide a rich evaluation context that allows and triggers an ACL patient to show more sport-specific behaviours and aids the physiotherapist in making a more meaningful consideration of the patient's functional movement performance during an RTS evaluation.

These two main objectives are reflected in two main components that are at the centre of this work. First is the adaptation of the standardised single-leg jump task for maximum distance to a repeated single-leg jump task at specific target distances to create a dataset for kinematic analyses. For this, rather than a single-leg jumping task in which a patient must jump their maximum achievable distance, we provide participants with a jump target at 20, 40, 60 and 80% of their maximum jumping ability to determine whether a repeated jump task in a non-fatiguing setup can generate more in-depth data than the current practice. Second, VR is used as a gamified system to create a rich evaluation context for these jumping tasks. The use of VR within the rehabilitation context is further evaluated for its potential to safely trigger sport-specific movements that could lead to more meaningful insights during the RTS evaluation.

1.3 Outline of this thesis

This thesis encompasses the key components addressing the research question above, supported by additional materials in the appendix and the supplementary materials that were provided alongside this thesis (see an overview in Appendix A). First, within Chapters 2 and 3, an overview of the existing body of knowledge on this topic was gathered to determine insights from the related field. These chapters serve as the literature backbone on which the continued design is based. This overview has been previously established for the author's Research Topics report, of which parts were adapted to compose these chapters. Once the literature foundation has been established, the design journey of this system alongside tooling considerations and design criteria is described in Chapter 4. The system design gives way to the evaluation of the system as described in the methodology provided in Chapter 5. The results of these evaluations and data analyses are described in Chapter 6. Finally, the outcomes are discussed in Chapter 7, after which practical implications and future work are summarised in Chapter 8.

2

ACL INJURY MECHANISM AND REHABILITATION

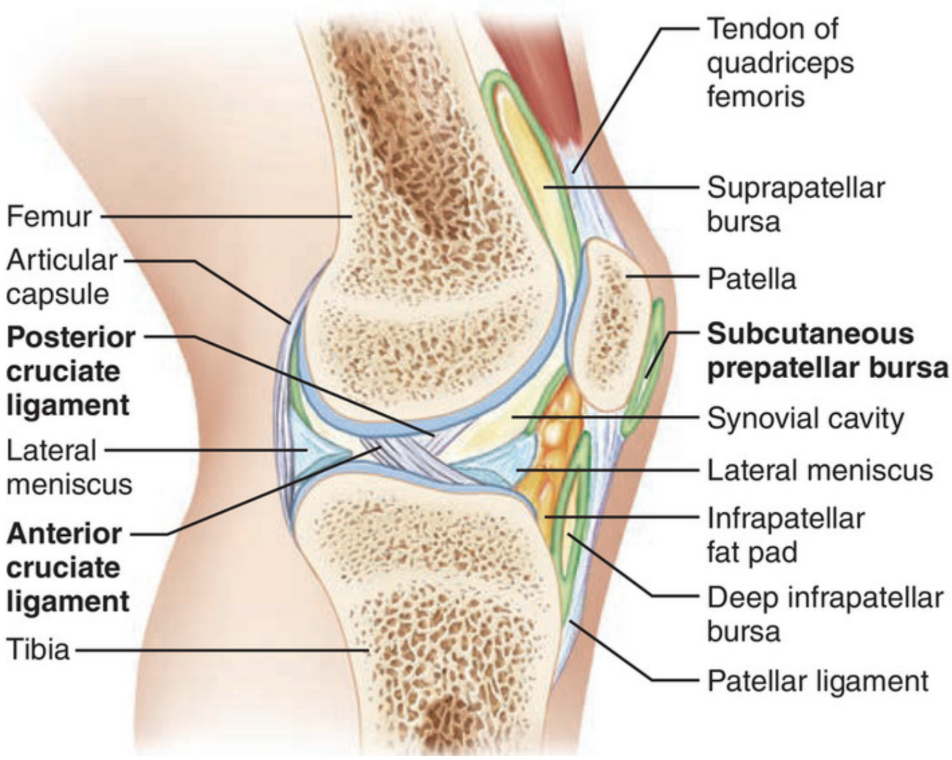
The literature background on this topic has been divided into two parts. This first chapter covers the anatomical characteristics of the ACL and the injury mechanisms of its rupture. In Chapter 3, key concepts and related work on biomedical sensing and (sports) interaction technology are provided. For a full understanding of ACL injury and rehabilitation, literature was combined with patient interviews as well as observations and sessions held at OCON Orthopaedic Centre, located in Hengelo, the Netherlands. For the shadowing observations at OCON, several patient consultations were attended. Where relevant, the observations from practice are indicated and serve as an insight into the current practice of ACL rehabilitation. Additional notes on the literature background have been gathered in Appendix B. An extensive overview of the observational sessions at OCON and the patient interviews are provided in Appendices C and D respectively.

2.1 ACL ORIENTATION AND INJURY MECHANISM

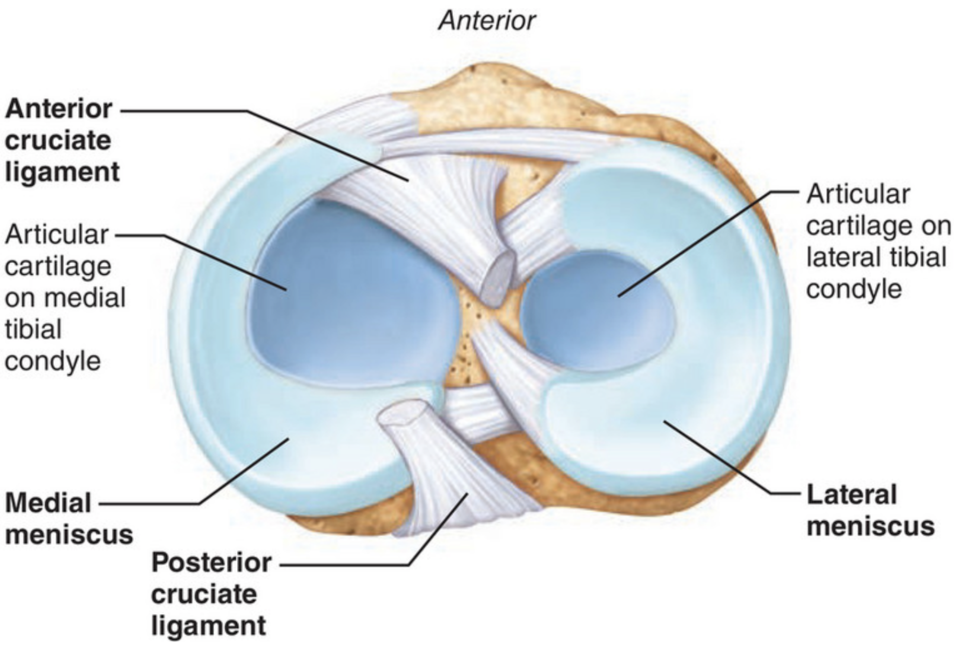
The ACL is one of the several ligaments stabilising the knee joint and crosses in front of the posterior cruciate ligament (an anatomical orientation which provides both ligaments with their respective names, ACL and PCL), see Figure 1. The ACL is one of the most often injured body parts during sports, either through contact with opponents (e.g. through tackling or collision [3]) or in non-contact (in which the injury is the result of the patient's own movements).

2.1.1 *Anatomical ACL orientation*

The knee is a complex joint cavity in which three separate joint compartments work [4], [5]. These three compartments consist of the femoropatellar joint, which works between the patella and the femur, and the lateral and medial tibiofemoral joints, which work between the femoral condyles and the menisci. The tibiofemoral joints are hinge joints that permit flexion/extension and varus/valgus movements and allow for some rotation when the knee is partly flexed. The knee is surrounded by capsular and extracapsular ligaments that prevent hyperextension of the joint. The intracapsular cruciate ligaments of the knee cross each other and serve as straps that prevent anterior-posterior displacement of the femur and tibia. The ACL is attached to the anterior area of the tibia and crosses lateral-superiorly to attach to the medial posterior side of the femur, see also the complete anatomical orientation of the ACL in Figure 1. The ACL consists of an anteromedial, posterolateral and (as found by some studies) an intermediate bundle [1]. Due to their attachments, the anteromedial bundle is primarily responsible for resisting anterior tibial load, while the posterolateral bundle counteracts rotational load. A rupture in the ACL would, therefore, allow for increased motion in the anteroposterior translation and tibial rotation, which forms the foundation of the ACL rupture diagnosis tests that check for increased laxity caused by a tear. The



(a) Sagittal view of the knee joint, showing the ACL as position relative to its surrounding structures.



(b) Superior view of the knee joint, showing the crossing of the ACL and PCL.

Figure 1: Anatomical overview of the right knee joint, from [4].

ACL prevents the tibia from sliding forward with respect to the femur when the knee is extended. The ACL is often considered to be the most important stabiliser of the knee by preventing anterior tibial knee translation (specifically at low knee flexion angles) and limiting internal/external rotation of the knee as well as varus/valgus motions [6]. The PCL is stronger than the ACL and is attached posterior to the tibia and crosses the knee capsule laterally to attach to the lateral anterior side of the femur. The PCL prevents the tibia from being displaced backwards with respect to the femur. The ligaments are composed of tough, fibrous material [7]. In addition to the ligaments, the knee is reinforced by the muscle tendons of the quadriceps (anteriorly) and semimembranosus (posteriorly) [4].

When the knee is extended, the strain in the ACL increases [5]. During the final ten degrees of leg extension, the ACL comes under tension and prevents rotation of more than five degrees alongside the leg axis. During flexion, both the ACL and PCL are put under tension, with a slight rotation allowed by the cruciate ligaments. During bending, the knee allows for less internal rotation than external rotation because endorotation twists the cruciate ligaments around each other (thus effectively locking them), which avoids a far rotation, while exorotation twists the cruciate ligaments apart. Without the restrictions of the ACL and other structures around the knee, the joint would theoretically be capable of both rotation and translation in three body planes (total of six degrees of freedom) between the femur and tibia [1].

2.1.2 *Description of injury mechanism*

The knee is responsible for providing balance and transforming body load when performing a rapid change of speed and direction [1]. When an ACL injury occurs, the primary contributing force to the rupture is found in the anterior vector of the quadriceps [8]. The quadriceps muscle is one of the primary producers of anterior knee force when the knee is near or at full extension and forms, together with the gastrocnemius muscles, the strongest contribution to the knee abduction moment [9]. The contraction of the quadriceps muscle, alongside co-contraction of the hamstring muscle, [8], therefore, contributes to the ACL rupture by increasing the compressive load on the tibiofemoral joint. The excessive joint compressive loads and an internal torque can lead to a complete ACL rupture, as was first determined in human cadaver studies. In these studies, peak compression loads of 2900 to 7800 N at knee extension angles between 30° and 120° resulted in ACL failure. During the rupture, the load is applied within 100 ms, leading to a tear in the ligament [1]. The compressive forces are the result of inadequate absorption of ground reaction forces (GRFs) of the lower leg, combined with the previously mentioned quadriceps and hamstring contraction. The GRF is the force that is exerted by the ground onto the body during contact. This measure can be used to identify human movement and different gait patterns and can be an indicator of injuries. The GRF can be divided into horizontal and vertical components. The GRF, even in straight running, can be up to three times the body weight. As the knee counteracts this loading force, it is at risk for injury and osteoarthritis. Generally, the hip, knee, ankle, and foot joints all help absorb the GRFs during landing and deceleration. The hip muscles absorb reaction forces generated by the upper body weight, while the knee, ankle, and foot structures absorb the GRFs. During an ACL injury, this GRF absorption by the lower leg does not happen effectively, primarily due to the calf muscles not having enough time to absorb the GRFs, which leads to a high load on the knee. This is especially the case under very high GRFs, such as for single-leg jump landings, where the experienced GRF can range between 2 to 18 times the body weight. If a person lands on their forefoot, the landing is unstable and there is less time for forces to dissipate than if the person had landed with a plantarflexed ankle. The resulting impulse force is created by a change in velocity and is inversely related to the time required for that change to take place. The high axial load results in the knee buckling or 'shooting out' from under the body (see also Figure 24 in Appendix B.1). In this movement, the tibia has an anterior displacement, while the knee has to reduce the impulsive force in a short amount of time. A final contribution to the ACL rupture can be a higher hip flexion angle during landing. This higher angle requires hip flexion and knee extension torque to stabilise the torso, which can be provided by the rectus femoris. The activation of this muscle adds to the compressive force on the knee and the anterior force on the tibia, thus adding to the ACL strain.

Because around 2.5% of the ACL consists of mechanoreceptors [2], this ligament affects the neuromuscular control of the knee through the arthrokinematic reflex arc. A rupture in the ACL can, therefore, affect the local, spinal, and supraspinal control of the knee, which, in turn, can lead to an adapted motor control strategy within the kinetic chain of the lower extremity [10] (consisting of the hip, knee and ankle joints linked together). Adaptations in this chain can be highly individual and can affect proprioception, postural control, muscle force during movement and muscle activation patterns. While an ACL rupture can affect how the knee is controlled and how movements are executed, the flexibility of the kinetic chain allows a reshuffling of the neuromotor system to re-adapt itself to its capabilities at any given moment. The analysis of this flexibility is of interest to understand in what regard adaptations can be made by the neuromotor system itself and where surgical or rehabilitation interventions may be needed (and are more thoroughly examined in the works of, for example, [11], [12]).

2.1.3 *ACL rupture prevalence and risk factors*

The high prevalence of ACL-related injuries (20% of all sport-related knee injuries [1]) results in 200 000 ACL injuries annually in the United States alone [13]. Other common knee injuries, aside from the cruciate ligaments, are collateral ligament and cartilage (menisci) ruptures [4]. Of the ACL injuries around 90% of the patients elect to undergo an ACL reconstruction surgery (ACLr, see also Section 2.2). In ACL injuries, there is usually a complete rupture in the ligament that leads to instability of the knee and can reduce a patient's ability to return to their pre-injury activity level. For partial tears, a patient may have the capacity to heal through physiotherapy, while complete ruptures more often require a surgical procedure [14]. Around 70-84% of ACL injuries occur in a non-contact sports setting [7], [15], for instance when quickly changing direction during running, thus twisting a hyperextended knee; when rapidly decelerating; or during simultaneous landing and pivoting/twisting manoeuvres. Through observations at the OCON Orthopaedic Centre, it was noted that most ACL injuries at that clinic occur when athletes make sudden (unexpected) adaptations to their established movement pattern. This is, for example, the case when they have to respond to a feint from an opponent or when a movement is suddenly made impossible, both requiring fast responses to the unexpected scenario midway through a movement. An ACL injury, therefore, has a strong prevalence in high-risk and high-intensity sports activities such as (American) football, skiing, basketball and gymnastics [16].

Once patients complete their surgical reconstruction and rehabilitation, not all return to their sports. A systematic review by Andriolo et al. (2015) [17] found that around 75% of patients return to some kind of sport [17], with around 43% being able to return to their previous sport activity level. For patients playing competitive sports, around 44-55% were able to return after their rehabilitation [2], [18]. Of this group, half indicated that their ACL and the risk of re-injuring the ligament was the reason for reducing their physical activeness [2]. The likelihood of RTS of an athlete was found to decrease with a lower pre-injury activity level of the patient, as well as their gender (with women having a further decreased likelihood), a high body mass index, and smoking during the six months prior to surgery [19]. To reduce the risk of ACL ruptures (and other knee injuries), large sports organisations have set up dedicated programmes to strengthen muscles and ensure good warm-ups for large groups of athletes (see for example the FIFA injury prevention programme for football players [20]).

Of the patients that complete the RTS evaluation, between 6-31% suffer a second ACL injury in the ipsi- or the contralateral limb [13], [18], making the second ACL injury incidence rate higher than the ACL injury incidence rate of healthy athletes [21], [22]. Several risk factors can increase the chance of a second ACL injury after RTS [13]. For the ipsilateral limb, it has been shown that younger patients are at higher risk for graft failure, with adolescents showing the highest risk. This may be because younger athletes are more likely to return to (competitive) sports compared to older ACL patients [19]. In addition to age, the graft type can affect the failure risk, with allograft tissue being 5,2-5,6 times more likely to fail than autografts [13]. Other relevant factors that may be related to failure risk are the surgical technique, the patient's body mass index and their posterior tibial slope. For the contralateral limb [13], the risk of a second ACL injury also increases for younger patients but also occurs for women more frequently than for men [21].

A possible reason for the high incidence of knee re-injury may be the evaluation of the RTS level after the ACL rehabilitation. Several studies evaluating RTS criteria have found them to be highly variable and poorly defined [23], with the majority of studies evaluated by Harris et al. (2014) [23] not having based the RTS allowance on any objective criteria. In the study of Paterno et al. (2010) [24], however, it was shown that there are meaningful biomechanical measures that can be used to determine the risk of an ACL re-injury by determining predictors of a repeated injury risk. These measures included the knee RoM in the frontal plane during jump landing, the asymmetries of knee moment in the sagittal plane during landing contact and the postural stability in general. This set of measures produced a reliable indication of a second ACL injury.

2.2 Current diagnosis and rehabilitation practice

When an ACL injury occurs, a diagnosis of the injury is made and the rehabilitation procedure should be determined. While there is a differentiation between practices [25] (also in particular for the RTS evaluation, see [23], [26]), there is some consensus on how the diagnostics should be done and which phases of rehabilitation should be distinguished. For the different phases of the recovery trajectory, the possible treatment and exercises per phase can differ between practices. In this section, an overview of general trends is provided, while keeping the understanding that there is not necessarily a coherent procedure that is used between different practices. Where appropriate, common deviations from the described trends are indicated.

2.2.1 *Methods for initial diagnose*

When an ACL injury occurs, patients often indicate hearing a pop and being unable to continue playing. The knee often swells for several hours, which often indicates to the patient that a medical evaluation is needed. To diagnose an ACL rupture, a clinical assessment of the injury is needed. The diagnosis of ACL builds upon the patient's injury history, the assessment of the general practitioner and imaging techniques [1]. During the assessment, the stability of the affected knee is determined to see if there is excessive motion within the joint as compared to the unaffected knee. Such procedures are often repeated throughout the rehabilitation of the patient to further monitor knee performance. The following clinical tests can be utilised to diagnose an ACL rupture (in the acute phase) or to later assess the performance of the knee as part of the physical examination [1], [27], see also Figure 25 in Appendix B.1.

- The anterior drawer test: the patient lies in a supine position with the knee and hip flexed to 45° and 90° respectively. The clinician keeps the foot stable on the examination table and applies gentle anteroposterior forces on the proximal side of the tibia and measures the subsequent displacement of the bone in this direction.
- The Lachman test: the patient lies down and flexes the knee at around 30° while the clinician stabilises the femur and provides an anterior force on the tibia. Knees with an ACL rupture will show a visible translation of the tibia.
- The pivot shift test: evaluates the internal rotation torque and valgus torque to determine the knee laxity. The patient will lie down with an extended knee, which is slowly flexed to a 40-degree bend. The ACL rupture can be diagnosed when there is a subluxation (i.e. a wrong joint movement) of the tibia moving forward during a sudden change in direction by the clinician.
- The KT-1000 test: the knee is flexed at a 30-degree angle, while a KT-1000 arthrometer is used to provide an anterior force on the tibia and measure the subsequent joint laxity. The laxity can also be measured with a manual device.

Evaluations of the anterior drawer, Lachman and pivot shift tests show that all exercises have a high sensitivity [27], [28], but the test accuracy can decrease significantly under the use of anaesthesia. In addition to the physical tests, imaging techniques can be used to further improve the diagnosis of an ACL rupture tear. Imaging techniques can help differentiate between a partial and a complete rupture, as well as the severity and location of such tears. For this, Magnetic Resonance Imaging (MRI) can prove to be valuable [14], as it can have an accuracy of more than 95% of diagnosis of an ACL tear (without distinguishing between partial and complete ruptures). Other options are Rontgen and keyhole surgeries, the latter of which can be done during the operation itself.

Within the Dutch guidelines for physiotherapists [29], the use of patient-reported outcome measures (PROMs) such as the Knee Injury and Osteoarthritis Outcome Score (KOOS) is also a recommended tool for the functional knee assessment. The KOOS has also been validated in Dutch and is useful for comparing the functionality of the affected knee with the healthy one. In addition, the movement of the knee, hamstring and quadriceps strength, but also the patient's pre-injury and expected post-rehabilitation sports level are important in determining a patient's rehabilitation procedure. Furthermore, the development of hydrops (i.e. building up of fluids within the tissue, to be treated through cryotherapy and/or compressions) in the knee should be monitored during the diagnosis and the continued treatment trajectory. During the diagnosis, physiotherapists may also use an isokinetic measurement to compare force differences between the two legs [2]. Within such a measurement, the force of the quadriceps muscles is compared between the legs, with a preoperative difference of more than 20% indicating a significant force difference in the legs up to two years after the ACLr.

Based on the methods and exercises described above, a diagnosis regarding the existence and extent of an ACL injury can be made. While a binary diagnosis (either having an ACL injury or not), the diagnosis encompasses a functional movement assessment. One method of outcome reporting is through the International Classification of Functioning, Disability, and Health (ICF) domains [30], which aims to provide a common language for describing (changes in) health-related states, outcomes and functioning. The ICF domains have been previously applied to ACL injuries (see for example Zebis et al. 2019, [31]).

2.2.2 *Postoperative rehabilitation care*

Once the ACL rupture is diagnosed, the physiotherapeutic treatment of an ACL rupture can consist of a surgical and a physiotherapeutic component. For partial ruptures, physiotherapy can be enough to let the patient return to their earlier stability, while a complete rupture is unable to completely heal without a surgical procedure [14]. During surgical ACL reconstruction (ACLr) [4], [7], the torn ACL is removed and replaced by a graft. This graft can either be from the patient themselves (autograft; e.g. from the hamstrings tendon, patellar ligament or calcaneal tendon) or a cadaver (allograft; e.g. from the ACL or a tendon similar to the autograft). After the surgery, there is a recommended immediate focus on postoperative rehabilitation, motion and early weight-bearing. During the rehabilitation [32], the knee RoM and quadriceps strength of the patient is improved. The current ACL rehabilitation also shows a focus on an earlier RTS and places additional attention on proprioceptive and neuromuscular control exercises. Within rehabilitation, physiotherapists generally create a tailored protocol for their patients, based on their needs.

When considering a full rehabilitation, alongside a surgical reconstruction, the following phases and focus points can be distinguished [2], [32], starting at the diagnosis of the injury. A description of specific characteristics and exercises typically used per phase has been added in Appendix B.1.1. First, the *preoperative phase* encompasses the time between diagnosis and an ACLr, during which a patient must prepare for their reconstruction. Second is the *Early postoperative phase* (first 4 weeks after ACLr), in which a normal gait pattern is slowly established through physiotherapy. During the *Strengthening phase* (4 weeks - 6 months after

ACLr), knee RoM is improved and muscle training takes place, while the *Return to activity phase* (3 months after surgery - until RTS) focuses more on sport-specific and jumping exercises to re-learn skills and focus on good form. Finally, a patient returns to sport. While there is no exact definition of when a patient is considered to have returned to sport [33], this can often be considered as having returned to play sports at the pre-injury level. This is, for example, considered to be the case when an athlete has competed in a game at their pre-injury level. The integration of on-field training as part of rehabilitation has been considered beneficial for restoring sport-specific skills with the adapted post-surgical neuromuscular control [34], [35].

2.3 RETURN TO SPORTS EVALUATION

Returning to sports is an important part of the rehabilitation process both for the athlete and the physiotherapist. The return to their sport can serve as a big motivator to patients and provide them with optimism in their rehabilitation. Other patients, however, can be apprehensive due to fear of movement and getting re-injured, which can reduce their RTS success [36]. When a patient is in their final stages of returning to sports, there is often more integration of pivoting movements, high-speed change-of-direction tasks and other tasks that require fast movement adaptations [37]. In addition, sport-specific elements such as ball-handling tasks may be incorporated. As such movements are often the cause of non-contact ACL ruptures (see subsection 2.1.3), such exercises can help prevent re-injury and can strengthen a patient's confidence in their movement.

To return to sports, patients should first regain their muscular strength and neuromuscular control in the affected joint while maintaining their static stability [32]. While studies often find a very low consistency in practice between recommended tests [23], [25], [26], [32], [38], [39], the consensus does seem to incorporate several parameters (see also a full overview in Appendix B.1.2), such as the relative performance of the affected knee based on the muscle strength, physical tests (see subsection 2.2.1) and the performance in jumping tasks. One of the most commonly used jumping tasks is the single-leg jump for distance. Here, a person balances on one leg and jumps forward as far as possible and lands in a stable and controlled manner on the same leg. The distance of the jump is compared between the legs to determine the limb symmetry index (LSI, determined by dividing the jumped distance of the affected with that of the unaffected knee, expressed in percentages). If the LSI is higher than 90%, the bilateral comparison indicates a roughly equal performance between the knees (although some recommend an LSI of 100% for contact and pivoting sports [39]). Specific test batteries of jump tasks have been proposed and evaluated by previous literature, which often includes single-leg jumps alongside vertical or side-ways hops [40], [41]. A typical jump evaluation method is through the use of the jump landing system or landing error scoring system, in which the movement of specific body segments is scored based on pre-determined characteristics throughout the jump, although it is not known whether and how the evaluation of movement quality is adequate for identifying re-injury risks [39].

Aside from these criteria, physiotherapists will often consider the general stability and function of the knee during clinical examination [42]. Finally, the sport-specific context to which patients return (and which is sometimes characterised by uncommon jumping techniques, such as in skateboarding), as well as patient-reported outcomes considering their psychological readiness and confidence in the stability of their own knees (often considered the 'fear of movement' of the patient) should be considered and is becoming more integrated into rehabilitation evaluations [38], [43].

2.4 PATIENT JOURNEY

Central to the rehabilitation progress is how the treatment is perceived by the patient. To understand the motivation and emotions experienced by patients throughout ACL rehabilitation, the patient journey as based on the evaluations by Scott et al. (2018) [44], as well as two interviews with ACL patients and observations from shadowing ACL rehabilitation evaluation sessions at the OCON Orthopaedic Centre were evaluated. The interviewed patients were participant P01, a 24-year-old woman who plays basketball and who was still in rehabilitation from a complete ACL injury at the time of the interview; and participant P02, a 23-year-old woman who does ice skating and had completed her rehabilitation for a partial ACL rupture at the time of the interview.

2.4.1 *Outcomes of the patient interviews*

For both participant P01 and P02, the ACL injury occurred in a non-contact setting while doing a non-competitive sporting match. Participant P01 had an unbalanced landing after a basketball layup and had her leg rotate and shoot out from under her, while participant P02 was decelerating after a sprint in ribbon rugby (i.e. a playful variant of rugby without tackling) and fell onto her bent knee. After the injury occurred, participant P01 was temporarily unable to stretch her leg, while with participant P02 the knee immediately started to swell up. Both participants were able to still walk right after the injury, albeit with some difficulties, and decided only days later to first visit a physiotherapist, before going to their general practitioner where the ruptures were diagnosed. This encompassed an MRI for participant P01 and a Rontgen and later an MRI for participant P02 to correctly diagnose the partial tear. For the full tear ACLr surgeries, participant P01 completed muscle training and performed stretching exercises to allow for easier placement of the autograft. Participant P01 waited two months until her ACLr, participant P02 had three months between her fall and her keyhole surgery.

After the ACLr operation, participant P01 performed stretching and bending exercises at home alongside three sessions per week with her physiotherapist. Participant P02 started with physiotherapy five days after her surgery for sessions twice a week. She focused on doing stretching exercises, as she was unable to fully stretch her leg. As her rehabilitation progressed, she increased the resistance in her stretching exercises and worked on rebuilding her running and cycling condition under a low impact.

At the physiotherapist, participant P01 rehabilitated back to walking, after which she worked on strength training and slowly started with running training. After being able to run, she worked on doing vertical jumps, starting with two-legged jumps and progressing to single-leg jumps as well as vertical drop-down jumps. During her physiotherapy sessions, participant P02 focused on skating-specific exercises, which mainly consisted of jumping exercises that would allow her to regain the explosive muscle force needed in her sport and balancing exercises. Participant P02 indicated that this focus on her sport within her rehabilitation was highly motivating for her.

Both participants indicated that they noticed a different control of their affected compared to their knee. In addition, both described a fear of movement throughout their rehabilitation by subconsciously locking the knee to absorb impact and being afraid to hurt their knee again during certain exercises. As both participants were avid sporters, the main motivation in their rehabilitation was also their wish to return to sports. This also led both to experience that they would push themselves too far at times and that they had to sometimes be held back by their physiotherapists during their exercises.

For her RTS evaluation, participant P02 had to undergo a few standard tests conducted by her therapist to compare the strength in her affected knee with her unaffected knee and determine the knee stability of her affected leg. This assessment consisted of jumping left and right over two lines for 30 seconds and doing a single-leg jump. When returning to ice-skating five months after her surgery, participant P02 experienced some hesitance in her movement, especially during moments when she felt some pain in her knee during training, which also made her return to her physiotherapist. When asked about her future return to activity, participant P01 indicated that she wanted to slowly get back onto the field and avoid competitor contact until she felt more secure in her movement.

While participants P01 and P02 were generally optimistic during the interviews, their injuries did have a large effect on their lives and, logically, their sporting activities. The work of Scott et al. (2018) [44] provides insights from a more negative recovery journey, with strong physical, psychological and social experiences occurring either directly or indirectly from the injury. These effects were especially found during the time between the injury and the operation. Such a difference in experiences likely stems from the age difference between both groups, with P01 and P02 having a mean age of 23,5 while the median participant age in the work of Scott et al. was 31 years, leading to participants in the latter study feeling old and becoming frustrated at their own physical limitations. For both groups, however, the fear of movement was found. A review by Feller et al. (2013) [19] showed that a fear of re-injuring the knee can be a significant factor for patients to decide not to return to their pre-injury activity level. In addition, patients who complete the RTS phase successfully show less fear of movement compared to patients who did not. This fear of movement is also affected by the timing of the ACL surgery, as patients who had surgery more than three moments after they had the injury show a greater fear of re-injury compared to patients who had their surgery sooner after injury.

2.4.2 *Outcomes of patient shadowing at OCON Orthopaedic Centre*

Within the rehabilitation practice at OCON, ACL patients are evaluated before their operation and six, twelve and twenty-four months after their operation. During each evaluation, patients perform an isokinetic force evaluation, during which three rounds of exercises are performed per leg using an IsoForce device. From this test, the performance of both legs is graphed and compared for extension and flexion. Based on this, the difference in leg performance is evaluated to ensure that, preoperatively, the difference is less than 20%, and decreases further postoperatively. Next to the isokinetic evaluation, a patient is asked to perform three single-leg jumps and three triple single-leg jumps (further elaborated upon below, see also Figure 26), where the maximum distance is noted down. Finally, the patient jumps with one leg sideways over two pieces of tape (with a distance of 30 cm between) as many times as possible for 30 seconds. Based on these measures, the patient's performance is monitored over time and their regular physiotherapy sessions may be adapted. A physical examination is then performed using the tests described in subsection 2.2.1 to determine the laxity and stability of the knee. In addition, the therapist may ask the patient about their complaints, progress and physiotherapist exercises. In most cases, the OCON physiotherapist is also in contact with a patient's day-to-day physiotherapist to keep track of their progress.

3
KEY CONCEPTS OF BIOMEDICAL SENSING AND (SPORTS) INTERACTION TECHNOLOGY

Within this chapter, an overview of key biomedical sensing and interaction technology concepts is given. Where appropriate, general procedures for ACL rehabilitation are provided alongside the in-practice procedures as they occur at OCON Orthopaedic Centre.

3.1 BIOMECHANICAL PARAMETERS FOR MONITORING ACL REHABILITATION

As was described in Chapter 2, the knee provides balance and helps to transform body load when performing a rapid change of speed and direction [1]. When an ACL injury occurs, the (translational and rotational) stability of the knee is affected. Because of this, (kinematic) parameters can be found that can provide insights into the performance of the knee during a (single-leg) jumping task. Within this section, an overview of such relevant parameters is provided and described in terms of their ability to discriminate between an affected and unaffected leg.

3.1.1 *Phases defining gait cycle and jumping process*

An ACL injury affects the kinetics and energetics of the lower extremity during the entire human gait cycle [45] as well as during specific jump tasks used for evaluating the rehabilitation process. Within this study, the focus is placed on the single-leg jump. To provide a full overview, adaptations in the gait cycle are described where relevant.

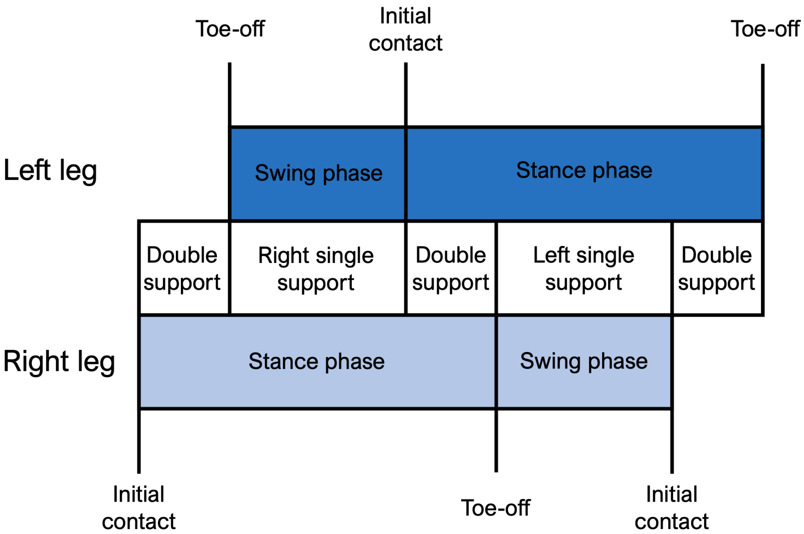
The gait cycle can be characterised through the following phases [46], see also Figure 2 below and Figure 27 in Appendix B. The gait starts with initial contact of the foot on the ground during which the GRF starts to apply onto the heel. After the heel strike, there is a loading response, during which weight is shifted onto the leg as its contralateral removes its contact with the ground. At the mid-stance phase, the heel and forefoot are in contact with the ground. The terminal stance indicates the moment where the body's centre of mass moves forward and the heel leaves the ground again. At the pre-swing, there is initial contact of the contralateral leg as the ipsilateral leg prepares for the swing itself. During the swing, the ipsilateral leg moves forward until the terminal swing phase, during which there is a renewed initial contact with the ground and the cycle is repeated. These phases form two main parts of the gait: the time that a leg is in swing (i.e. not in contact with the ground) and the time that a leg is in its stance phase (i.e. making contact with the ground).

For a single-leg jump, several key moments can be defined [47], see Figure 2. Before the jump, the person balances on their jumping leg with the swinging leg being pulled from the ground. The person can bend their jumping leg to help generate power for the jump propulsion. As the jump starts, the toe-off phase encompasses the time between the person starting to extend their jumping leg until the moment of toe-off in which the jumping leg becomes fully disconnected from the ground. The time in which the jumping leg moves forward through the air to catch the landing is the flight phase. After the flight phase, the jumping leg has an initial contact moment with the ground. After this initial contact, the person decelerates and balances on their jumping leg in the landing phase. During the landing, the jumping leg has a peak flexion, after which the leg extends again. Once the person is fully balanced, the jump is complete and the swinging leg can make contact with the ground again.

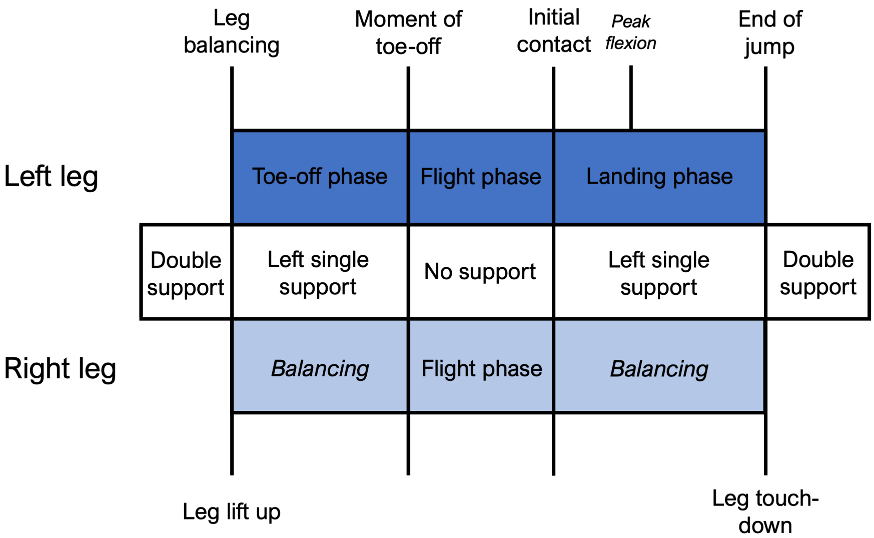
3.1.2 *Gait and jumping adaptations after ACL injuries*

In general, for low-demand gait tasks such as level-ground walking, ACL patients demonstrate similar tibiofemoral joint kinematics compared to healthy individuals [49]. For high-demanding tasks, such as movements with rapid deceleration and turning or single-leg jumps and single-leg vertical drop landings, ACL individuals have a different flexion motion of their affected knee compared to their unaffected contralateral knee. During single-leg lunges, ACL-reconstructed knees show more tibial translation and external tibial rotation [49], [50] compared to unaffected knees. For deceleration (e.g. when running downhill), the ACL-affected knee shows more adduction and external rotation of the tibia (taken relative to the femur).

During jumping tasks, a large eccentric quadriceps and hamstrings force is required to control the flexion of the knee during deceleration of the jump [51]. In general, ACL injury is considered to be the result of a stiffer landing pattern (with a decreased knee, hip and torso flexion), combined with knee valgus and knee internal rotation [52]. For single-leg jumps, the study by Laughlin et al. (2011) [53] showed that 'soft' drop landings, in which the bending of the knee is maximised, decrease the load on the ACL. This is because the peak ACL force occurs between 15 and 40° of the knee flexion, therefore letting an increased flexion reduce the ACL load. When comparing the kinematics for the single-leg jump between a healthy and an ACL-affected knee, the work by Kotsifaki et al. (2022) [54] showed that while the LSI can higher than the 90% benchmark for patients at their RTS evaluation, significant differences within the kinematics, moments and joint work contributions could still be found between the two legs. The work of Gokeler et al. (2017) [55] adds to this by showing that despite achieving an LSI higher than 90% patients can still show differences in performance for both legs compared to healthy athletes. In the study of Kotsifaki and colleagues, the ACL-affected knee seemed to generate significantly less work than the healthy knee during the propulsion of the single-leg jump. Furthermore, more knee and hip flexion was found for the ACL-affected leg during toe-off, as well as more involvement of the lateral hamstrings and soleus muscles (but with a decreased contribution from the lower gluteus medius muscle) for the affected leg. During the landing, the ACL-affected knee absorbed less work than the unaffected knee, with the unaffected knee even absorbing more work than the healthy control group. The ACL-affected leg's single-leg jump resulted in more hip flexion and ankle plantarflexion at the moment of initial contact, as well as a higher peak hip flexion, peak pelvis tilt forward and peak torso flexion than the unaffected leg and the control group. The ACL-affected knee had a lower peak knee flexion than the unaffected limb. For the landing, the ACL-affected knee has greater contributions from the lateral hamstrings and the medial



(a) Schematic overview of the stance and swing phases over the duration of a gait cycle, based on [48].



(b) Schematic overview of the jumping and swinging leg phases over the duration of a single-leg jump.

Figure 2: The phases of the gait and single-leg jumping cycle.

gastrocnemius. The study by Kotsifaki et al. (2022) concluded that the use of LSI for distance relies mostly on the performance of the hip and ankle, making it a poor measure of knee function.

The work of Kotsifaki et al. (2022) [54] is supported by the review of Johnston et al. (2018) [56]. In this work, a decrease was found in the peak knee flexion angle and the peak knee internal extensor moment during the landing of a single-leg jump with an ACL-affected leg as compared to the unaffected leg and a healthy control group. The reduced knee flexion during landing was further connected to a possible increased risk of further injury, as the stiffer landing technique increases the forces on the knee joint. However, contrary to the work of Kotsifaki et al. (2022), Johnston and colleagues did not find significant differences in the peak hip flexion angle between the affected and unaffected leg. The review by Kotsifaki (2020) [57] further shows that the ACL-affected limb has a stiffer landing, with less knee flexion and internal rotation compared to the unaffected leg and healthy subjects, as well as lower knee and hip flexion moments.

The study by Orishimo et al. (2010) [58] also showed a lower knee RoM during the toe-off for a single-leg jump of an ACL-affected leg compared to the unaffected leg. During landing, the knee RoM was also found to be smaller for the affected compared to the unaffected leg, albeit with a smaller margin. The reduced power in the knee was compensated for by higher moments and power of the hip during the toe-off and a greater power absorption of the ankle during landing.

In addition to these measures, the KNGF [2] recommends the use of the dynamic knee valgus and reduced neuromuscular control of the torso at landing as predictors of ACL injury in women and the dynamic knee valgus and a decreased knee flexion angle on jump landing as predictors for re-injury after an ACL. Furthermore, studies [49], [50] have shown that the tibia of an ACL-affected leg has a more extended, externally rotated and anteriorly displaced position (relative to the femur) during jump landing compared to the unaffected contralateral leg. During hopping exercises, an ACL-affected knee is also more extended compared to a healthy knee. This may be a strategy for providing greater knee stabilisation to compensate for the increased anteroposterior laxity caused by the ACL rupture.

During focus groups at the OCON Orthopaedic Centre, the physiotherapists indicated that the stiffer landing profile of a single-leg jump with an ACL-affected leg (also described by [54], [56], [58]) was often accompanied with compensatory movements, such as strong torso flexion and arm waving to regain balance and slow the landing down. These compensatory movements were also often considered in practice as qualitative aspects of a single-leg jump performance to accompany the LSI outcomes.

3.1.2.1 *Kinematical adaptations for jumping tasks within VR*

When performing jumping tasks within a VR environment, the biomechanics may be altered [59]. In the study by Brazalovich et al. (2022) [59], vertical drop tasks were performed by healthy participants under the conditions of eyes open, eyes closed and in VR. The VR condition resulted in less knee flexion and more knee abduction at the moment of initial contact compared to the other two conditions as well as an increased knee abduction during maximum flexion. However, no adaptations in peak knee flexion were found between the three conditions despite previous literature showing changes between the eyes open and eyes closed conditions. Nonetheless, given the kinematic adaptations for this vertical landing task, Brazalovich and colleagues concluded that by using VR, the manipulation of the virtual environment had an impact on the neuromuscular control of their participants.

Main literature findings for ACL-affected kinematic adaptations

An ACL injury affects the execution and landing of single-leg jumps. During the toe-off phase of a single-leg jump, an ACL-affected leg shows more hip and knee flexion, while during landing the knee peak flexion and RoM are decreased compared to the unaffected leg. The stiffer landing shown for the ACL-affected leg can be compensated for with additional hip and torso movements as well as arm movements to regain balance. In addition, muscle activation patterns are adapted for the affected knee.

3.1.3 *Neuromuscular causes for ACl-affected gait and jumping adaptations*

As described above, the gait and jumping compensation techniques after ACL reconstruction may be due to weaknesses in neuromuscular activation in the lower extremity, hip and gluteal muscles [47], [51], [58], [60]. Especially the coordinated activation of the quadriceps and the hamstrings can be considered essential to providing dynamic knee stabilisation [60]. Aside from the tendons and ligaments, muscle strength is important for the stability of the knee. When a rupture of the ACL occurs, the muscle strength of the quadriceps is one of the main predictors of re-injury after rehabilitation [18]. In addition to the quadriceps, hip muscle strength has also been linked to a reduction of lower extremity injuries. In the study by Gokeler et al. (2010) [47], the electromyographic (EMG) activity during the hopping task was analysed. Specifically, the muscle activity before landing was considered to determine the stiffness of the joints. The study recorded EMG data of the gluteus maximus, biceps femoris, semitendinosus and semimembranosus, vastus medialis and lateralis, rectus femoris, medial and lateral gastrocnemius and the soleus muscles. The affected leg showed reduced knee flexion and knee RoM during the take-off of the jump and more plantar flexion in the ankle at initial landing contact. During the landing, a decreased RoM for the hip and knee joint of the affected leg was found, but an increase in the ankle joint. For the EMG data, an earlier onset of all muscles (except for the vastus medialis) was found for the affected leg. For the healthy subjects, differences in onset times were also found between the dominant and non-dominant legs. The study showed that the earlier muscle onset times might be the result of (conscious or unconscious) pre-tension in the affected limb before and during the single-leg jump landing to enhance joint stability.

With regards to the hip muscles, the work of Tate et al. (2017) [61] showed an indirect relationship between hip extensors and the hip abduction/adduction angle in single-leg jumps. It was considered that ACL patients with relatively strong hip extensors show less dynamic knee valgus compared to patients with relatively weak hip extensors. The strength of these muscles may, therefore, be a cause for varus/valgus adaptations in ACL patients.

Table 1: Overview of the modified Borg scale interpretation. For scores without interpretation, the perceived fatigueness lies between the surrounding interpretations. The Borg scores for which fatiguing effects are expected to (significantly) affect the movement behaviour of a person is indicated by an asterisk (*).

Borg score	**Interpretation**
0	At rest
1	Very easy
2	Somewhat easy
3	Moderate
4	Somewhat hard
5	Hard
6	-
7 *	Very hard
8 *	-
9 *	-
10 *	Very, very hard

3.1.4 *Effects of fatiguing on biomechanics and determining perceived exertion*

In previous research (see for example [22], [34], [62], [63]), it was shown that fatigue alters the movement quality and knee kinematics during the jumping tasks of an ACL-affected leg. This can affect knee flexion and abduction [64]. In addition, it has been found that experimentally induced fatigue may increase the risk of ACL injury during sport-specific movements [34], [64], [65].

While fatigue can be determined through biomechanical parameters (see for example [66]), the perceived exertion of a participant can also be utilised to estimate the effects of their fatigue using the Borg scale. This scale ranges the difficulty of a person to perform a task between 6 and 20 [67]. This scaling was used as a multiplication of the given score by 10 would give an estimation of the person's heart rate. In practice, this scale is commonly modified to range between 0 and 10 for easier interpretation. In Table 1, an overview of the interpretation of the modified Borg score scale is given. Based on this scale, a person can indicate how hard they find a specific task to complete. While the Borg scale is a subjective measurement of perceived fatigueness, it can be used to estimate when fatiguing effects are expected to be considerable for a person's movement behaviour, with the tipping point usually being taken at a Borg score of 7.

3.2 TECHNOLOGY FOR FUNCTIONAL MOVEMENT MEASUREMENT OF THE KNEE

The biomechanical parameters described in Section 3.1 above can be measured with various sensor systems. Such systems include, for instance, inertial measurement units (IMUs), motion capture (MoCap) systems, pressure-sensitive floors (which have been previously applied for studying gait symmetry analysis both in an interactive setting [68] and in combination with other sensors [69]); force sensing insoles (used for determining knee asymmetries in jump landings after an ACLr [70]); force and motion measuring shoes (such as the Xsens ForceShoe) and biophysical sensors (see for example an on-skin sensor used for knee rehabilitation by Xu et al., 2021 [71]). Within the continuation of this section, a focus is placed on further elaborating the possibilities for knee performance measurement through inertial measurement systems. The main alternative for sensors in this study was a MoCap setup, for which an overview is provided in Appendix B.3.1.

3.2.1 *Inertial measurement units*

IMUs provide a non-invasive method of human movement tracking in which sensors are directly attached to the body. While MoCap systems (see Appendix B.3.1) require a fixed setup with cameras and ground force sensors, IMU measurements only require the on-body placement of the sensors, thus allowing for 'in the wild' studies. IMUs can even be integrated into clothing for comfortable 'on the job' measurements (see for example the BIONIC shirt [72]). Within an IMU (which is a type of micro-electromechanical system [73]), a gyroscope and accelerometer are combined to exploit the principle of inertia in providing angular velocities and accelerations in two dimensions, while a magnetic sensor can be applied to provide 3D orientation within the sensor itself [74]. By combining IMUs in different orientations, a 6D overview of the body motion can be gathered (with 3D acceleration and 3D angular rates). The data of the two or three sensors within the unit is fused (e.g. by applying an extended Kalman filter [73]) to provide more accurate estimations. For kinematic estimation, the orientation of a body segment relative to another joint is needed, as well as linear accelerations. Through joint kinematics, the relative orientation between body segments can be estimated with a multibody kinematic model. This model should be based on an anatomical model and be adapted to the subject wearing the sensors. The angular velocity of the sensors is measured through the gyroscopes, angular acceleration can then also be obtained through differentiation of the velocity.

In general, a benefit of IMUs over motion capture is that the setup is simpler and has a lower time investment. A downside of IMUs is that the resulting data relevant for knee stability evaluation consists of accelerations. To go from this data to the relative sensor positions, it needs to be integrated twice. This leads to integration drift, which can affect the measurements and needs data filtering.

IMUs have been previously applied to measure movement behaviours and characteristics in a variety of sports contexts, see for example [66], [74]–[78]. Previous work has also been able to use IMU data to perform classifying tasks in sports, see for example the work of Beenhakker et al. (2020) [79] on classifying volleyball movements through machine learning modelling.

Within rehabilitation settings, IMUs have also been previously applied, such as within the study by Yin et al. (2018) [80] where a wearable sensor was developed to recognise patients' upper limb movement and to use the sensor input within a rehabilitation game. This setup measured body and arm angles to calculate posture and control the game. The setup was made to be used at the patient's homes and to encourage continued rehabilitation exercises by providing immediate assessment and adapting levels of difficulty. Aside from their own methodology, Yin and colleagues provide an overview of state-of-the-art IMU applications within rehabilitation. Based on this overview, Yin et al. concluded that the IMU had an angle measurement and body position estimation of acceptable accuracy (sometimes even better than commercial motion recognition systems). The study by Zhao et al. (2017) [81] developed an IMU-based gait analysis system. This system was able to assess the gait rehabilitation process of a patient during straight-level walking. The study showed that gait disorders could be accurately determined with IMUs. For applying IMUs within ACL rehabilitation to compute body joint kinematics, two challenges can be identified [82], namely determining the sensor orientation and the sensor position relative to the body. Solving these issues can be done through sensor fusing combined with the careful manual alignment of the sensors on anatomical landmarks or through performing calibration motions.

3.3 RELATED SPORTS INTERACTION TECHNOLOGY CONCEPTS

Interaction technology can be used within sports settings to improve the learning and engagement of training and competition. Sports interaction technology is a part of the human-computer interaction field that uses digital-physical exercise systems to boost the performance, engagement and motor learning of the athlete [83]. In addition, numerous applications from the interaction technology field have found their way to sports rehabilitation, injury prevention and diagnosis. Given that the relative movements and the underlying biomechanical parameters of different body segments can be measured, interaction technology can be applied to create diagnostically rich interactions in which specific movements are triggered under controlled perceptual-cognitive pressure such that rehabilitation evaluations can take place in a more sport-specific context [84]. Here, a rehabilitation patient should be triggered and motivated to perform movements, based on which the sensor technology can provide insights into the movement characteristics that are of interest.

An example of creating such a diagnostically relevant situation is in the study by Weichenberger et al. (2015) [85], which developed a fencing robot that triggered athletes to perform specific movements that could be used to evaluate their fencing performance. The use of interaction technology was applied to make the athletes in the study focus on the outcomes of the movements (external focus) and not on whether they were performing each movement correctly (internal focus), such that the performance was more relevant to the eventual sports context in which it should occur rather than isolated movements to be analysed. Having an external focus of attention has been previously shown to increase the performance of an athlete and to help in their skill learning compared to internal learning [86], [87].

An interesting study that also focused on improving the transfer of neuromuscular training interventions to reduce the risk of ACL injuries is by Bonnette et al. (2019) [88]. Here, the research team focused on creating a system that manipulates the visual feedback during a squatting exercise to increase the retention and transfer of the intervention to a basketball context. The study utilised external perceptual control, which engages automatic and implicit motor strategies rather than deliberate and conscious movement control. Bonnette and colleagues further hypothesised that this would increase the retention and transfer of the training to the sport-specific context. Participants in the study received a visual stimulus that mapped onto a range of biomechanical variables (including the knee, hip and torso). On a screen in front of the participants, a two-dimensional rectangle defined by six points was presented, see Figure 30 in Appendix B.4. The biomechanical variables were mapped onto the abstract geometrical shape on the screen and were adapted dynamically through the participants' movements. During a squatting movement, participants were instructed to move in such a way that the abstract stimulus shape would remain as close as possible to a perfect, symmetrical rectangle. The shape would remain a perfect rectangle if the participants would move in such a way that their biomechanical variables would have values associated with a low ACL injury risk. This setup allowed participants to effectively train on good execution of the squatting movement, without having to understand exactly which variables would result in the lowest ACL injury risk. The accurate mapping from the kinematics of the participant to the feedback showed an improved performance in the squatting movement.

3.3.1 *Extended Reality as a gamified system*

An interesting method to adapt the world around us for the purpose of motor learning, communicating with others or experiencing something that cannot (or is not wanted to) be experienced in reality, is the use of Extended Reality (EX). EX is used as an umbrella term containing the real world, Augmented Reality (AR), Augmented Virtually (AV), Virtual Reality and virtuality [89], [90]. Within AR, a computer-generated image is superimposed onto the real world to enhance the real world, while AV enhances the virtual world with real-world objects. VR is a 3D (interactive) simulation of a virtual environment that replaces the real world. The final step of the reality-virtuality continuum encompasses that everything is virtual (a state that cannot be perceived). A final distinction is made for Mixed Reality (MR), which merges the real and a virtual world and encompasses AR, AV and VR. Within the MR systems, the visual experience can be provided through a head-mounted device (HMD, also commonly known as AR or VR goggles). Within this subsection, the key elements of applying VR to a rehabilitation context are discussed. See for an overview of additional methods of applying gamified systems Appendix B.4.4.

An important benefit of VR is the immersion [89] it can provide. This term indicates how strongly the computer-generated visuals provided to the user mimic real-life sensory inputs and how well these visuals substitute the sensory input provided by the real world. In other words, immersion expresses how well the user is 'drawn in' the virtual environment and disconnects the senses from the real world. The immersion is dependent on the visuals and interactions presented to them but may also be improved by a higher pixel density and field of view (FoV) of the HMD used. In addition to the immersion, the fidelity of the system is used to determine the degree to which the virtual environment represents a real-world system. Both immersion and fidelity can contribute to the feeling of presence the user has, which relates to their feeling of actually being in the virtual environment as if it were the real world. This feeling also requires the VR rendering to have very little latency. Finally, the engagement of the virtual simulation indicates how well the user can stay focused on the provided visual stimuli. This is also sometimes described as how well the user remains interested in the simulation. Drawbacks to VR, especially when applied to a rehabilitation context, are the limited integration of real-world objects into the virtual world that could otherwise be utilised in (rehabilitation-related) exercises and the possibility of cybersickness that users may experience from (prolonged) VR usage. The latter term refers to the uncomfortable feeling a user may have when they are in the VR environment, resulting in nausea and headache [89]. This occurs when there is a mismatch between the visual input from the HMD and the user's vestibular sensation. Cybersickness can be the result of a low refresh rate or unsharp images in the HMD. Especially in a rehabilitation setting in which a user may suffer from imbalance, such a drawback should be considered in development.

To add to the VR experience, VR simulations can also be integrated with other forms of technology, [89], such as treadmills and cycles for transportation or sensors to visualise information or animate movement. This requires the data from the external technology to be linked through the VR stream into the HMD and thus has limited options at present. In addition, researchers and VR development companies are currently making the first steps to integrate avatar legs within virtual environments through the use of predictive algorithms using the HMD and controller movement as input [91], [92].

VR has been previously applied as a method of triggering and motivating movement within rehabilitation (see for example [59], [93]–[97]). It has also been previously explored as a method of training in jumping tasks (e.g. [98], [99]). By being immersed in the virtual environment, an ecologically valid task can be created while utilising the positive transfer of task learning in VR to real-world task performance [100]. However, VR has also been shown to increase instability during balance tasks [101], which has led VR immersion to also be successfully applied in balance and gait improvement training [59]. When applied to ACL rehabilitation by Gokeler et al. (2016) [96], VR was used within a stepping-down task to distract users from their conscious motor control and provide standardised delivery of visual (and/or auditory) feedback while having movement kinetics similar to those when acting in real-world conditions remain. The distracting effect of VR within a stepping-down task led patients, fully rehabilitated after an ACL rupture, to change their movement patterns approximating those of healthy subjects, which differed from the non-VR group of ACLr-recovered patients.

For integrating VR within rehabilitation, there should be patient willingness to make movements without being able to see the real world around them. VR has been previously applied in the rehabilitation of patients who had a fear of movement and for which positive experiences were found with this method [102] (see also Appendix B.5 regarding physiological effects related to VR). During observations and sessions at OCON, physiotherapists as well as patients themselves indicated that there is likely a strong willingness of patients to use VR as part of a rehabilitation evaluation.

For selecting the HMD to run a VR simulation on [89], important considerations are the FoV, the resolution for each eye, the refresh rate and whether the HMD allows for dynamic movement (e.g. walking around in the physical space; using six degrees of freedom) rather than stationary movement (only head rotations; using three degrees of movement). When building the VR environment from a computer-run game engine, the ability of the HMD to be cableless may be a consideration, as it provides a greater freedom of movement in the play space, see Figure 3. Similarly, the use of external tracking units such as base stations that need to be positioned around the playing area or whether the sensors are integrated into the HMD to track the head movement (referred to as inside-out tracking) may affect the VR experience. Further considerations may be the ability to include audio in the interaction, the weight of the HMD and its price. The final features to consider are the ability to allow

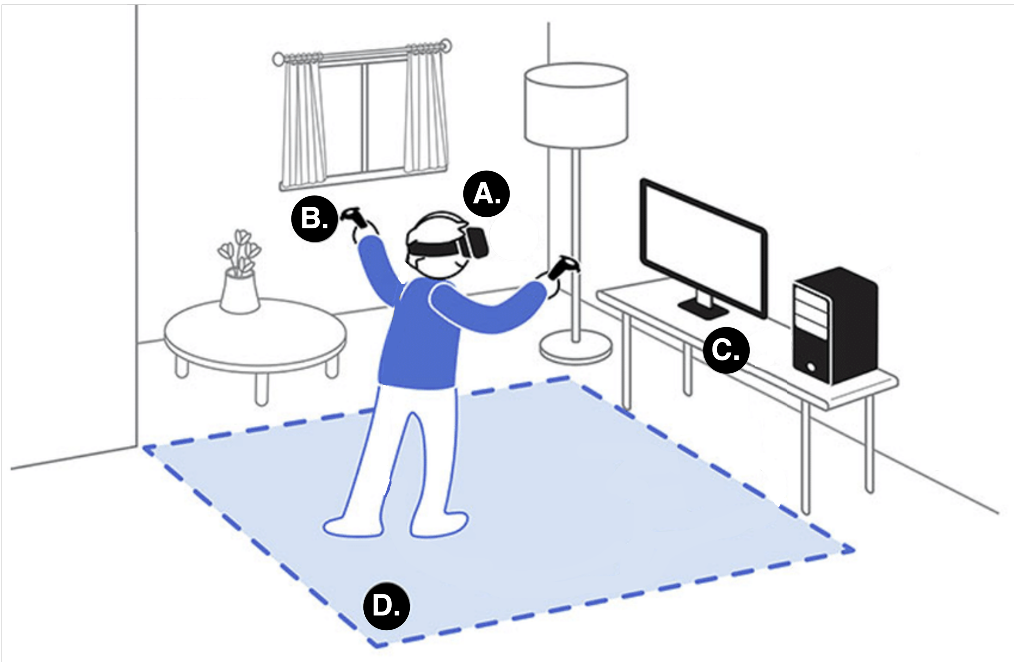


Figure 3: HMD components and playspace, adapted from [103], showing (A) an untethered HMD; (B) hand-held controllers; (C) a VR-capable computer setup and (D) the VR playspace as it is located in the real world.

the user to view the outside world from within the HMD (called pass-through), how it can keep users safe from accidentally interacting with real-world obstacles and whether it can purposefully bring in real-world objects into the virtual world to be interacted with.

3.3.2 *Perceptual-cognitive factors in applying sports interaction technology*

During a sports performance, an athlete does not only need to use their physical capabilities but also their ability to withstand the perceptual-cognitive pressures related to successfully completing the movements. Both physical and perceptual-cognitive factors are therefore needed to make correct movements for the sports task at hand [104]. When an athlete moves, their performance context is shaped by the individual, environmental and task constraints that apply to that movement [105]. Individual constraints relate to the body characteristics of the athlete (such as their height, weight or limb length), as well as temporary characteristics (such as their energy level at the moment of performance) and psychological factors (such as fears or anxiety they feel). Environmental constraints consider the environment in which the movement is conducted and which can be affected, for instance, by the size of the available space, the type of terrain and temporary restrictions such as weather conditions. Finally, task constraints include any limitations to the execution of the task, which can, for instance, be the goal that should be achieved and the rules of the task or how objects and other players behave during a game. All constraints of the movement may be subject to change both between and during task execution, which can affect how the person performs the movement each time that the execution is needed.

Within ACL rehabilitation studies, movement tasks are often evaluated in isolation and in a laboratory setting, thus removing or simplifying the environmental and task constraints.

However, adding a rich rehabilitation environment that provides sensory and perceptual-cognitive stimulation to the patient has been considered valuable for a successful recovery after ACL reconstruction [106]. During a sports task, the more stimuli are provided to the athlete, the more difficult they are to anticipate and the more it may negatively affect the athlete's performance [104]. Within the sports context, this can include the unpredictable actions of other players and game artefacts (e.g. a ball or baseball bat) which can also lead to scenarios in which non-contact ACL ruptures occur. The creation of a rich rehabilitation setting with an increased perceptual-cognitive pressure can, therefore, trigger more realistic movements of a patient that can provide more meaningful insights into potential risks when returning to sport. The addition of stimuli during RTS evaluations could therefore assess the knee stability in a more ecologically valid context (see also Appendix B.4.2 for an overview of the use of ecological validity in sports interaction technology).

The way that a movement task is perceived by an athlete further affects their sports performance [59], [104], [107]. Deficits in reaction time and processing speed (also considered to be the ability to reconcile proprioceptive, visual, auditory or other cues for motor correction during tasks) may decrease their performance and show a higher risk of ACL injuries. For this reason, some rehabilitation exercises may include decision-making tasks to retrain a higher processing speed. Here, the athlete can focus on increasing their strategic (i.e. not time-dependent), tactical (i.e. time-dependent and with increasing uncertainty) and reactive (i.e. with limited or no time for functional task exploration) control. Especially this third method of control may result in unsafe movement performance that can lead to ACL (re-)injury and may warrant additional attention during rehabilitation.

3.3.2.1 *Use of dual-tasks*

In everyday life, movements are often accompanied by additional tasks, such as walking and talking or eating while looking something up. Such a combination of tasks is called dual-tasking [108] and can lead to a decrease in performance in one or both of the tasks due to a division of attention, especially as the tasks become more complex. In general, adding cognitive demands such as attending to a specific goal or affecting decision-making to a jumping task have been shown to affect a person's biomechanics [109], [110]. To direct the attention of someone performing a movement away from the execution the use of dual-tasks can be applied as well. Dual-tasks can further be used as a method to create a more sport-specific context by adding game-like variables that are inherent to the sport. These elements can be, for instance, adding a dribbling or ball-catching/ball-passing task within a change-of-direction movement [105]. The addition of the ball can create a task that is more related to the actual sport that an athlete can return to (in this case basketball) and ensures that the patient performing the movement cannot focus on the execution but needs to focus on dribbling or passing correctly. The use of dual-task has also been proven very efficient in the impact recovery of functional walking tasks [108].

To apply a dual-task or provide other forms of information or feedback (see Appendix B.4.3 for an overview of the different modalities used in sports interaction technology) that add to the providing perceptual-cognitive pressure, additional consideration should be made at the disruptiveness of such additions, especially in a VR environment. In the foundational work of Zijlstra et al. (1999) [111], the extent to which something (either an informational message, feedback or a secondary task to be performed) interrupts a primary task can be evaluated by the extent to which the primary task can be continued by the person. If the disruption is too strong, the user cannot continue to perform the primary task and must instead fully focus and address the disruption. If the disruption is too weak, it barely registers with the user and they are not motivated to put focus on it. For a dual-task, the primary task remains the main focus, while the secondary task should only provide a medium disruption that allows them to complete the primary task while still addressing the secondary task.

3.3.2.2 *Use of VR for increasing cognitive lead*

When external focus is utilised, athletes may improve their ability to automatically process the movement and reduce their needed cognitive effort. This method has been successfully applied to various sports and balancing tasks [86]. In the work of Cochran et al. (2021) [86], the effect of external focus was considered for a single-leg jump within a VR environment. In this study, the external focus improved the VR performance, but it did not improve retention of the task or transfer to the real-world performance.

In general, VR can increase the cognitive load on its user [112]. By immersing the user within the virtual simulation, a perceptually rich environment is presented to the user which can adapt the additional cognitive load as required for the given task. However, the presence of additional cognitive load itself is not necessarily an obstacle for a user but should, similar to the use of a dual-task, be considered in terms of how it affects the execution and performance of the primary task.

4
DESIGN AND DEVELOPMENT OF THE INTERACTIVE VR-ACL EVALUATION SYSTEM

Based on the literature and expert input provided in Chapters 2 and 3, the designing journey is described in this Chapter. For the final interaction, a sensor and VR system work together to trigger participants to make single-leg jumps at 20, 40, 60 and 80% of their maximum jumping ability with each leg within the virtual environment. To create a diagnostically rich environment, increased perceptual-cognitive pressure is applied with a dual-task, as well as virtual distractions and competitive elements. The jumping task itself is presented utilises external focus.

Within this chapter, the full journey of the development of the interactive VR-ACL evaluation system is provided. This contains first the description of various tooling considerations as they flow from the literature background provided in earlier chapters, followed by the concept creation and selection, and finally a full description of the interactive system itself. Additional notes to the design and development have been added in Appendix F.

4.1 TOOLING AND PLATFORM CONSIDERATIONS

For the development of the study, several tooling and platform considerations were made to create a system that can combine sensor technology with an interactive environment. These considerations were partly based on the literature review provided in Chapter 3 as well as evaluations made throughout the development phase itself and expert input.

4.1.1 *Selecting the sensor system*

With both the IMU sensors and motion capture (see subsection 3.2.1 and Appendix B.3.1 respectively), the movement characteristics of various segments, including knee stability, can be analysed. While the motion capture systems are better integrated within the existing body of literature, the IMU sensors are more wearable, portable, cheaper, require less time for setting up and can be implemented outside the laboratory setting. As this study has a strong focus on practice, the final system should be able to be integrated within practice without difficult transitions. The easier-to-use IMU systems are, therefore, more suitable to implement within the already packed schedules of physiotherapists. In addition, because the IMU system does not require a fixed laboratory setup with cameras, it allows for more flexibility for implementation into a physiotherapist's office or outside environment. Based on the possibilities of both systems, the IMU system is considered the most suitable for this research project.

Based on the availability of the hardware and software, the MVN sensors by Xsens (part of Movella) were selected for this study (see Figure 36 in Appendix F). These IMUs has been applied and evaluated previously for ACL rehabilitation (see for example [52], [113], [114]) and gait performance studies (e.g. [115], [116]), and have been validated in previous studies (e.g. by [115], [117], [118]). The MVN setup consists of a maximum of 17 sensors, which can be used as loose IMUs attached to the body with straps (MVN Awinda, sampling at 60 Hz) or within a suit as a wired configuration (MVN Link, sampling at 240 Hz) [115]. While the Link system provides a lower latency (20 ms compared to the 30 ms of the Awinda system), the Awinda allows for a minimum sensor setup with a subject smaller preparation time, thus being the more suitable option. IMU systems do not directly gather knee positions and knee flexion angles but do so through the integration of acceleration data. The required double integration to find the positions of relative IMUs causes drift, which requires adaptive algorithms to correct for. For the MVN systems by Movella, an MVN Analyse software tool was developed for extracting and processing the raw data, while simple recording and streaming of the data can be completed with MVN Record. Based on the data, Movella uses its own biomechanical model to provide joint angles and segment positions. For this study, it was decided to focus on the data analysis as it can be presented to and utilised by physiotherapists in practice. These initial preprocessing and filtering steps completed by the MVN Analyse software were, therefore, considered outside of the scope of this work. Aside from the kinematic analysis, the MVN data allows for streaming into Unity, thus enabling animation of the MVN sensors (displayed as a lifesize avatar) in the virtual environment. For this, the interaction with the floor is removed, which fixes the pelvis in space but does not allow for evaluations in which the ground contacts are ill-defined (e.g. if the foot-ground contact would be altered) [115]. Finally, to maintain a fast setup and quick use for future practice, a minimum sensor setup was chosen which only includes lower body sensor configuration. For individual purchases of the MVN sensors and suit, the price for the whole setup is 3490 Euro [119].

4.1.2 *HMD and game engine selection*

While a great number of HMDs are on the market and more are being added each year (leading to a projected annual market growth until at least 2030 [120]), only several HMDs were considered for this study based on their availability for the development and execution of the study. These three models were a Meta Oculus Quest 2, an HTC Vive Pro and Vive Pro 2. Based on the characteristics and overall availability of the HMD for the study, the Oculus Quest 2 was selected (see Figure 36 in Appendix F). This HMD [121] has an FoV of 100 degrees, a resolution of 1832 x 1920 and a refresh rate of 90/120 Hz, making it better performing than the Vive Pro but worse than the Vive Pro 2. The weight of the HMD is 503 grams, making it the lightest out of the three options. The major advantage of the Quest 2 over the Vive HMDs is its ability to run simulations standalone whereas both Vive HMDs are tethered and thus limit the mobility of the user. For its standalone feature, the Oculus streams the virtual simulation from the computer over WiFi using its AirLink functionality, which was still in its experimental phase at the time of development and testing but has since been made a mainstream functionality of the Quest 2. To prevent users from interacting with real-world objects around them, the Quest 2 uses a virtual Guardian to demarcate the playing area. When a user moves towards the Guardian, it appears in front of the user as a virtual grid wall. If a user moves through this Guardian wall, the Oculus view shifts from the virtual environment to its pass-through view that projects the real world into the HMD. As of February 2023, the Quest 2 also includes a 'Space Sense' option, that allows users to bring real-world objects (such as walls, furniture or pets) into their virtual environment for mixed reality purposes. This HMD operates unthreatened with inside-out tracking and allows for pass-through, albeit in black and white and at a low resolution (with plans made by Meta to create a Quest Pro with high-resolution and full-colour pass-through functionalities). The price of the Quest 2 is around 350 Euro [122].

To run the virtual environment of the VR-ACL evaluation system, a game engine was needed that would allow for VR development, as well as integration of the sensor system. Unity 3D is one such game engine that can be used for the development of 2D and 3D games as well as AR and VR environments [123]. It works well with the Meta Oculus Quest 2 and has extensive documentation available for its integration. Programming within Unity 3D is done in C# and JavaScript, while much of the worldbuilding can be done with self-made or pre-existing 3D assets. Unity uses a component system that allows for assets to be built up as a collection of individual components rather than the less flexible object-oriented programming. This is particularly beneficial for implementing a variety of separate (but similar) tasks for which individual adaptations are needed, as for a component system specific adaptations for a user or other features only need to be defined once rather than individually for each type of task. The downside of this platform is that everything within the interaction is manually programmed and the platform has a high learning curve. In addition, the platform does not allow for quick adaptations when used in practice by physiotherapists, as in-depth knowledge of the world-building and coding structure would be needed for specific alterations.

Similar to Unity 3D is the Unreal Engine 5 platform, which can provide 2D and 3D interactive experiences. It uses graphic programming as well as C++. As is the case for Unity, the Unreal platform has extensive documentation for the Oculus Quest integration. The same drawback for Unity 3D on adaptation complexity applies to Unreal.

One platform that was designed for easy world-building is the Aryzon World platform, which has a low-code built that can be adapted within the VR environment itself. The main objective of this platform is to provide professionals with an easy and accessible method to create virtual environments in which they can collaborate from a distance. The platform is compatible with the Oculus Quest 2 but was, at the time of development, still in its bèta phase, although available for demonstrations for select users. An initial try-out of the platform showed possible use for a future version of the software.

Due to its intuitive method of world-building and extensive documentation, Unity 3D was chosen for the VR development of this study. Within the development and final design of the VR environment (see Sections 4.2 and 4.3 respectively), the asset library of Unity was utilised to create the main environment on which the rest of the interaction with its game elements was built.

4.2 VR INTERACTION DEVELOPMENT

Central to the system development is the interaction in which patients are triggered to make the specific movement behaviours that have the potential to generate rich sensor data. As was described above, this interaction consists of a VR setup that was designed within Unity to be streamed onto the Oculus Quest 2 VR headset. Within this section, an overview is given of the design journey that led to the development of the VR environment and the overall interaction.

4.2.1 *Design restrictions and success criteria*

For the design of the VR interaction, several restrictions were considered in the development. For these restrictions, the use case of implementing the final system at a physiotherapist clinic was considered, while taking into account the proof-of-concept nature of the development stage.

- ACL simulation constraint: to avoid injury risks with ACL patients, healthy participants will be used within the study. These participants should be perturbed on one leg such that their jumping behaviour simulates that of an ACL-affected leg on one side and a healthy leg on the other.
- Time constraint: to allow for optimal availability of testing participants within this study as well as providing a fast and feasible rehabilitation evaluation in practice, a maximum of 1,5 hours should be considered for the entire session, including participant preparation. To avoid cybersickness, the maximum time spent consecutively within the virtual environment should be one hour, with frequent opportunities for a participant to conclude the session.
- Room constraint: the testing location should allow participants to move and jump freely within the virtual space and should thus be of adequate space, with no fixed objects and an adequate ceiling height.
- Fatiguing constraint: to avoid interference fatiguing in the kinematic data collection, the perceived fatigueness of participants should be monitored throughout the interaction such that kinematic data from a fatigued state (i.e. a self-indicated Borg value of higher than 7) can be excluded from the dataset.
- Sound constraint: to make sure that the researcher and participant can be in continuous contact throughout the measurement session, no sounds can be used in the interaction. Only visual stimulations may be provided.

Aside from adhering to the restrictions provided above, the interaction should successfully achieve the following goals.

- Trigger single-leg jumps for both the perturbed and non-perturbed leg during the interaction at the specified distances of 20, 40, 60 and 80% of their maximum single-leg jump distance of that leg in random order.
- Provide the interaction within specific rounds of gameplay in which jumps are provided with adequate rest in between consecutive jumps (10 seconds minimum) and between rounds (30 seconds minimum).
- Make jump triggers appear straight in front of the participant such that they can be executed completely without the movement interference of turns or additional jumping behaviours.

- Provide (visual) distractions to the patient between consecutive jumps.
- Provide an increased perceptual-cognitive pressure on the participant throughout the interaction using a dual-task.
- Provide a time-based competitive element to participants throughout their gameplay.
- Allow for kinematic data gathering and analysis that provides insights into the movement performance of participants to physiotherapists.
- Make the system as much plug-and-play as possible with a minimal sensor setup and system adaptations needed between participants.

4.2.2 *Concept development and iterations*

To comply with the design restrictions and success criteria, three concepts were designed for the VR interaction. These concepts were based on the initial research study, expert and patient discussions as well as iterative designing. Each concept was designed with a unique setting and game elements to support the diagnostic purpose of the system. After the concept design, a user evaluation study was held to determine the best concept for development. Within this section, the final concepts are provided alongside the imagined scenery for each concept (created by the Midjourney AI art generator), see Figure 4. For the concept description, the terminology of 'player' rather than '(ACL) patient' was used to let participants of the evaluation study feel more engaged with the proposed concepts. For consistency, this terminology was kept in this subsection.

In the box below, the description of the first concept is provided. This concept describes an immersive setting in the form of an unknown extraterrestrial planet. This allows for creating colourful and unique visual distractions for the player (e.g. flying items, far away planets, coloured night sky) and can give a storyline in letting the native inhabitants of the planet set up rules for a player to follow (thus motivating them to perform single-leg jumps). The concept additionally incorporates a competitive element by letting players gather points for correctly executed jumps (which could be based on accuracy in reaching the target of the jump or a kinematic measure of jump performance similar to the approach of Bonnette et al., 2019 [88]).

(a) Imagined scenery of Concept 1 - Exploring an extraterrestrial planet. AI input: "*Make an extraterrestrial planet with a rocky desert ground and a purple coloured sky. Make a big moon and planets in the background*".

(b) Imagined scenery of Concept 2 - Sport-specific athletics setting. AI input: "*Make, in realistic animation style, an athletic running track with public stands far away*" and "*Make, in realistic animation style, a full-body coach looking happy*".

(c) Imagined scenery of Concept 3 - Playing an adventure game. AI input: "*Make an adventure game environment with crocodiles and water streams. Make open grass fields and forests in the distance. Make a backdrop of mountains and volcanoes*".

Figure 4: Virtual scenery of the three concepts generated by the Midjourney AI art generator, alongside the provided input to generate the images in italics.

Concept 1 - Exploring an extraterrestrial planet

Scenario description: *In an extraterrestrial planet, the player walks around on a rocky ground with a purple-coloured sky above. While walking around, the player suddenly comes across the alien inhabitants of the planet they are visiting. These native inhabitants require the player to make a single-leg jump over a puddle of dangerous alien goo that is lying on the ground, using the specified leg and making sure they safely get across each distance.*

Player motivation in the interaction: *As a reward for each jump, the aliens will provide the player with traveller coins, but they will take coins from the player if the jump is incorrect. Between different rounds of playing, players can see how many coins they gathered to compare how well they are doing over time.*

Additional distractions in the interaction: *Within the virtual environment, different distractions can be provided by having spaceships fly over or rockets take off in the distance.*

In the second concept, players find themselves on an athletics track with stands on the side where they follow a course of single-leg jump exercises at the specified distances. Close by, a virtual coach is placed who encourages the player and provides instructions where needed. When a jump is successfully executed, a cheering audience is visualised from the stands. This concept focuses specifically on providing positive feedback to the player to make their jumps correctly, as well as adding (individually targeted) instructions that the physiotherapist can use to help their patient improve throughout the interaction.

Concept 2 - Sport-specific athletics setting

Scenario description: *The player walks around on an athletic run track. Right next to them, a coaching persona motivates the player to make single-leg jumps of specific distances.*

Player motivation in the interaction: *When a jump is correctly executed, a cheering audience will show their approval. In addition, the coach provides positive feedback to the player.*

Additional distractions in the interaction: *A player in this scenario can have interactive game objects relating to sports (e.g. a basketball or football) lying around in the interaction that can be virtually picked up and played with in between sessions.*

The final concept that was used consists of an arcade-like adventure-like game where players must complete an obstacle-like jumping course to safely reach the end of the game. As with Concept 1, this concept uses a storyline in which players must reach the end of the round that motivates the interaction and puts the focus on the gameplay. The game motivates intuitive movement by providing the player with elements that they should not walk through (but instead jump over), such as lava streams or open crocodile mouths. Additional pressure is given to the player by providing them with a time constraint in which they must complete the level, thus forcing them to jump without (significant) preparation time.

Concept 3 - Playing an adventure game

Scenario description: *Within the adventure game, the player has to jump over dangerous crocodiles and lava streams to safely reach the next level. The player's goal is to reach the end of the road while avoiding the dangerous elements around them before their time runs out.*

Player motivation in the interaction: *Players must move quickly before their time runs out and try to reach their fastest round. Throughout the interaction, they have to avoid the danger around them, as it leads to deductions in time.*

Additional distractions in the interaction: *The virtual world around the player comes to life with different dangerous creatures and elements they must stay away from to avoid time deductions. They might not always see where the danger is coming from, so they will have to pay attention to their environment to make sure they can respond in time.*

An overview comparing the different key elements of the three concepts as well as possible drawbacks to be considered is provided in Table 2. Based on the existing concepts, the user evaluation was held to create a final design encompassing the initial designs' strongest points.
The three interaction concepts described above were evaluated through a dedicated focus group session with the physiotherapists of the OCON Orthopaedic Centre as well as with a survey that was sent out to gather insights into the rehabilitation process and the established concepts (of which all insights are gathered in Appendix G). In total, two physiotherapists and one sports doctor participated in the evaluation session at OCON, while $n = 35$ people filled in the survey (response rate of 85%).

Based on the evaluation of the three concepts with the physiotherapists at OCON, it was noted that the first concept seems to be the most immersive. The ability to fully take the patient from the physical testing location into an immersive environment would benefit the evaluation by potentially providing a similar cognitive load as is given to a patient during sporting events. For Concept 2, it was noted that this seemed to be the most effective environment if the sports setting could be adapted to the individual patient (e.g. having a basketball court for a patient rehabilitating to return to playing basketball) but might not be stimulating if the patient or participant would play a different sport. The final concept was seen as immersive with a lot of opportunities to trigger specific movement behaviours within a game setting. The use of a competitive element was also seen as motivational, as the physiotherapists often observe patients wanting to compete against themselves or others during their rehabilitation.

While the physiotherapists focused mostly on the immersion of the concept, the survey that was sent out provided insights that were more focused on the game elements of the interaction (see Appendix G). For all three elements of general preference, enjoyment of the motivational elements and the engagement of the additional distractions, Concept 3 was preferred by most participants. Subsequent comments also provided insights into possible combinations of the different elements. Specifically, participants enjoyed the game elements of Concept 3, where a player has to complete individual levels to see their performance over time. For the first concept, participants indicated that they would enjoy the immersion, es-

Table 2: Summative comparison between the three interaction concepts.

	Scenario description	**Player motivation**	**Additional distractions**	**Potential drawbacks**
Concept 1 Exploring an extraterrestrial planet	Strongest focus on immersiveness through unique setting. Uses a clear storyline in the interaction. Easiest to design and develop in VR by using unconventional and abstract concepts.	Motivation based on storyline and intuitive visualisations.	Objects flying overhead and use of vibrant colours.	Because of individual jumping styles, determining critical elements that make a correct execution of the single-leg jump outside of distance and measured in real-time is difficult.
Concept 2 Sport-specific athletics setting	Use of athletics track settings and sports objects to create a direct and strong relation to the rehabilitation.	Use of external motivators (audience and virtual coach).	Use of interactive sports objects.	For optimal evaluation of the sport-specificity of this concept, the player should also be engaged in (track) athletics.
Concept 3 Playing an adventure game	Strongest use of gamification and entails a clear storyline.	Motivation through clear storyline-related visuals.	Distractions by adding the element of suspense within the virtual environment.	The setting could restrict players' movement by having virtual objects in their near surroundings (e.g. trees and mountains) to ensure that they jump over the obstacles.

pecially through the use of flying distractions that add to the VR experience. The use of competition in this concept by gathering coins was found to be motivational, although this did raise the question of whether the collected coins could be used somewhere in the game, which would affect their motivational use. Within Concept 2, some participants found the explicit lack of timing in the interaction to be less stressful compared to having a timer, while others did seem to want to have this as a competitive element as was included in Concept 3. For Concept 2, the sporting element was found very fitting with the rehabilitation context, and the cheering audience and having a virtual coach were found motivational by some. In general, the use of a storyline was considered important, as well as making full use of the VR immersion by having visuals all around the player or having interactive objects present in the game.

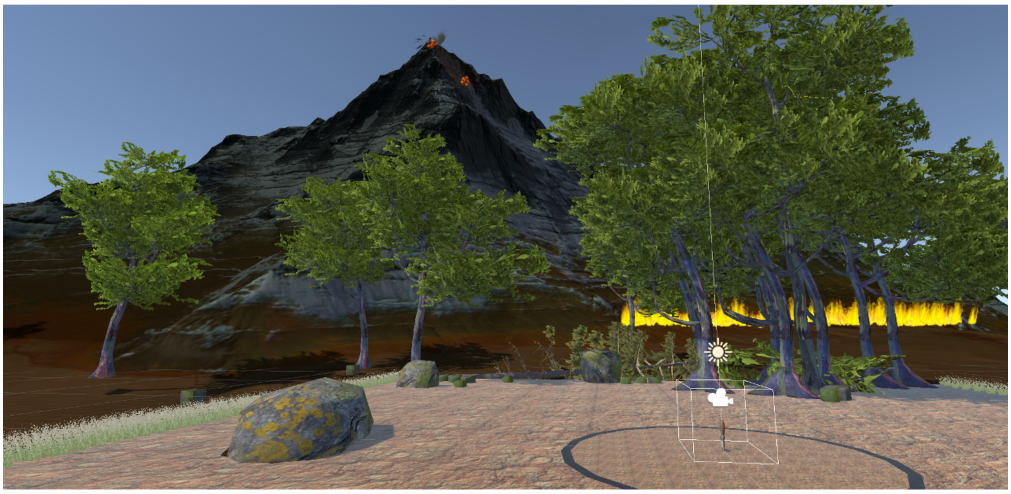
Combining the feedback from the physiotherapist focus session and the survey, the third concept was considered to be the most promising for development. The use of a storyline-like rationale for having players complete the jumping exercises and adapting the game elements and visuals to fit with that narrative without overpowering the overall interaction seems to be the most immersive. To keep a competitive element but avoid high pressure in moving, a timer counting up rather than down was used, which would let players compare their time over different rounds of gameplay. This was considered to lead to more sport-specific behaviour, as in gameplay a long preparation time for a movement may not be directly punished but can negatively influence a player's performance. In addition, the required adaptability to unexpected elements in a game environment was considered by increasing the perceptual-cognitive pressure during the interaction. For this, a dual-task was used by having the player shoot down virtual objects appearing and approaching mid-jump using their controllers. Adding to the competitive element was that time bonuses (in this case reducing the time of the round) were awarded for objects correctly shot down, and time punishments (adding time to the round) when the objects would hit the player. A full overview of the final interaction is provided in Section 4.3.

4.3 Description of the complete interaction with the VR-ACL evaluation system

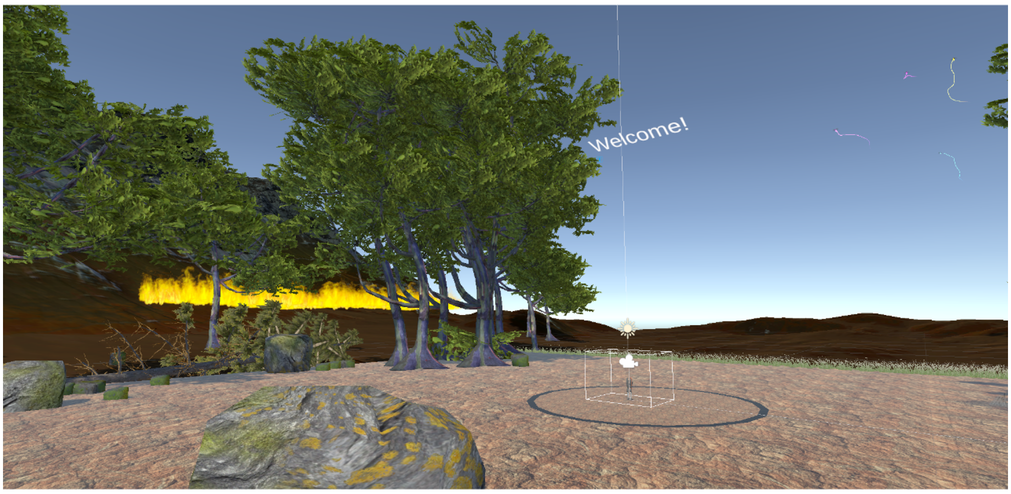
As part of the final interaction with the developed system, the participant wears the Movella MVN sensor setup with the configuration of the lower body plus sternum. The sensor movement is streamed and recorded from the Movella MVN Record software (2018 license) to Unity to animate the recorded movement of the player within the virtual environment in real time. Additionally, participants wear the Oculus Quest 2, which receives input from the virtual environment from Unity through SteamVR and allows them, in turn, to interact with the virtual environment and game elements through the HMD movement and controllers. See for an overview of the interworking of the different components Figure 8.

4.3.1 *The VR environment*

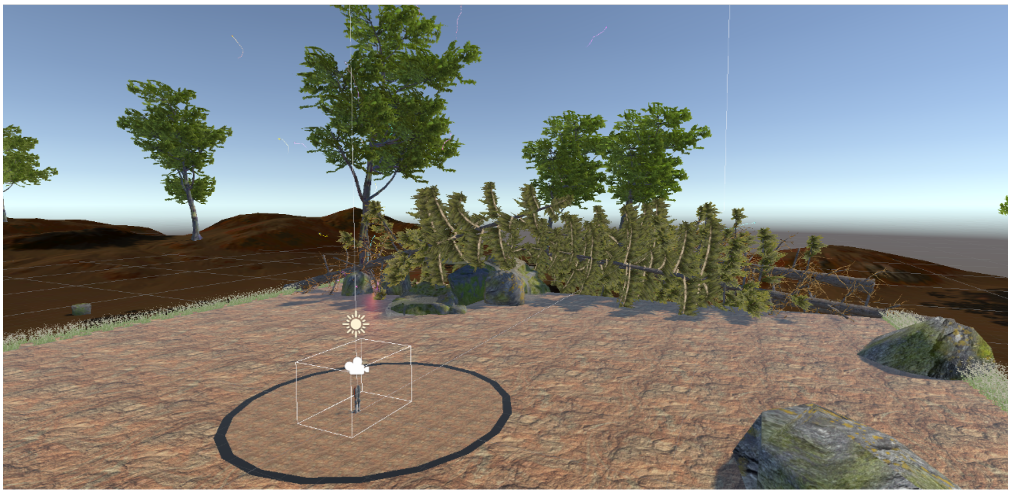
When entering the VR environment, the participant was placed within the centre of a volcanic landscape. While a large open space was provided to give a sense of physical safety, several key virtual elements were used to draw the participant's attention, see Figure 5. Central in



(a) Right side view of the virtual environment, showing the volcanic explosions and wildfires.



(b) Right-back side angle of the virtual environment, showing the text used for welcoming participants, game instructions and round timers displayed in the sky.



(c) Left side view of the virtual environment, showing the fireflies.

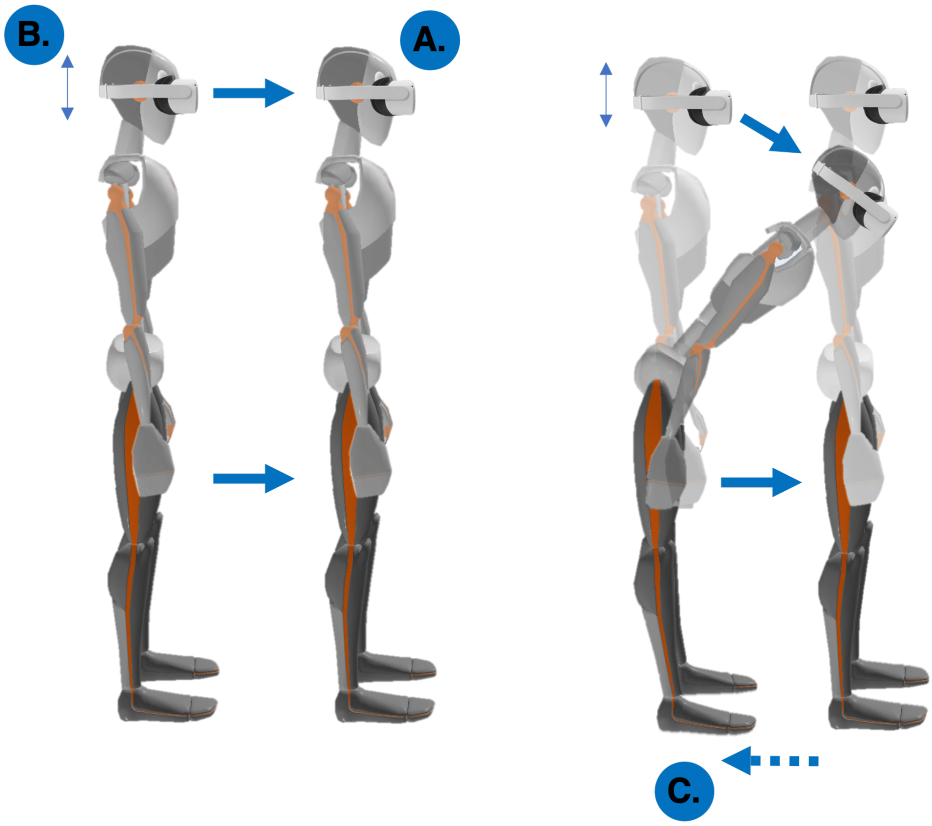
Figure 5: Overview of the virtual environment at three angles, shown from the developer's perspective. At the centre, the Movella MVN avatar is shown (only the legs and feet made visible) alongside the camera viewpoint of the HMD (indicated with a camera icon). For each angle, the key elements visible are indicated.

the interaction is the integration of the MVN avatar into the virtual environment, allowing the participant's lower body movement (as recorded with the MVN IMUs) to be shown in the virtual environment. The full avatar can be seen in Figure 7 to give a sense of the relative dimensions used in the virtual setting. During the interaction, participants were only able to see the avatar's legs and feet moving from a first-person perspective based on their own leg movements.

To keep the first-person perspective, the MVN avatar was coded to follow the HMD movement in its horizontal position and rotation. For this, the root locus (as placed on the pelvis) within MVN Record was kept fixed and, within the virtual environment, the game object origin of the avatar's pelvis (as projected onto the ground) was matched to the origin of the HMD (projected to the ground). For the vertical position of the avatar, the pelvis was positioned below the HMD at a calibrated distance. This vertical calibration of the avatar, separate from the standard sensor calibrations completed for the IMUs, was needed to prevent the feet from sinking into or floating above the virtual floor upon starting the data stream of MVN Record (when the MVN avatar's dimensions would be synced with the participant's height). After the initial calibration of the vertical location of the avatar root locus, the pelvis was kept steady within a bandwidth of this vertical location to keep the legs from sinking into the ground when a user would bend forward.

As the pelvis position of the avatar would move alongside the HMD's horizontal movement, strong bending forward movements (e.g. when a participant would look at their virtual legs) would result in the MVN avatar's legs moving forward to remain positioned below the HMD, see Figure 6. Such bending movements were expected to occur frequently with participants checking their position before and after jumps. To avoid the incorrect positioning of the avatar's legs, its forward movement was restricted whenever the HMD would deviation outside a vertical bandwidth of the calibrated position, see Figure 6(b). As a result of this restriction, forward bending movements kept the MVN avatar's hips at the pre-bending location (thus matching where the participant's real-world legs would also be at the bending moment). To resume the avatar's following of the HMD horizontal position, a participant would have to return to stand up straight (moving the HMD back within its vertical bandwidth). With these corrections, participants would be able to experience natural walking, jumping and bending movements, but would not be able to move in a crouched or hunched-over position without the avatar's legs staying behind. With regards to rotations around all axes of the MVN avatar, no restrictions were provided to keep the natural movement of the individual body segments. Finally, any deviations in axis orientations between the MVN Record stream and the Oculus HMD-based configurations that slowly occurred over the course of the interaction could not be automatically corrected for (as they were inherent in the axis orientation of either sensor system) and were instead manually re-aligned between playing rounds of the interaction.

Because the MVN avatar was programmed to follow the HMD's horizontal position whenever the participant was standing up straight, several elements were used within the virtual environment that would motivate the participant to keep their line of sight higher. These elements are also highlighted in Figure 5. First, a text canvas was displayed in the sky above the participant, displaying messages and instructions before the start of the interaction and, throughout the rounds, showing the time elapsed (see also Figure 7). For each round, the



(a) Movements of the HMD (A.) within the horizontal plane and no deviations larger than the calibrated vertical bandwidth (B.) result in the MVN avatar legs moving along the HMD position.

(b) Movements of the HMD with a vertical component outside the permitted calibrated bandwidth (such as bending) would move the MVN legs as if they were still below the HMD location and have to be corrected (C.) back to their previous location to match the position of the participant's legs.

Figure 6: MVN avatar legs following the HMD movements. The MVN upper body and arms were not visualised in the interaction but are shown here with a higher transparency for completion. Shown is the MVN avatar behaviour during HMD movements without and with a (significant) vertical component.

timer would start over and count up until the round was completed. At the end of each round, the time of that round was shown, as well as a list of the times of all previous rounds, with the fastest being shown in green for comparison. Second was the volcano which shaped the virtual landscape. On top of this volcano, fiery explosions were visible and smoke appeared. At the participant's line of sight, wildfires were placed at the edge of the playing field to the left, while at the right a small waterfall was added on top of large rocks. Finally, to the participant's right, a swarm of fireflies in multiple colours made a fluttering movement upwards. The rest of the environment was completed by trees, boulders, plants and grasses placed at the edges of the field.

The playing field itself was based on an even rocky underground. Because participants would have to make jumps within a virtual environment, it was important to match the proprioceptive feeling of the physical ground with the visual stimuli of the VR environment to ensure jump safety and increase VR fidelity. Because of this, the ground was visualised with a hard material with a repetitive, even pattern. In the middle of the open playing space, a circle was added to the playing ground. This was used to help participants orientate within the environment and to encourage them to stay and return to the middle, where game elements could not spawn under the virtual objects placed at the edge of the field. This was especially important when the teleportation functionality was enabled. While this was initially designed to be restricted in the interaction, the teleportation was enabled during the testing sessions to accommodate all virtual movement in the relatively small testing space (see Section 5.2). With teleportation, participants were able to jump to traverse the entire virtual environment by means of ray casting. This method was used as it is considered less prone to causing cybersickness as opposed to other methods of virtual teleportation.

To protect the participant from the real-world obstacles that might be in place, a virtual guardian was placed around the playspace. This was shown to the participant as a blue line continuously in sight and a virtual wall that would appear as the participant would near the edge of the playspace. When the participant would walk through the virtual guardian, the virtual environment vanished in exchange for the passthrough view of the real world.

4.3.2 *Game elements and jumping task*

Separate from the stationary assets mostly incorporated from pre-existing Unity assets (and adapted in components as needed), were the elements used for the jumping task. These elements spawned and disappeared as needed for the gamification of the interaction. The main element triggering each jump was the jumping plane, see Figure 7. To trigger single-leg jumps of specific distances, these jumping planes were spawned as a lava-coloured plane on which two starting circles and one landing circle were placed. The plane always spawned with the two starting circles placed towards the participant's side, with one green and one white. The green circle indicated which jump was the jumping leg, which matched a green landing circle on the same side at the edge of the plane (e.g. in Figure 7 the avatar is standing ready to jump with its left leg from one end of the plane to the other). The sides of the plane showed steam rising to motivate participants to land safely on the landing circle and avoid the lava. The distances between the starting and landing circle were based on the single-leg jump distances made before the interaction (see 5.3). Based on the jumping distance of each

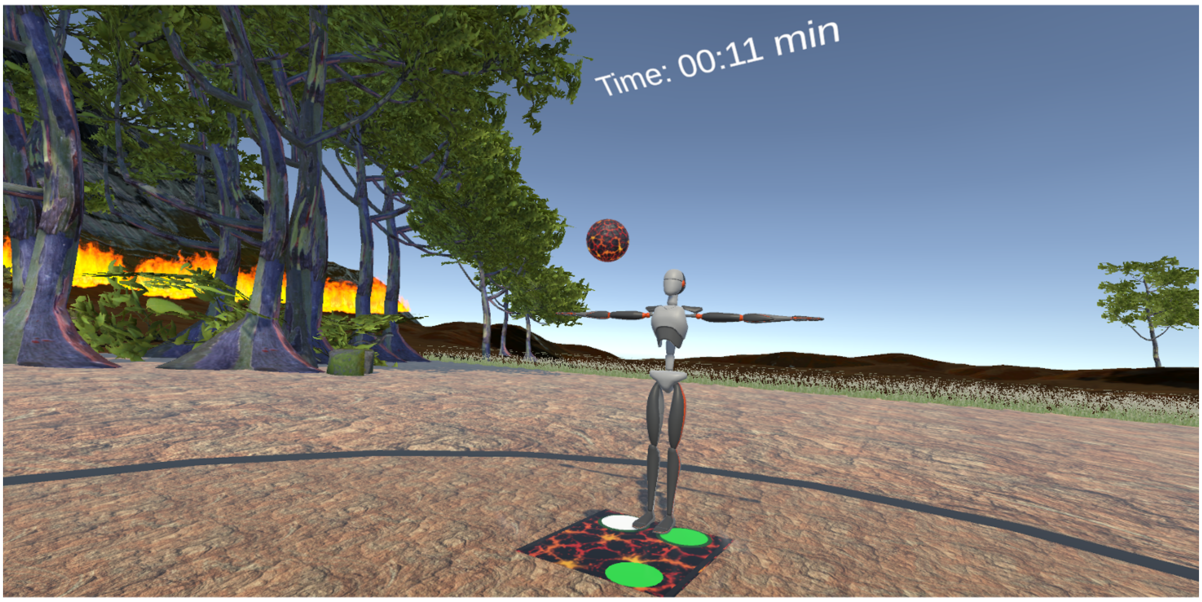


Figure 7: Full MVN avatar standing at a jumping plane, while a lavaball is approaching from the sky. In the background, wildfires part of the volcanic environment are visible, as well as the time counter in the sky. Participants within the virtual environment experienced the MVN avatar from a first-person view, with only the legs and feet being shown. To show the scale within the virtual environment, the full MVN avatar is visualised. In the interaction, participants were only able to see the lower half of the avatar (i.e. up to the upper legs).

leg in the VR condition, the jumping targets in the interaction were adapted to be at 20, 40, 60 or 80% of the maximum.

As part of the jumping task, a dual-task was incorporated to increase the perceptual-cognitive pressure during the movement. The chosen task was to shoot down an appearing and approaching lavaball while preparing, performing or landing during the jump task. This dual-task was chosen to represent a common dual-task strategy of ball handling as well as fitting with the chosen VR setting and to increase immersion in the virtual volcanic environment. The dual-task was applied to the jumping task as follows. At the start of the jump, the participant would have to stand ready on the starting circles of the jumping plane. To make sure that the system recognises the start of the jump, trackers were added on the avatar's feet and on the starting circle. If a foot was correctly positioned on a starting circle, a green edge would appear around it to indicate to the participant it was ready for the jump. Participants were instructed to only start their jump once both starting circles were green. After triggering the start of the jump, a lavaball (shown in Figure 7) could suddenly appear as a solid ball with a diameter of 20 centimetres and immediately start to approach the participant (aiming for and continuously adapting to be headed directly at the HMD location). The lavaball is spawned in front of the participant's line of sight, at 2,5 Unity units of distance (roughly equivalent to 2,5 meters within the perception of the real world), with a slight deviation either to the right or the left to not obstruct the participant's view of the landing location. The vertical height of the lavaball was based on the vertical position and rotation of the HMD (e.g. if a participant was looking down, the lavaball would appear as if coming from the ground) to always appear in the line of sight. The ball approached the participant with a speed deviating between 1 and 2,5 Unity units per second (equivalent to 1-2,5 meters per second) and was spawned with a delay between 1,5 and 5 seconds after triggering the start of the jump. In addition, it had a 75% chance of appearing (thus trying to wait them out after triggering a jump would be a time-costly decision). By randomising the location, speed, delay, and chance of appearing, the lavaball remained an unpredictable game element for the participant during the jump. The variables of the dual-task could be adapted from the master script (see Table 13 in Appendix H.4) if needed.

As the lavaball approached the participant, they were told to shoot it down using their right controller before they were hit. Pressing a button on their controller spawned a red shooting ball that was shot in the direction they were pointing. For each lavaball, they had two tries to shoot it down. The shooting balls had a diameter of 10 centimetres and were modelled to move under an impulse away from the controller (e.g. as if shot like an arrow from the controller). This meant that it would move away from the controller in a curved trajectory and return (and bounce) on the ground after being shot. Participants would, therefore, have to aim carefully to hit the target (similarly to as they would when in a sporting environment) and could not approach the hitting of the lavaball as they might do in a first-person shooting game (where the shooting element would often be modelled as guns or lasers that would move straight from the barrel to the target without any deviation). Participants, therefore, had to aim carefully and engage in motor learning to correctly complete the shooting task, while completing the jumping task. This allowed for a diagnostically richer environment. Similar to a sports scenario, the participant had a competing focus in completing the movement.

Once a lavaball is correctly shot down, it explodes (see Figure 37 in Appendix F), thus giving an engaging completion of the dual-task. If the lavaball was destroyed by the participant, the round timer displayed in the sky would be green for a few seconds and show a 10-second deduction (thus making the participant faster in that round). If the participant was not successful in destroying the lavaball before it 'hit' them, the timer would show red and 10 seconds would be added (making the participant slower). During the introduction of the interaction, participants were allowed to practice shooting down the lavaballs before starting the playing rounds.

Once a participant completed the jumping task by landing with their correct leg onto the landing circle (determined by the tracker on the avatar's jumping leg being in relative horizontal proximity and the exact vertical location of a tracker at the landing location), the jumping plane would disappear again and a new jumping task would appear after a 10-second break. For the landing, the moment of 'hitting' the landing circle was made less sensitive than the hitting of the jump starting circles. In other words, the participant had to stand exactly right on the starting circles (to make sure that the jumping target would be at the right distance from the participant), but when landing near the landing circle, the landing was immediately registered to make sure that the correct jumping distance relative to the target position was recorded. Because the task required participants to jump and land onto the target circle, an external focus was implemented into the jumping task.

After all jumps in a round were completed, explosions moving upward were used to draw the attention of the participant to the final round time presented in the sky. Once a new

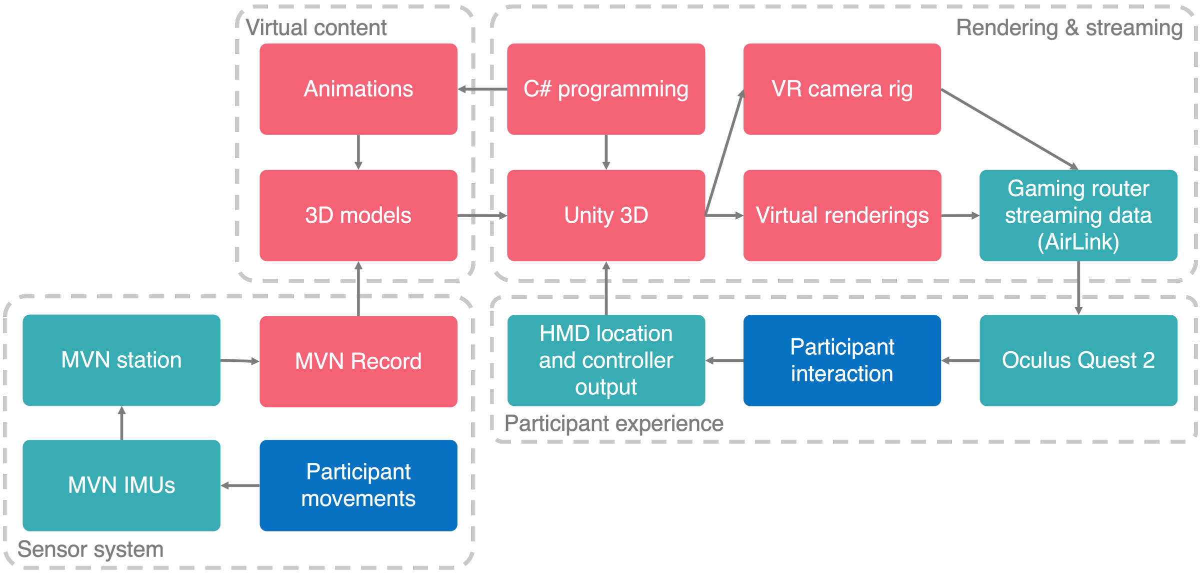


Figure 8: Overview of the interworking between the components running the interaction system, with the components directly relating to the participant (shown in blue), software components (red) and hardware components (green).

round started, the participant's view faded and they respawned at the centre of the virtual open playing space again (see Figure 37 in Appendix F).

4.3.3 *Overview of the back-end components*

To control the entire interaction, different components work together within four main groups, see Figure 8. Within the sensor system, movements made by the participant are recorded through the lower body MVN sensor setup. The IMUs stream the data to be recorded with the MVN Record. This software additionally streams the data to its Unity Avatar model, which is placed alongside the other 3D assets and animations in the VR environment. Unity combines all renderings and programmed features to be streamed to the HMD based on the virtual camera rig position. The participant sees the feed through the Oculus, where its movements and behaviours are used to control what is shown and how specific game elements behave (e.g. what is shown by the VR camera rig, how the MVN avatar moves and which game elements and animations are spawned).

5
METHODOLOGY OF SYSTEM EVALUATION

The ACL VR evaluation system as it was developed and described in Chapter 4 was evaluated through a series of testing sessions in which participants interacted with the system in three different interaction conditions: the real-world condition (without VR), the VR condition (without game elements, such as the timer and the lavaball dual-task) and the VR gaming condition, see also Figure 11. The full flow of the entire evaluation is shown in Figure 9 and describes the main elements of the test sessions.

1. The welcoming and preparation of the participant, including adding a perturbation on the non-dominant leg of the participant to simulate an ACL-affected leg and MVN sensors in a lower body configuration to record movements.
2. Completing single-leg jumps in the real-world scenario (denoted SL-RW) as shown in Figure 10.
3. Completing single-leg jumps in the VR scenario (denoted SL-VR).
4. The rounds of the VR game interaction in which the participant is triggered to make jumps at 20, 40, 60 and 80% of the maximum SL-VR distance of each leg.
5. Closing survey and interview.

Before the evaluation sessions, the system included pilot tests and a selection of a perturbation that could simulate the ACL-affected jumping behaviour. Furthermore, two additional measurements were included to compare the effect of the VR game element condition with that of the real world and VR condition and to determine the influence of leg dominance as a co-founding variable on the leg perturbation effect.

5.1 PARTICIPANT DEMOGRAPHICS AND CHARACTERISTICS

For this study, eighteen participants ($n = 18$) were recruited through convenience and snowballing and scheduled to partake in the evaluation sessions, each being provided with a 1.5-hour timeslot at the testing location. Additionally, the two patient participants interviewed in Section 2.4 were asked to join a walk-through of the system. The testing population (excluding the patient participants) consisted of $n = 9$ male and $n = 9$ female participants, of which $n = 4$ were aged 18-21, $n = 14$ were aged 22-26 and $n = 1$ was aged 27-30. The mean length was 175,5 cm (standard deviation of 8,9). Participants joined the study voluntarily and did not receive monetary compensation for their participation. For each participant, the dominant leg was determined by asking the participant to stand up straight and lean forward, letting one of the legs catch them (with that leg being denoted the dominant leg). Based on this method, $n = 14$ participants were found to have a right dominant leg. Additional insights regarding the participants' experiences with physiotherapy and VR interactions were gathered through a post-test survey (see subsection 5.3.5). From this survey, it was found that

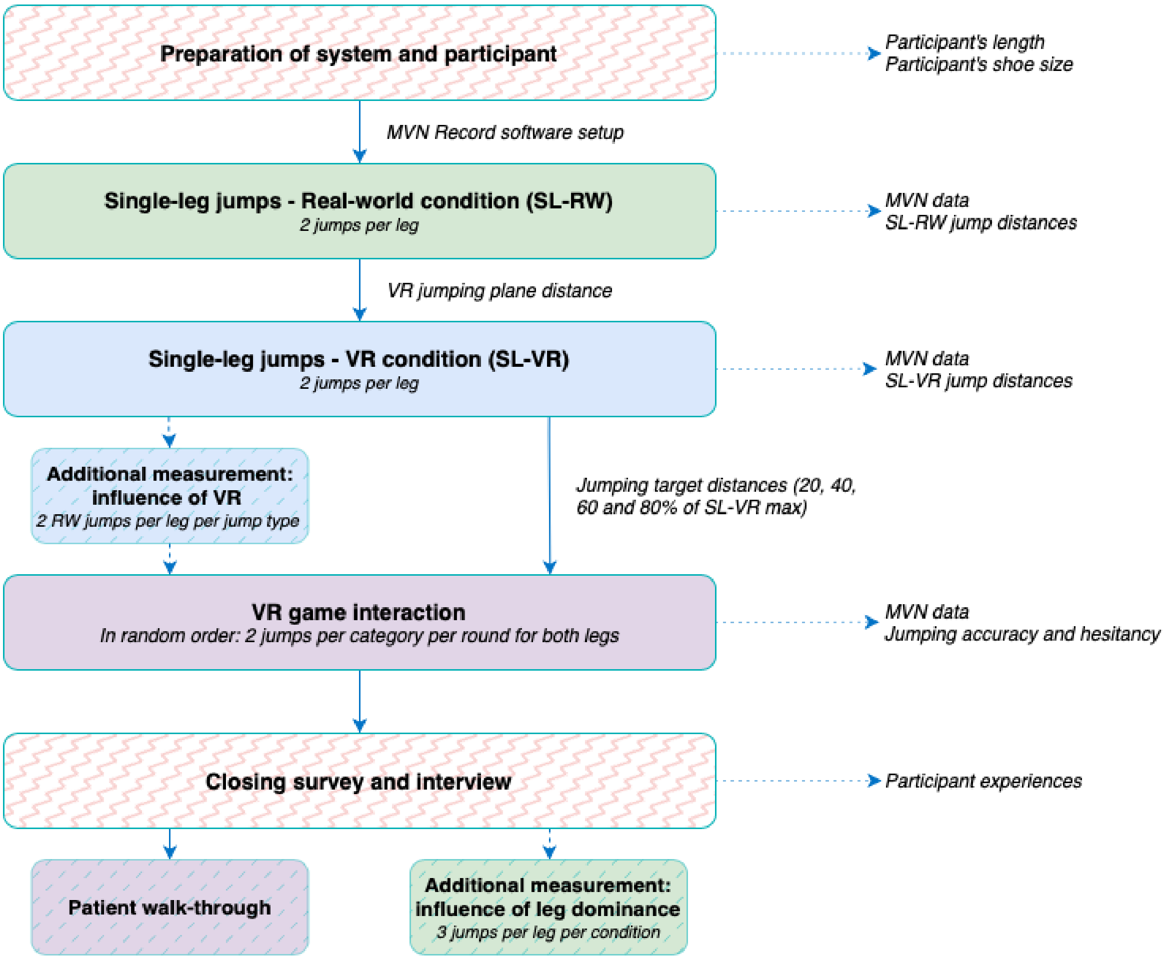


Figure 9: Flow of the measurement protocol. Shown in green are the measurements completed in the real-world condition; in blue are the measurements in the VR condition and in purple are the measurements completed in the VR game condition. Filled boxes indicate elements in which quantitative data was collected, and boxes with zig-zag lines indicate qualitative measurements (i.e., no continuous quantitative data). Boxes with dashes (and dashed arrows) indicated additional measurements outside the standard measurement protocol. For each step, the data gathered is indicated to the right with dotted arrows.

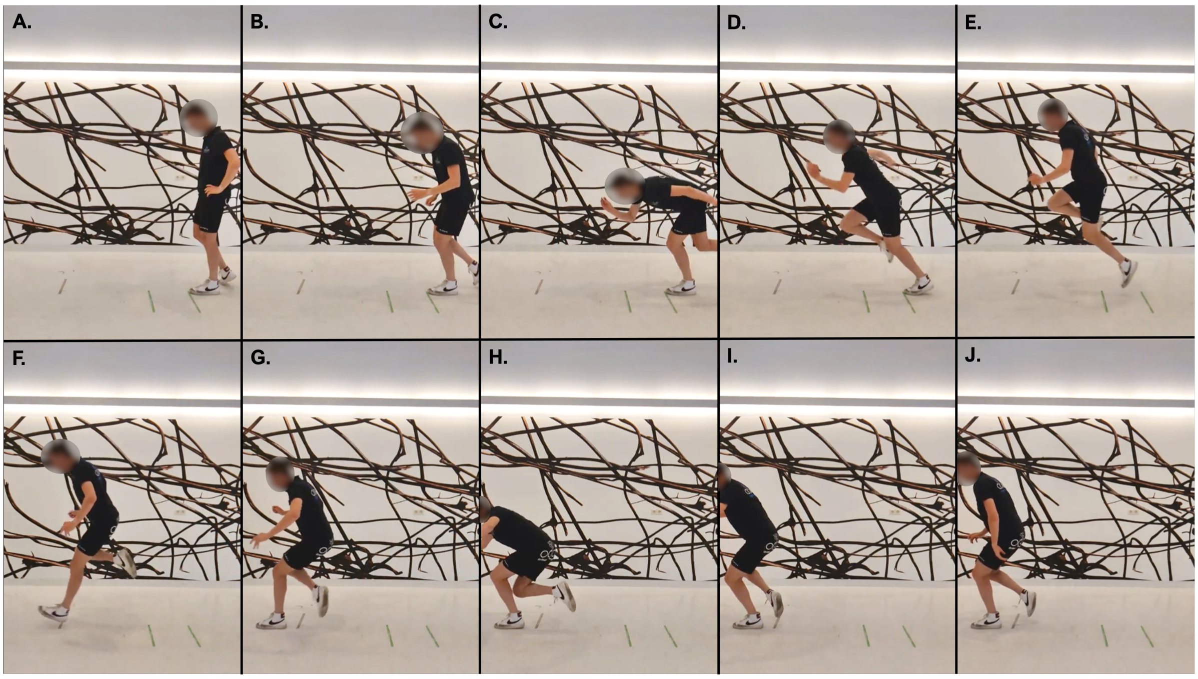


Figure 10: Sideways view of non-dominant single-leg jump movement of participant P21 during the perturbation selection study (subsection 5.2.1), serving as the zero-measurement to determine how each perturbation affected the jumping movement.

the participants were generally not experienced with gait-related physiotherapy. Several had used physiotherapy for unrelated complaints (such as back issues, $n = 2$, or other unrelated issues, $n = 3$), but only $n = 2$ had experienced (non-ACL) related knee injuries, which were either not surgical or had been over a decade prior to testing. Participants were divided on their use of videogames, with $n = 7$ never playing videogames, while $n = 11$ played at least once per week. In terms of physical activeness, $n = 2$ were active for less than one hour per week; $n = 5$ were active for one hour per week; $n = 9$ were active for 2-3 hours per week and $n = 2$ was active for more than 3 hours per week. Participants participated in fitness or running (combined $n = 6$), football ($n = 3$), racket sports ($n = 3$) and a variety of other sports (including bouldering, triathlon, cycling and dancing).

Before starting the full evaluation, the setup at the testing location was user-tested with a pilot study with participants P03 and P06. Both participants also returned for a second measurement session of the system as well as joining in one of the additional measurements (P06 returning for the measurement of VR influence and P03 returning for the measurement of dominance influence).

Participants were screened on the following inclusion and exclusion criteria. These criteria were communicated to each potential participant through an informational brochure and were confirmed once more at the start of the experiment.

- Participants were only eligible to participate if they were between the ages of 18-35.
- Participants were only eligible to participate if their English level allowed them to follow the English written and oral instructions.

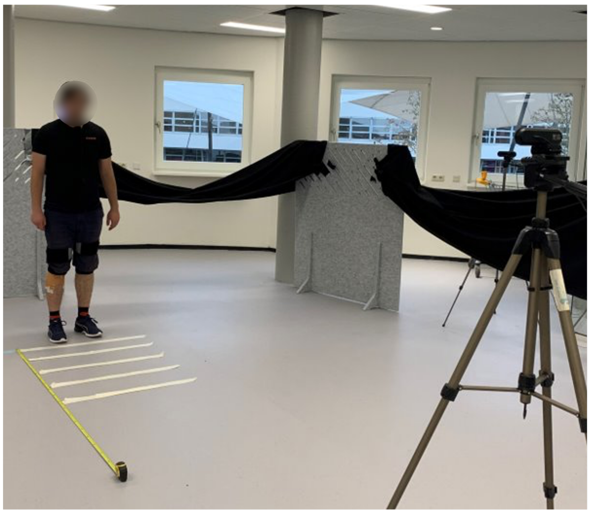
- Participants were not eligible to participate if they were currently rehabilitating for any knee- or gait-related injuries.
- Participants were not eligible to participate if they had any lower limb disabilities or any other serious injuries within 12 months before the start of the experiment.
- Participants were not eligible to participate if they suffered from any neurological disorders.
- Participants were not eligible to participate if they often experienced (moderate or severe) disorientation.

Before the experiment, participants received the following documents (also added as supplementary materials to this thesis, see Appendix A):

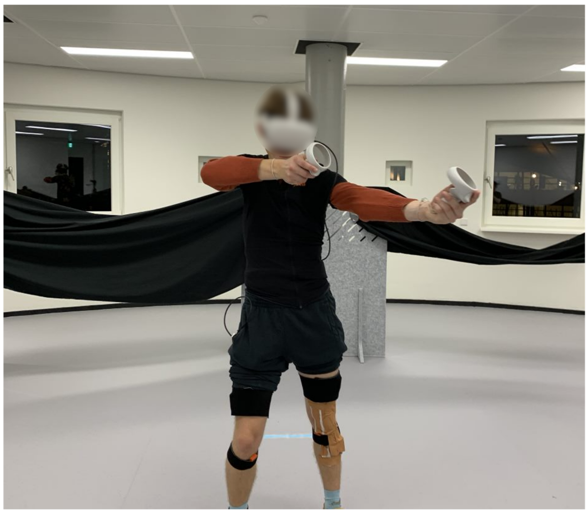
- Informational brochure, outlining the important information and possible risks of the experiment. This brochure also included information about the inclusion and exclusion criteria, which were confirmed with the participant during the scheduling of the testing appointment and at the start of the experiment.
- Informed consent of the experiment, to be signed before the session commenced.
- Information about the VR controls of the experiment and the single-leg jump.

5.2 MEASUREMENT SETUP

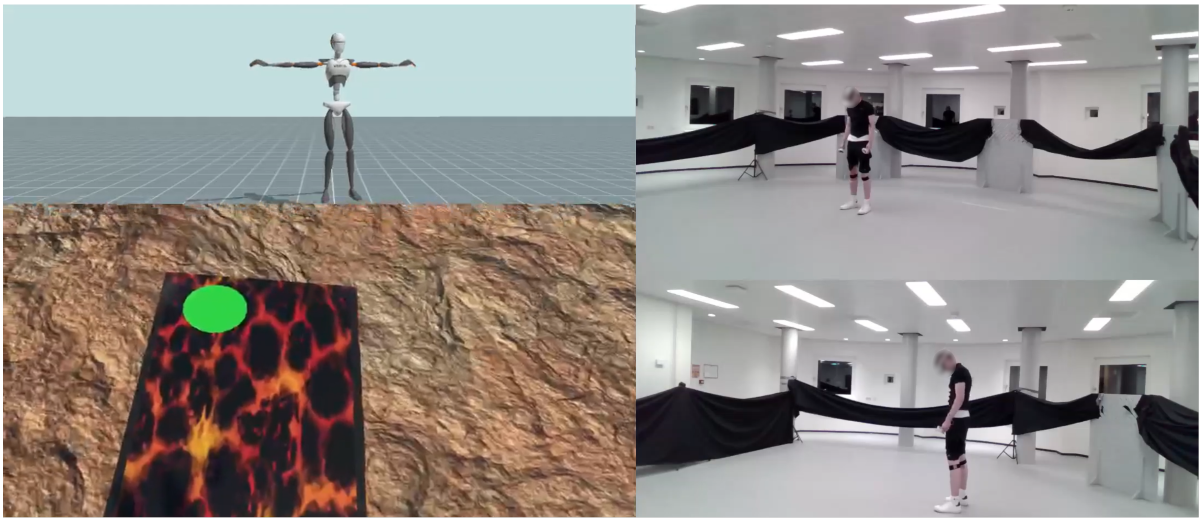
All evaluation tests were held in a room of roughly 9,9 by 10,7 meters shown in Figure 11, except for the dominance influence measurement described in subsection 5.6, for which an empty room of size 5,1 by 6,4 meters was used). The evaluation room contained seven large pillars were present (see also in Figure 38(a) in Appendix H.1), as well as two glass offices which were used for storage and as a control room to overlook the experiment. To prevent participants from hitting any of the real-world obstacles, soft grey dividers were placed 20 cm in front of the pillars and interconnected with drapes. This cordoned part of the room off and ensured that participants would have a soft tactile warning as they reached the end of their real-world playing space. Only the entrance to the control room was kept without a soft boundary to allow quick access to the playing space from the control room. The resulting space for the interaction was roughly 7,3 by 8,0 meters. This was smaller than what was anticipated during development, therefore the teleportation option of the system, which was previously disabled to only allow physical movement in the virtual space, was enabled. This ensured that participants would be able to navigate to any location in the virtual space, even if this was virtually located outside the real-world boundaries. For the evaluations, the materials shown in Table 11 (see Appendix H.1) were used. This included the Oculus Quest 2, the MVN sensors and setup, a computer and gaming router for data streaming, the perturbation tape as well as other necessities for the test session. In Figure 11(b), a participant is seen rigged up with the hardware getting ready to start the VR interaction. The setup of materials within the control room is provided in Figure 38(b) in Appendix H.1.



(a) Setup of the additional VR influence measurement in the real-world condition for a participant, including a webcam setup to the front and the side of the participant; the distances of 20, 40, 60 and 80% of the maximum that the participant should jump taped on the ground and the participant standing ready to jump, with his non-dominant leg perturbed with sports tape.



(b) Participant getting ready to play the VR-ACL system game. Visible is the participant in the testing environment, wearing the Oculus headset (with a cable connected to a portable charger) and holding the Oculus controllers. The MVN sensors are placed and attached (out of view are two MVN sensors that were placed within the participant's shoes and the sensor attached posteriorly to the pelvis). The participant's non-dominant leg (left) is perturbed with Leukotape P sports tape.



(c) Screenshot of the in-game VR interaction of participant P18 getting ready to jump. Shown is the stream from MVN Record (top left), a cropped view of the virtual environment shown through the HMD (lower left) and two webcam streams set up in the room (right).

Figure 11: Overview of the setup for the three interaction conditions in the VR-ACL system evaluation: jumps made in the real-world (shown here, the interval jumps described in subsection 5.5); setup of jumps made in the VR and jumps made with the VR game elements.

5.2.1 *Selecting knee perturbation for evaluation*

As an initial proof of concept, this study was conducted with only healthy participants (i.e. screened for not having any gait or knee movement deficits within 12 months prior to testing). To simulate the adapted jumping behaviour that an ACL-affected patient would show, a perturbation to one of the participants' legs was applied. Here, the simulated movement was targeted to resemble that of an ACL-affected patient roughly halfway through their rehabilitation progress. The perturbation was selected based on an evaluation session at the OCON Orthopaedic Centre. For this, a 25-year-old male physiotherapist (P21) was asked to make single-leg jumps to try out a set of pre-selected perturbations. Participant P21 was familiar with the single-leg jump and its (correct) execution (through 1.5 years of experience) and was an active ice skater and cyclist. With each perturbation, the participant was asked to make a single-leg jump alternately on his dominant and non-dominant leg, which was videotaped in slow-motion from the front and side (see also the side view of P21's single-leg jump without any perturbations in Figure 10). The recording of these was immediately reviewed and discussed with a second physiotherapist and participant P21 to evaluate how well the perturbation affected P21's jumping behaviour and the likeliness of the behaviour to that of an ACL-affected leg seen in rehabilitation patients. Based on the zero-measurement jumps (without any perturbations) of both legs, each subsequent jump with a perturbation was evaluated based on the knee flexion angle at initial contact and the maximum flexion during landing, the wobble of the knee at initial contact and the amount of compensatory torso, arm and swinging leg behaviour during landing stabilisation. The jumping distance (and LSI) were ignored due to the focus on qualitative simulation of the ACL-affected knee. Within his natural jumping behaviour, P21 displayed a deep torso flexion, which was attributed to his active ice-skating and cycling training. Generally, deep torso flexion is considered a compensatory behaviour relating to ACL rehabilitation, as patients would have less quadriceps strength and are less able to catch their landing with knee flexion, and was considered in the preparation of this perturbation study to be one of the indicators for an effective perturbation. While such deviant natural jumping behaviours can be hard to quantify in individual patients, it was dismissed as a significant indicator in this perturbation study based on P21's individual jumping behaviour. After the zero-measurement, seven perturbation categories were tested in different configurations, of which the outcomes are presented in Table 12 in Appendix H.2. Based on these measurements, a subsequent discussion session was held with the consulting physiotherapist and participant P21 about the most optimal perturbation and its location.

The main perturbations, of which the most abstract have been shown in Figure 39 in Appendix H.2, resulted in different adaptations of participant P21's jumping behaviours. To best simulate an ACL-rehabilitated leg, sports tape was considered most effective as an ACL-affected simulation by generating additional stiffness in moving while taking a participant out of their regular movement patterns By being directly attached to the skin, the tape would also provide a safer landing mechanism while making jumps in the visually restricted VR setting as opposed to adding weights on the knee or shoe that could alter the momentum of the jump after the initial landing or elements inside the shoe which could result in landing adaptations after initial contact. The taping was considered most effective when applied in extension, with strokes centrally, laterally and medially on the leg, to restrict flexion of more than 20 degrees. For this purpose, Leukotape P was considered optimal for taping the knees non-elastically and providing rigidness to the knee flexion movement. This tape is also more adhesive than the tape used during the perturbation tests. The perturbed leg was decided to be the non-dominant leg, as this seemed to give the strongest difference between the landing strategies of both legs. An example of the final sports taping technique that was used during the VR-ACL system evaluation tests can be seen in Figure 12.

(a) Central view.

(b) Medial view.

Figure 12: Example of knee taping of a participant during the VR-ACL system evaluation. One central stroke and at least one stroke lateral and medial were placed, with additional strokes being used if needed to provide the same stiffness to all participants and horizontal strokes to improve the attachment of tape to the skin.

5.3 MEASUREMENT PROTOCOL OF VR-ACL EVALUATION SYSTEM STUDY

The overall evaluation of the VR-ACL system addresses the usability and reliability of the overall system, as well as the richness of the gathered kinetic and behavioural data. The overall test session is shown in Figure 9 and is described below. For each participant, the test session included at least two correct single-leg jumps in the real-world condition and two in the VR condition per leg, as well as at least two jumps at 20%, 40%, 60% and 80% of the maximum SL-VR distance of that leg per round of interaction, with a minimum of at least three rounds.

5.3.1 *Pilot testing*

With the given VR system and game tasks (see Section 4.3), the testing environment was set up and pilot tests were held with two participants. Due to planning constraints with the testing environment, these sessions were held right before the real testing. Based on the pilot tests, it was determined that the testing environment was mostly large enough for the game as planned, but that the transportation feature was needed to accommodate the real-world restrictions. After the pilot tests (P03 and P06) as well as the first initial tests (P07, P08 and P16), the virtual guardian was made permanently visible in the VR environment This was, at the time of testing, an experimental feature of the Oculus Quest 2, which has since been made a standard feature (alongside an extended Presence Platform [124], in which users can bring their real-world objects into their virtual environment). During the pilot tests, issues were found with the MVN movement recording, which led to additional checks in the measurement protocol. Finally, based on the experiences of the initial tests, an additional measurement was planned to determine the effect of VR on the jumping movement of the interval jumps (see Section 5.5).

5.3.2 *Preparation beforehand*

During the preparation before the experiment, all materials were prepared and charged and the datastream between the sensors, HMD and the computer was established. During testing, the MVN Record version of 2018 was made available. For each participant, relevant data (such as participant ID, length, shoe size and dominant/non-perturbed leg) was noted down and provided to the relevant systems. Where needed, the variables of the master script of the VR interaction were adapted (see also the overview of main variables in Appendix H.4). During the preparation of each session, the COVID-19 safeguard measures (e.g. the VR cleaning box and the disposable hygienic covering for inside the HMD) were prepared and the virtual guardian was checked as a security measure.

When the participants arrived for the test session, they were briefed and given an opportunity to ask any final questions about the experiment. After signing the informed consent, participants were prepared for the session by having the perturbation with Leukotape P applied to their non-dominant leg. After the perturbation, the MVN sensors were placed within the lower leg configuration including the sternum (thus placing a sensor on the upper and lower legs, on each foot inside the shoe, posteriorly on the pelvis and anteriorly on the sternum) and were calibrated.

5.3.3 *Single-leg jumps in the real-world and VR condition*

As an initial determination of the participant's jumping ability, they were asked to perform the standard single-leg jump as shown in Figure 10 with both legs in the real-world condition. Participants were asked to balance on their jumping leg for roughly two seconds after each single-leg jump landing. The maximum jumping distance of each leg was used to create a jumping plane in VR based on that distance (at 1,25 times the jumping distance of that leg). After the real-world single-leg jumps, participants were given the Oculus 2 Quest HMD and controllers and were given instructions on how to navigate using teleportation and interact with the elements of the virtual environment through the controllers. Participants were also shown how to see the virtual guardian around them and how this marked their real-world playing space. Once they were familiar with the VR, participants were asked to perform single-leg jumps within the VR condition for each leg. Once the VR single-leg jumps were completed, participants were taken into an instructional introduction to familiarise themselves with the environment and its game elements.

5.3.4 *Rounds of VR game interaction*

In the VR game, the participants played the full interaction described in Section 4.2. For each round of the VR game, participants completed jumps of 20, 40, 60 and 80% of the maximum SL-VR distance of each leg, presented to the user in random order. The participants were asked to balance after landing on their jumping leg before putting the swing leg down. Once the round was completed, the participant was asked to indicate their perceived level of fatigue on the Borg scale (see Table 1), which was noted down. This indication of perceived fatigueness was used to remove data in the data analysis if the Borg score of that round would be higher than 7 (which was considered the tipping point to introducing fatiguing effects into the kinematic data). After noting the Borg score down, the MVN recording was stopped and saved after each round and the MVN avatar axes orientation was reset to match the SteamVR orientation. Between rounds, the placement of the MVN sensors was checked and, if needed adjustments and recalibrations were completed. After three rounds, participants were asked per round whether they wanted to continue or stop the interaction. For each jump in the interaction, the landing distance to the centre of the landing circle, as well as the time elapsed between triggering the start of the jump and the landing, was recorded.

5.3.5 *Closing survey and interview*

Once all interaction game rounds were completed, participants were given a moment to re-adjust to the real-world environment and remove all sensors and sports tape. Afterwards, participants were asked to fill in a survey that gathers their previous experiences with rehabilitation, sports and virtual reality, as well as their experiences with the interaction (partly based on the ITC-Sense of Presence Inventory survey [125]). The Likert scale questions on VR experience were rated by participants between 1 (strongly disagree) to 5 (strongly agree). After the survey, an interview was held with open-ended questions to dive deeper into their experiences. Participants were furthermore asked about their focus on the jumping task throughout the session. The full list of survey and interview questions is included in Appendix I.

5.4 PATIENT PARTICIPANTS WALKTHROUGH OF VR-ACL SYSTEM

The patient participants (P01 and P02) did a non-jumping walk-through of the virtual environment and gaming setup. The patient participants were given the same information and setup as the other participants but were not MVN recorded and were given the option to walk or move seated through the virtual environment. The participants were asked to think aloud throughout the session and consider how they would behave in the interaction as a patient. Once they had familiarised themselves with the interaction and the game, the participants were interviewed about the interaction and how the interaction would relate to their own rehabilitation experiences.

5.5 ADDITIONAL MEASUREMENT: INFLUENCE OF VR

To determine the effect of the interaction condition on the jumping kinematics, six participants were asked to perform an additional jumping measurement alongside the standard session. The participants were asked to make jumps at the intervals of 20, 40, 60 and 80% of their maximum distance in the real-world condition and in the VR condition without the inclusion of gaming elements. In the real world and the VR condition without gaming elements, the interval distances were marked on the ground (either with tape in the real-world condition, see Figure 11(a), or shown virtually in the VR condition). This additional measurement was completed by participants P03, P04, P06, P10, P12 and P20.

5.6 ADDITIONAL MEASUREMENT: INFLUENCE OF LEG DOMINANCE

To determine the influence of leg dominance on the perturbation effect, an additional measurement was held as a manipulation check during which the perturbation was alternatively applied to either leg of a participant. For this, six participants were invited back to perform single-leg jumps in the real-world condition under the following three perturbation conditions.

1. No perturbation tape attached to either leg.
2. Perturbation attached to the dominant leg.
3. Perturbation attached to the non-dominant leg.

For each measurement, participants were asked to perform three single-leg jumps with their right and left legs, with the same sensor setup as within the VR-ACL system evaluation. Between measurements, participants had a moment to rest while the new perturbation was applied. This additional measurement was completed by participants P03, P05, P10, P12, P16 and P19.

5.7 DATA ANALYSIS METHODOLOGY

The full dataset was analysed to determine the outcome of the research question presented in Chapter 1. During the evaluation, the following forms of data were gathered for the data analysis. First, the MVN sensor data was recorded through the MVN Record software. Second, the single-leg distances were recorded through measurements during the interaction. Third, the jumping accuracy, lavaball hit accuracy and timing data were recorded per jump through the distances between the landing of the participant and the target; the number of lavaballs destroyed out of all fired per round, and the time between the triggering of the jump start and the landing, and the overall time per round was noted, respectively. Fourth, the remarks on the interaction both from the participant and the researcher were noted down alongside observations on movement behaviours throughout the entire experiment (where needed supported through analysis of the video recordings of the sessions). Finally, the participant experience was recorded through a post-test survey and interview questions after the interaction. An overview of the data distribution for the two objectives of this study is shown in Figure 13.

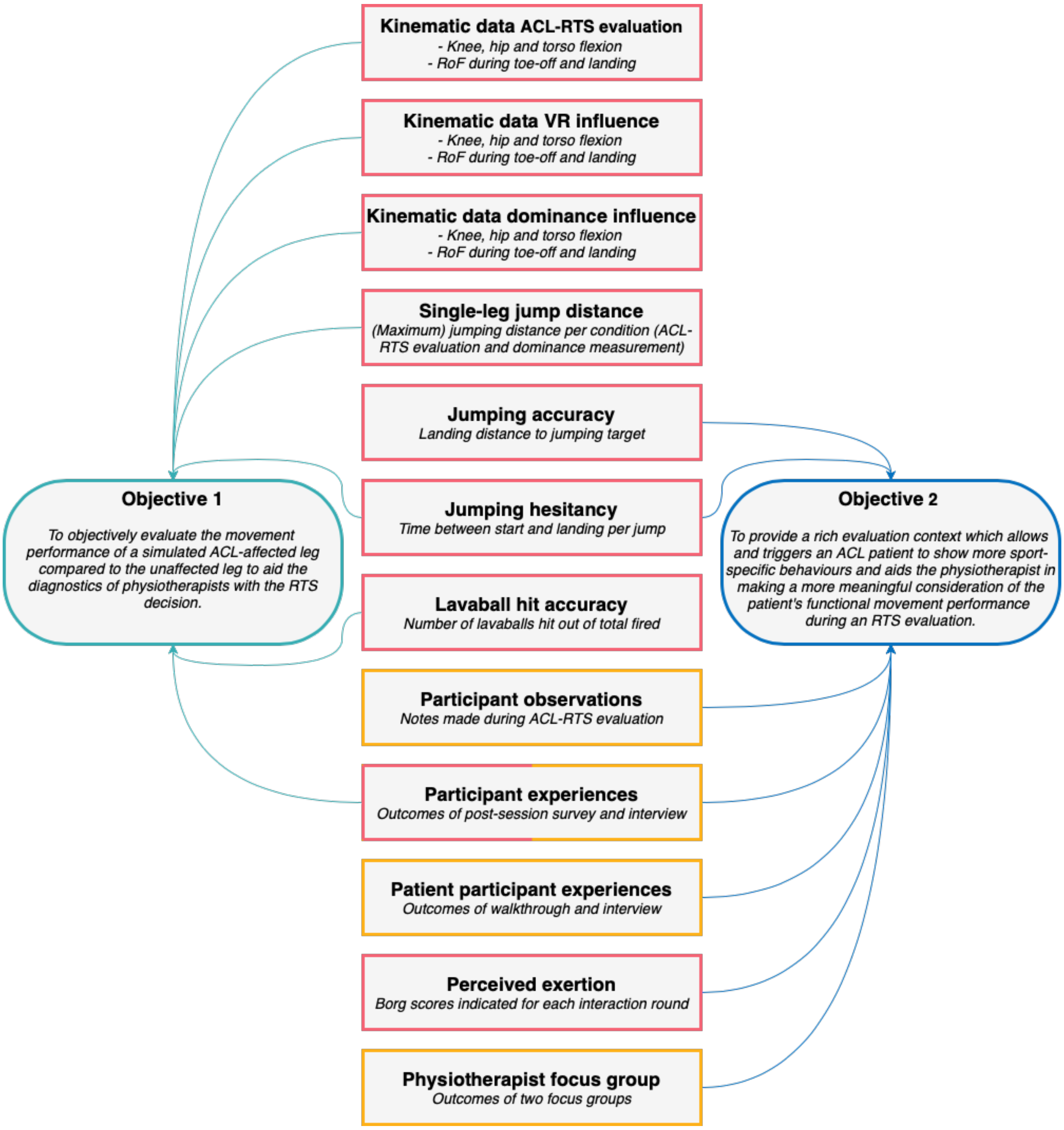


Figure 13: Schematic overview of the data gathered per objective, quantitative and qualitative data provided in red and yellow boxes respectively.

5.7.1 *Quantitative data analysis*

For the quantitative data, the MVN data and the jumping accuracy and timing were included for all jump types: SL-RW, SL-VR and 20%, 40%, 60% and 80% of the maximum SL-VR distance. The MVN data from the MVN recordings was analysed together with video data and data logs showing the quality and indicating the sequence of the jumps. For the data analysis of the MVN data, MVN Analyse Pro was used with a 2021 license. Due to issues that occurred during testing with the MVN setup (described as part of the results in subsection 7.3), however, all recordings first had to be HD reprocessed with a reinitialise MoCap engine to remove the magnetic influence that was, based on expert input, likely the cause of some of the MVN issues. This was completed in MVN Analyse Pro (2021 license). The HD reprocessing removes all previous filters and optimises the data based on a large time window (one minute before and after each timeframe) to correct for issues with magnetic influence or buffering and give a more consistent estimation of the position and orientation of each body segment [115]. The HD processing resulted in a shift of the segments as compared to the original file, of which the effect can be seen in Figure 40 in Appendix H.3. Because of the HD reprocessing, no additional smoothening processes were used in the data analysis. As the purpose of this study was to determine the effectiveness of the data from the interaction, the focus was put on data interpretation and analysis from the HD reprocessing rather than adding raw data manipulations.

Using the HD reprocessed data recordings, the individual jumps were extracted and labelled first as belonging to either the non-perturbed dominant leg or the perturbed non-dominant leg and second as being either an SL-RW, SL-VR or one of the interval jumps of either the real-world or VR condition. Because especially the smaller jumps had similar movement characteristics as walking, sprints and unrelated jumps made by the participants throughout the interaction, the identification and extraction of all jumps had to be completed manually. In addition to this, the visual analysis and the statistical analysis of the data described below required each jump to be divided into three main phases (for this work denoted the toe-off, flight and landing phases, respectively). To this end, for every jump, the corresponding timestamps separating these three phases were manually added. Several options were considered for defining these phases based on the available data, of which the chosen definition was considered to provide the most consistent jump phases. The start of a jump was considered at the first well-defined z-peak of the jumping leg position. The toe-off point was taken at the negative acceleration z-peak of the jumping leg as it corresponded with the toe-off shown by the MVN avatar. The initial contact point was at the negative acceleration z-peak of the jumping leg as it corresponded with the initial contact of the jumping leg with the ground shown by the MVN avatar. The end of the landing was chosen at the moment in which the participant was balanced and upright again after the maximum knee and torso flexion upon landing. The landing could not be consistently defined for all participants, as it was dependent on the participant's behaviour within the interaction (e.g. if they would remember to balance on their jumping leg after landing, or whether a lavaball would appear and disrupt their balance). Therefore, based on the estimated landing timeframes, a mean landing time was defined per jump category based on all jumps in the dataset which was used to define the landing phase in the visual analysis of the MVN data. See Figure 41 in Appendix J for an example of the defined phase indicators.

Throughout the analysis, each jump was also qualitatively analysed on its movement quality, with jumps being excluded when having a double feet offset (rather than only one-foot jumping) or opposite foot offset (in which the offset was with the incorrect foot, landing with the correct foot); double feet landing; an additional hop/step during landing (either through an imbalance or because the participant was hurrying towards the next jump), touching the group with one of the hands during landing, severe imbalance (i.e. large torso movement such that a correctional step is needed to regain stable balance) or any other major discrepancies from a standard jump as based on the background of this work (Chapters 2 and 3). Jumps were also excluded if there were hardware or sensor issues or if the start or landing was incorrectly triggered.

Once all correct jumps were extracted from the data with their metadata, different analyses were applied. Within these analyses, the focus was placed on the knee, hip and torso flexion data. While the ankle is also related to the injury mechanism (see subsection 2.1.2) and seems to be adapted in behaviour movement for the ACL-affected gait (see subsection 3.1.2), it was decided to put focus on the joints found most relevant from the sessions with physiotherapists and the literature research. For the analyses, first, the flexion of the knee, hip and torso during the jump of the non-perturbed dominant and the perturbed non-dominant leg were considered for statistical analysis and graphical presentation. For the statistical analysis, the range of flexion (RoF) of the knee, hip and torso was gathered for all jumps, alongside the metadata of that jump, for further analysis. For the remainder of this work, the term RoF was chosen instead of RoM to avoid confusion with the hypothetical RoM that the knee would be able to achieve under the chosen perturbation. Rather, the RoF is used to indicate changes made in the flexion due to the physical perturbation effect as well as any change in landing strategy adopted because of the scenario in which their jumping task is presented. In other words, while the perturbation might affect the RoM of the leg, the RoF is used to indicate any changes found in the flexion pattern caused by all interventions in this study. The three chosen segments and the focus on the flexion-extension movement (thus limiting ourselves to one plane of movement) were motivated through literature (see [24], [52], [54], [56]–[58], [113], alongside Section 3.1) as well as expert input from the University of Twente, OCON Orthopaedic Centre and Movella.

The main area of interest for the RoF was between the moment of initial contact of the jumping leg with the ground and the maximum flexion of that segment during the landing. In addition to RoF during the landing, a secondary moment in which discriminating trends may be found for the non-perturbed dominant and perturbed non-dominant leg was the toe-off phase, for which the RoF was considered between the moment of toe-off and the maximum flexion of each segment during the flight phase. See also Figure 41 in Appendix J for an example of the moments making up the toe-off and the landing phase RoF for the knee segment. Based on the RoF during the landing phase for the knee, hip and torso, the following statistical comparisons were completed.

- Between the non-perturbed dominant leg and the perturbed non-dominant leg for all jump types.
- Between the non-perturbed dominant leg and the perturbed non-dominant leg for the smallest jump types (20%, 40% and 60% of the SL-VR maximum); completed for the knee segment only.

- Between the interaction conditions of real-world, VR and VR with game elements (see the additional VR influence measurement description in Section 5.5).
- Between the dominant and the non-dominant leg when perturbed or non-perturbed (see the additional dominance influence measurement description in Section 5.6).

For the toe-off phase RoF, the following additional analyses were completed.

- Between the non-perturbed dominant leg and the perturbed non-dominant leg for all jump types.
- Between the dominant and the non-dominant leg when perturbed or non-perturbed.

The statistical analysis was done through linear mixed effects (LME) regression models, for which the methodology of [126] was used. An overview of assumption compliance has been provided in Appendix K. Aside from the range of flexion per segment, the metadata shown in Table 3 was added per jump to be used as input for the linear mixed effects model.
Within the linear mixed effects model of each segment, the range of flexion values of the knee, hip and torso respectively were used as dependent values. The model was designed using a stepwise forward (bottom-up) approach, in which only those effects resulting in a significant effect were kept. For the systematic part of the model, we further included an analysis of the interaction between perturbance and jump type to rule out whether the effect of the perturbation would be dependent on the jumping distance.

The random effects structure was based on theoretical rather than data-based considerations, which were subsequently tested for their effect on the model. The considerations for random effect inclusion were as follows. Because the effect of each trial ID is measured multiple times by each participant, the by-trial ID independence was accounted for by adding it as a random effect. Furthermore, two slope effects were introduced for the participant, namely with the intercept and perturbance and the intercept and jump type to account for individual variation of the participant with respect to their perturbation and their ability to jump the different distances. The latter combination of participant and jump type was removed during analysis because the added complexity caused the model to not converge for all three segments. For the other two random effects, their effect on the model improvement was evaluated through the Akaike Information Criterion (AIC) [127], which determines whether the model complexity can be justified by the explained variance of that model. This criterion postulates, following Occam's razor, that if the addition of a random effect does not provide strong evidence of contributing to the model fit relative to the true model, the simplest model is favoured and the random effect should be removed. For each random effect, a positive ΔAIC or a negative ΔAIC of less than two favours the simplest model (as a negative ΔAIC indicates a decrease in AIC when adding the random effect and thus a more favourable balance between model complexity and explained variance).

Where needed to comply with the assumptions of the LME models (provided in Appendix K), data transformations were applied to remove heteroskedasticity. For the dominance effect measurement, the assumptions indicated categorisation of the knee, hip and torso RoF data, therefore motivating a simplification of the data by only including data from the furthest single leg jump per condition per leg for each participant.

The graphical presentation of data (see for example Figure 44 in Appendix J) was considered as summative graphs per phase. For knee and hip plots, the behaviour of the two legs

Table 3: Overview of effects used for statistical models.

Effect	Description
Perturbance	A binary measure indicating whether the jumping leg was non-perturbed and dominant or perturbed and non-dominant.
Jump type	Indicating whether the jumping leg was an SL-RW, SL-VR or of 20%, 40%, 60% or 80% of the maximum SL-VR distance.
Participant ID	Indicating the participant number of the person jumping.
Trial number	The number of the jump indicating the order of jumps in which they were presented to the participant (thus increasing in the order in which they were encountered by the participant). This measure relates itself to fatiguing effects as well as the effectiveness of the perturbation (as the sports tape was found to stretch over time for participants, thus decreasing its effectiveness).
Trial ID	Indicating the unique combination of perturbance and jump type (or perturbance and dominance in the dominance influence analysis).
Interaction condition	Indicating whether the jump was made in the real world, within the VR without any gaming elements. For each jump type except the single-leg jump, data from all three conditions were gathered. For the single-leg jump, the VR gaming condition was not used as it was considered a higher risk for participants to perform in this condition.
Gender	Indicating the gender of the participant within the categories of male, female and other.
Age group	Indicating what age group the participant belonged to at the moment of testing, differentiating between the categories of 18-21, 22-26 and 27-30 years of age.
Leg dominance	Indicating whether the participant had a dominant right or left leg.
Participant length	Indicating the length of the participant in centimetres.
Physical activeness	Indicating the physical activeness of the participants within the categories of no activity/less than once a week; at least one hour per week of activity; two to three hours per week or more than three hours per week.
Perceived fatigueness	Indicated by the Borg scores that the participant provided as their perceived fatigueness for a set of jumps. This measurement was not given for all sets of jumps as the Borg score was not asked after single-leg jumps or for the additional measurements, which led to missing values.
Jumping leg dominance	Used only for the data analysis of the dominance influence and indicates whether the jumping leg for that particular row of data is dominant or non-dominant.
Tape condition	Used only for the data analysis of the dominance influence and indicates whether the jump occurred in the no tape, perturbance on the dominant leg or perturbance on the non-dominant leg condition.
Round number	Used only for the analysis of jump accuracy and timing and indicates the round number of the interaction.

was plotted both while jumping and swinging. For the dominance influence measurement, visual analysis was also completed to compare trends between the no-tape condition and the perturbance of the dominant and non-dominant leg. These plots were analysed to determine common trends occurring for each phase over the different jump types.

To determine how the outcomes of the MVN data analysis related to the standard LSI evaluation of the single-leg jump, the distance measurements were compared between the non-perturbed dominant and the perturbed non-dominant leg as well as between the conditions of real-world and VR. To further put the MVN data analysis into context, the jumping accuracy and hesitancy data were analysed to provide more insights into the jumping behaviours. In addition, the average lavaball shooting accuracy was evaluated over the playing rounds. The jumping accuracy was determined based on the participant's landing distance from the target for each of the jumps in the VR game condition. The jump times were evaluated for each individual jump in the VR game condition. Because not all jump times were correctly registered, outliers were identified and removed from this dataset.

5.7.2 *Qualitative data analysis*

The qualitative data includes the notes, video recordings and participant experiences. This also separately includes interviews done with the two patient participants who performed a walk-through of the system. Aside from the participant experiences, limitations found with the hardware and software were gathered. The qualitative data was analysed to report common trends and insights.

5.7.3 *Evaluation of VR-ACL system and data with physiotherapists*

As one of the main functions of the VR-ACL system, the data resulting from a patient's interaction should contribute to a meaningful RTS diagnosis or analysis of a patient's functional movement behaviours. To this end, the output from the data analysis was discussed with several physiotherapists from the OCON Orthopaedic Centre during two separate sessions. The first session discussed the use of the system itself and how it affected the movement behaviour of the participants. The aim here was to determine whether the VR environment and gamification affected the validity of the jumping tasks. This was done through a guided focus group in which selected videos of participants P04 and P06 were discussed. Participant P06 was selected as a very enthusiastic participant in the study who made the largest single-leg jumps, while, in contrast, participant P04 was selected for being very stiff in the jumping movements and only making small jumps. Both participants wore long pants, hiding the perturbed leg from view in the videos to let the physiotherapist evaluate the movements without bias. During the second session, the output of the data analysis was discussed to determine how well the physiotherapists were able to interpret the data and how meaningful this could be in a diagnostic setting. During this session, data from participants P06 and P16 were presented, alongside summative graphs of all participants. P16 was included in the presentation as the most experienced jumper among the participant population. Both analysis sessions were held on-site at the OCON Orthopaedic Centre. During each session, the attending physiotherapists were first introduced to the topic before the data was presented.

6 RESULTS

Within this chapter, the results and initial interpretations of the VR-ACL study described in Chapter 5 are presented. Due to the complexity and dimensionality of the data, as well as the objectives to utilise the data for the interpretation by physiotherapists, the data is analysed, summarised and (partly) interpreted as it builds towards understanding other parts of this results chapter. In Chapter 7, a full discussion of the outcomes links the components presented in this current chapter. The rest of this chapter is organised as follows. For the quantitative data, first an overview of the dimensionality of the jump dataset (Section 6.1) is presented. This is followed by a statistical analysis (Section 6.2), including analyses to determine the significance of the smaller jumps in differentiating between the legs (6.2.1) and the effect of the VR influence (subsection 6.2.2) are added. Continuing, a graphic presentation of the MVN data (Section 6.3) is provided to give an overview of the movement behaviour. After this, the visual and statistical analysis of the dominance influence measurement is presented (Section 6.4). Completing the quantitative analysis part are the analyses of the single-leg jump distances (Section 6.5) and the analyses of jump accuracy and timing (Section 6.6). Afterwards, the qualitative outcomes of the measurements are presented (Section 6.7) to show the participant experience. Finally, the outcomes of the two data interpretation sessions with the OCON Orthopaedic Centre physiotherapists are provided (Section 6.8). For Sections 6.2 to 6.6 an overview of the main findings is provided at the end for quick review. Furthermore, additional materials for the analyses in these sections (such as formulaic model descriptions of the LME models, tables and figures) have been added in Appendix J.1 and assumptions for the LME models have been added in Appendix K.1. Within Sections 6.7 and 6.8, participant and physiotherapist quotes have been edited for clarity and consistency in terminology.

6.1 QUANTITATIVE DATA DIMENSIONALITY

Out of the total dataset of 1482 performed jumps, the analysis resulted in a total of 1116 included jumps (75,3% inclusion rate) of which 567 were made with the perturbed non-dominant leg, containing 87 single-leg jumps in the real-world condition; 68 single-leg jumps in the VR condition; 244 jumps in the VR interaction of 20% of the maximum distance; 247 of 40% of maximum distance; 244 of 60% of maximum distance and 226 of 80% of maximum distance. A full overview of the number of included jumps per jump category and for each jumping leg per participant can be found in Table 14 in Appendix J. Within this overview, participants who included an additional measurement (to determine the VR influence and dominance effect) are indicated as well.

An overview of the significant effects of the LME models of the RoF in the landing phase of the evaluation data set is presented in Table 4, with a visual overview being shown in Figure 14.

For the knee range of flexion (Figure 14 top row), the perturbance decreased the flexion ($t(24) = -4,38, p < 0,001$), while the jump type (increasing by distance) and perceived fatigueness increased flexion ($t(13) = 5,71, p < 0,001$ and $t(956) = 2,54, p < 0,05$ respectively). No significant effect was found for the interaction between the perturbance and jump type (see for example also the boxplot of this interaction in Figure 42, where a similar deviation for perturbance can be found in all jump types). Given the strong significance of the fixed effects of the knee range of flexion, the additional analysis of the effect of the smaller jumps (of 20, 40 and 60% distance) described in subsection 5.7.1 was considered only for the knee range of flexion dataset, and is provided in subsection 6.2.1. In addition, while the VR fixed effect did not give any statistically significant results for this segment, a highlight of the VR effect was added in subsection 6.2.2 that shows the trend the VR condition provides for the knee range of flexion.

For the hip range of flexion (Figure 14 middle row), the jump type was found to increase the flexion ($t(1057) = 10,03, p < 0,001$), while the VR condition decreased the flexion ($t(1064) = -2,09, p < 0,05$). The perturbance did not significantly affect the hip flexion.

The torso range of flexion (Figure 14 bottom row) was found to increase significantly for the jump type ($t(1036) = 9,14, p < 0,001$) and decrease for the participant length ($t(15) = -2,81, p < 0,05$). No effect for perturbance was found.

Table 4: Fixed and random effects structure of linear mixed effects models for predicting knee, hip and torso range of flexion. Note, the estimate consists of log odds; standard errors are denoted by SE; confidence intervals are denoted by CI; standard deviation is denoted by std. dev.

Knee range of flexion

Fixed effects	**Estimate**	**SE**	**T-value**	**P-value**	**Lower 95%-CI**	**Upper 95%-CI**
Intercept	20,74	2,01	10,34	<0,001	17,33	24,04
Perturbance	-5,77	1,32	-4,38	<0,001	-7,94	-3,71
Jump type	0,08	0,01	5,71	<0,001	0,06	0,11
Perceived fatigueness	0,85	0,34	2,54	<0,05	0,31	1,38
Random effects	**Variance**	**Std. dev.**	**ΔAIC**			
1 | Trial ID	2,06	1,44	-14,66			
1 + Perturbance | Participant *Perturbance*	18,18	4,26	-451,45			
1 + Perturbance | Participant *Full slope*	33,92	5,82	-67,68			

Table 4 - Continued from previous page.

Hip range of flexion (log transform)						
Fixed effects	**Estimate**	**SE**	**T-value**	**P-value**	**Lower 95%-CI**	**Upper 95%-CI**
Intercept	1,29	0,17	7,71	<0,001	1,01	1,57
Jump type	0,01	0,00	10,03	<0,001	0,01	0,01
Interaction condition	-0,06	0,03	-2,09	<0,05	-0,12	-0,02
Random effects	**Variance**	**Std. dev.**	**ΔAIC**			
1 + Perturbance | Participant *Perturbance*	0,08	0,29	-30,04			
1 + Perturbance | Participant *Full slope*	0,42	0,65	-499,11			

Torso range of flexion (log transform)						
Fixed effects	**Estimate**	**SE**	**T-value**	**P-value**	**Lower 95%-CI**	**Upper 95%-CI**
Intercept	4,40	1,82	2,42	<0,05	1,10	7,48
Jump type	0,01	0,00	9,14	<0,001	0,01	0,01
Participant length	-0,03	0,01	-2,81	<0,05	-0,05	-0,01
Random effects	**Variance**	**Std. dev.**	**ΔAIC**			
1 + Perturbance | Participant *Perturbance*	0,15	0,39	-38,18			
1 + Perturbance | Participant *Full slope*	0,25	0,50	-190,43			

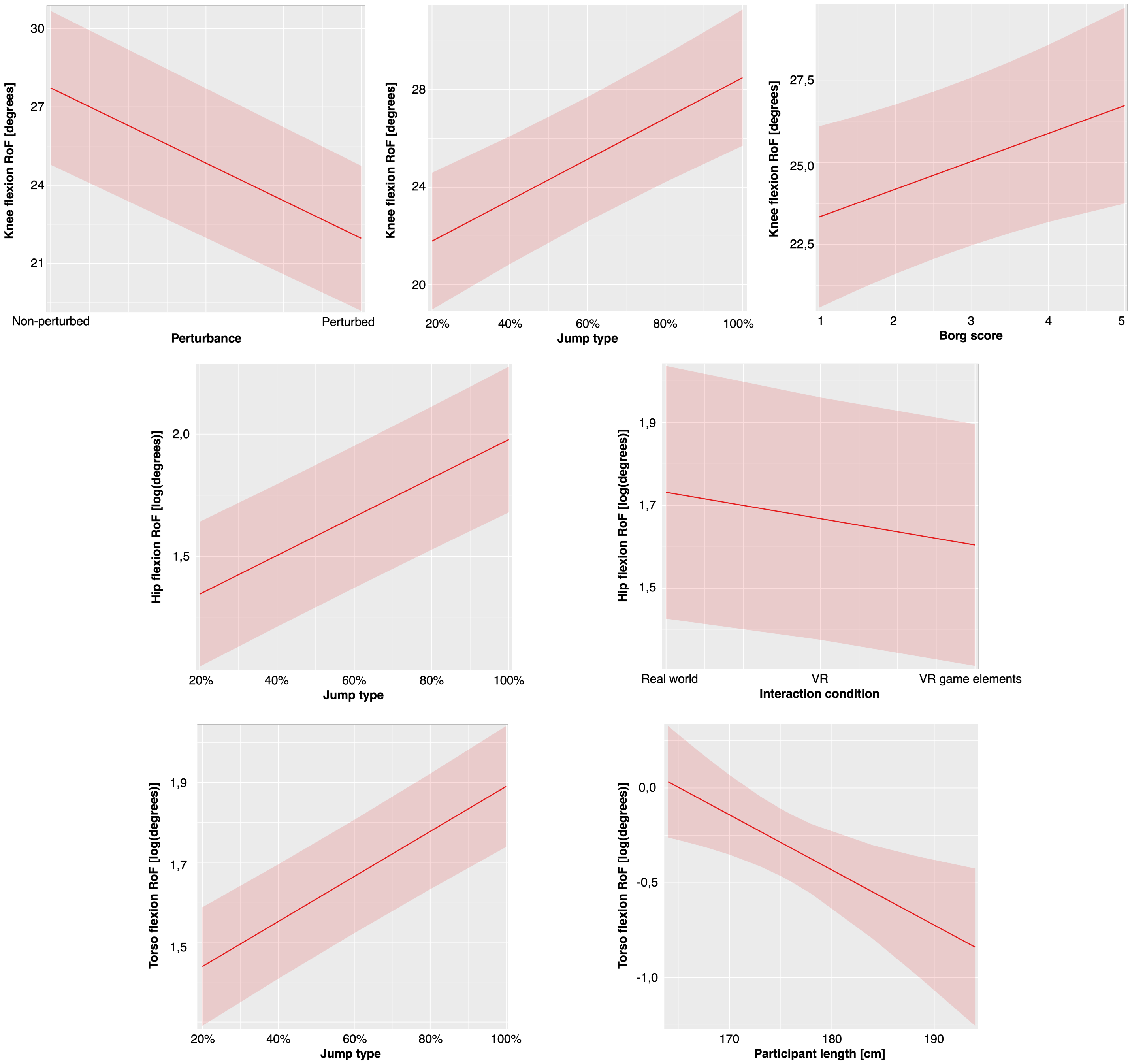


Figure 14: Predicted value plots of the significant predictors of the linear mixed effects model on knee (top row), hip (middle row) and torso (bottom row) range of flexion.

6.2.1 *Knee landing RoF analysis for 20, 40 and 60% jumps*

Within the linear mixed effects model for the knee RoF during landing described in this section, a strong significance was found for both the perturbance and the jump type, although no interaction effect was found. Therefore, because it seems that the type of jump did not affect the influence of perturbance, it is interesting to consider whether the linear mixed model can still find a significant effect of perturbance with only the jump types of the shortest distances present in the dataset. With this reduced dataset and considering the knee RoF during landing, significant effects were again found for perturbance ($t(14) = -3,91, p < 0,01$) and the jump type ($t(696) = 11,42, p < 0,001$), see also the overview in Table 5.

Table 5: Fixed and random effects structure of LME models for predicting knee range of flexion for the three smallest jump types (20%, 40% and 60% of the max single-leg jump in the VR condition). Note, the estimate consists of log odds; standard errors are denoted by SE; confidence intervals are denoted by CI; standard deviation is denoted by std. dev.

Knee range of flexion

Fixed effects	**Estimate**	**SE**	**T-value**	**P-value**	**Lower 95%-CI**	**Upper 95%-CI**
Intercept	21,23	1,56	13,58	<0,001	18,55	23,87
Perturbance	-5,25	1,34	-3,91	<0,01	-7,37	-2,89
Jump type	0,15	0,01	11,32	<0,001	0,12	0,17
Random effects	**Variance**	**Std. dev.**	**ΔAIC**			
1 + Perturbance | Participant *Perturbance*	28,75	5,36	-62,03			
1 + Perturbance | Participant *Full slope*	37,09	6,09	-356,74			

6.2.2 *Analysis of the VR effect*

As was shown in Table 4, the statistical analysis did not provide any significant results for the interaction condition for the knee and torso, but did show significance for the hip RoF. Further analysis of the interaction condition effect on the flexion of the three segments does show trends seen in Figure 15. For the knee flexion (top boxplot), it can be seen that, on average, the range of flexion between the initial contact and maximum landing flexion decreases when comparing the real world to the VR environment without game elements (comparing the white and light grey boxes respectively). However, when adding the game elements in the VR (shown in the dark grey boxes), the knee range of flexion seems to increase for the different jump types. For the hip and torso range of flexion (middle and bottom boxplots in Figure 15), no distinctive pattern emerges from the boxplot analysis.

6.2.3 *Analysis of the toe-off RoF*

Between the toe-off and maximum flexion during the flight phase, the perturbed non-dominant leg provided a lower knee RoF compared to the non-perturbed dominant leg ($t(12) = -2,60, p < 0,05$), while the increasing distance of the jump type increased the knee RoF ($t(8) = 10,27, p < 0,001$), see Figure 16. Furthermore, the trial number and the participant length both increased the RoF of this segment ($t(1094) = 2,00, p < 0,05$ and $t(16) = 2,23, p < 0,05$, respectively). For the hip, the jump type increased the toe-off RoF ($t(9) =$

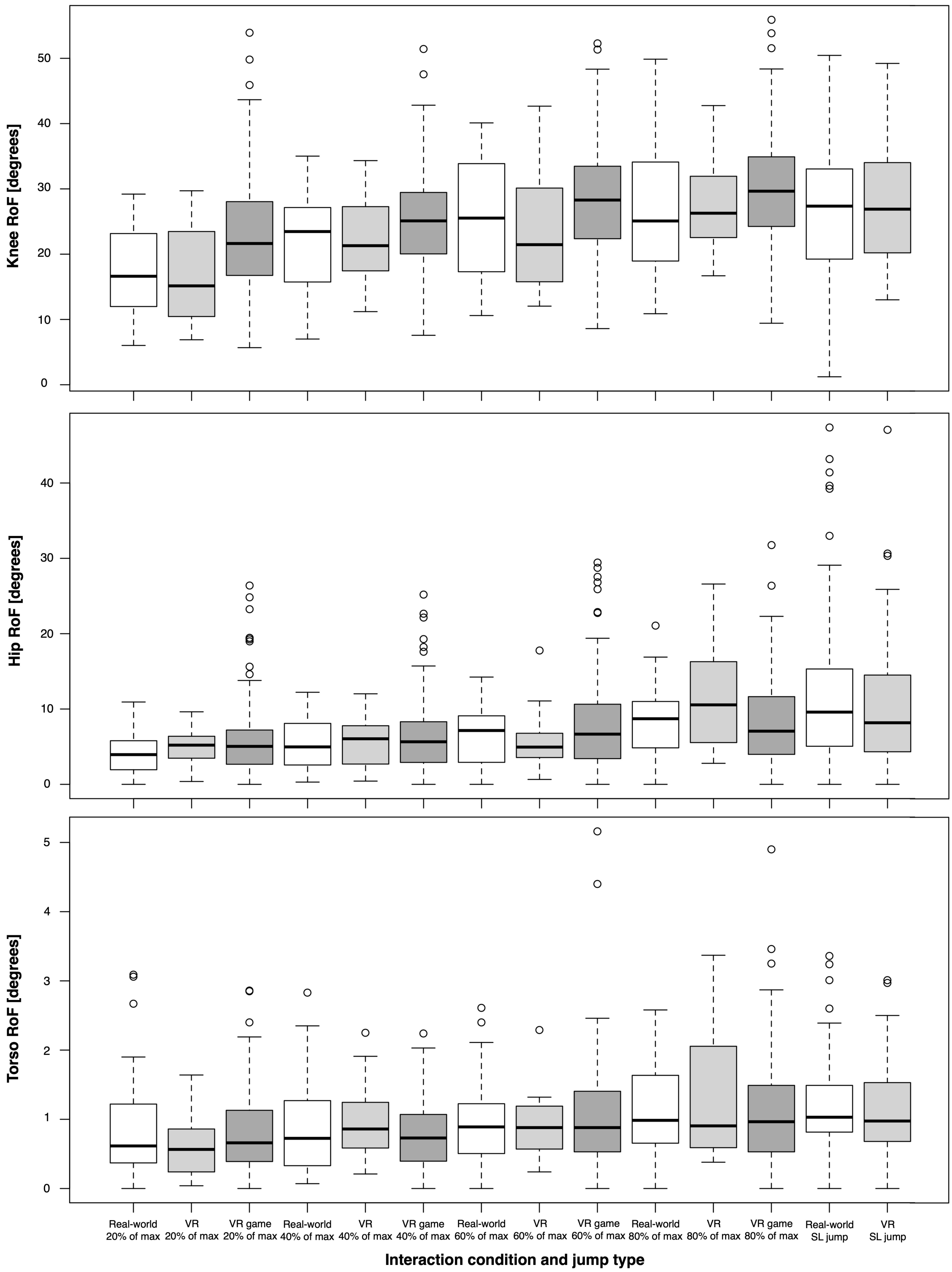


Figure 15: Boxplot of the knee (top), hip (middle) and torso (bottom) RoF as a function of interaction condition and jump type. Shown is the accumulated data for all participants. Note, for the single-leg jumps, only the data from the real world and the VR condition without gaming elements were gathered. No data transforms were used for these boxplots.

$9,67, p < 0,001$), while the interaction condition (going from the real-world to VR to VR with game elements) decreased the RoF ($t(26) = -5,20, p < 0,001$). For the torso, four significant fixed effects were found. The perturbance, interaction condition and perceived fatigueness were found to decrease the RoF ($t(16) = -2,12, p < 0,05$, $t(43) = -2,33, p < 0,05$ and $t(957) = -3,38, p < 0,001$, respectively), while the participant length increased the RoF ($t(15) = 2,13, p < 0,05$).

A full overview of the statistics of the toe-off RoF is provided in Table 15, alongside a boxplot showing the effect of perturbance and jump type for each segment in Figure 43 (see for both Appendix J.2).

Quick review - statistical analysis of MVN data from the VR-ACL system evaluation

Between the initial contact and maximum peak flexion in landing, the knee segment showed significantly less RoF for the perturbed non-dominant leg than for the non-perturbed dominant leg. In addition, there was an increase of the RoF with an increase in jump length, which was unaffected by the perturbance of that leg, and an increase with the increase in perceived fatigueness of participants. For the three smallest jump distances, similar significant trends of the perturbance and jump type were found. The effect of the interaction condition did not affect the knee RoF, although a general trend of decrease between the real-world and VR conditions and an increase between the real-world and VR with game elements conditions was found.
Between the toe-off and the maximum peak flexion in the flight phase, the perturbed non-dominant leg showed significantly less knee RoF than the non-perturbed dominant leg, while the jump distance again increased the RoF. In addition, the trial number and the participant height significantly increased the RoF.

For the hip and torso, an increase in the jumping distance showed an increase in landing RoF, while the interaction condition and the participant length showed to decrease the hip RoF and the torso RoF respectively. For the toe-off RoF, the perturbance and interaction condition decreased the hip RoF, while the perceived fatigueness decreased but the participant height, opposite to the landing RoF, increased the toe-off RoF.

6.3 GRAPHIC PRESENTATION OF MVN DATA

After data extraction and labelling, the full dataset was used to create a summative plot per jump type. The summative graphs for the knee angles are presented in Figure 17, where the focus is placed on comparing the non-perturbed dominant and perturbed non-dominant legs as jumping legs. The behaviour of the swing legs is included in Figure 45 in Appendix J. For this section, only an initial description of the presented visuals is given. A further interpretation of this data by the physiotherapist focus group is presented in Section 6.8.

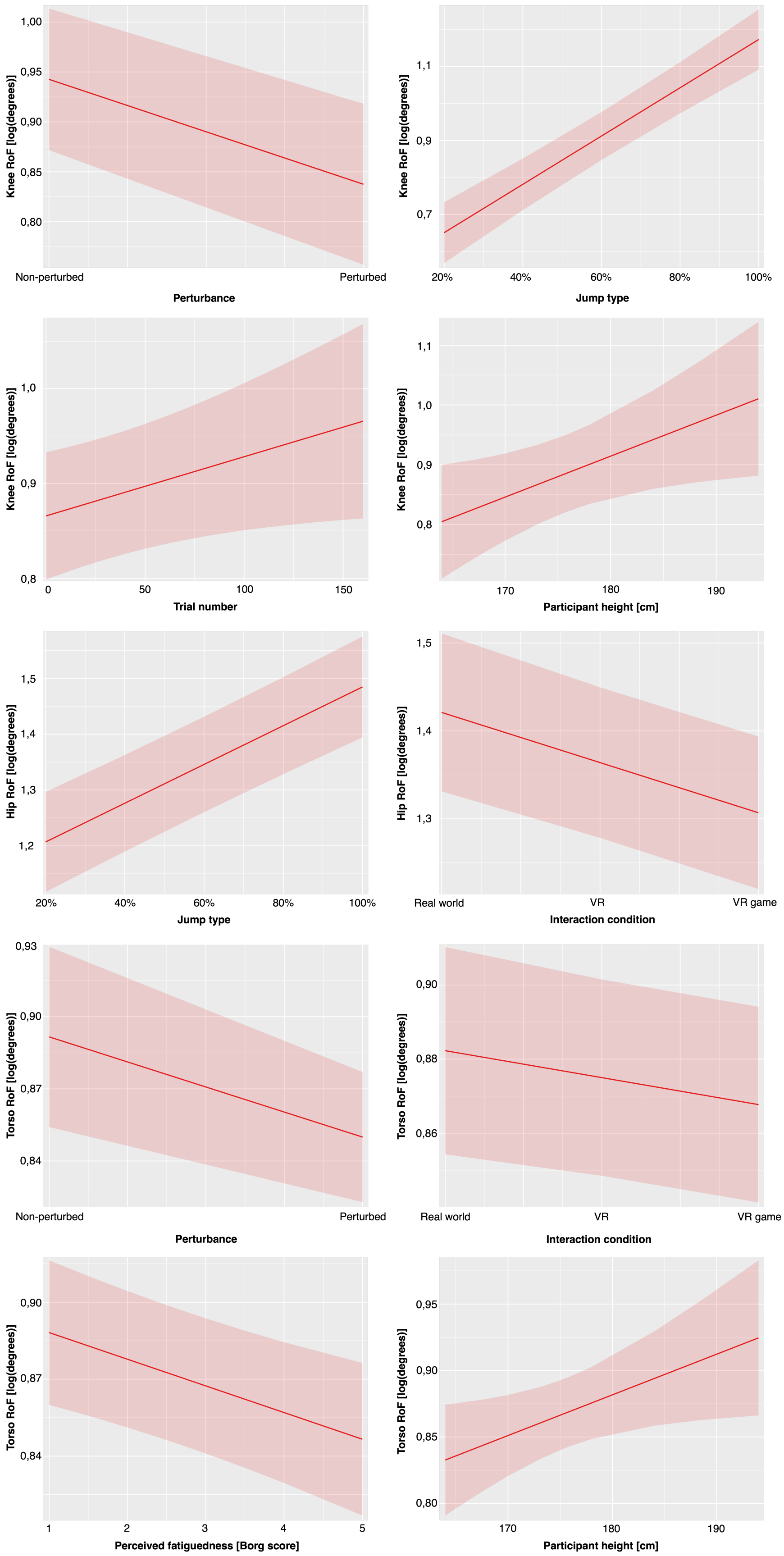
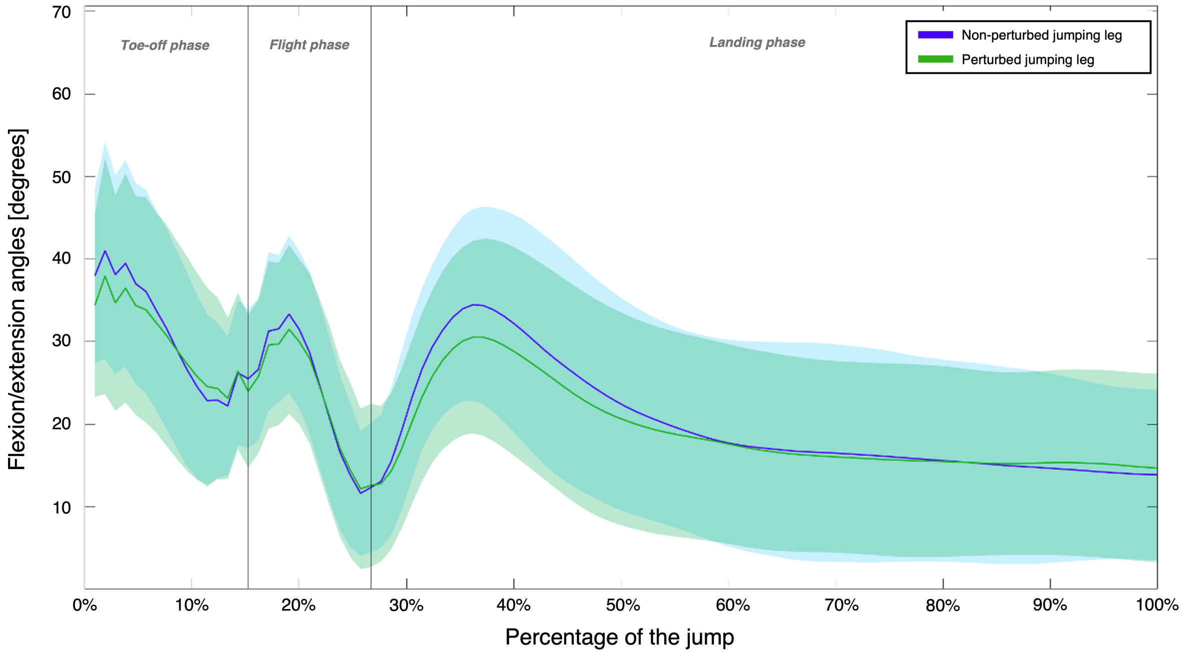
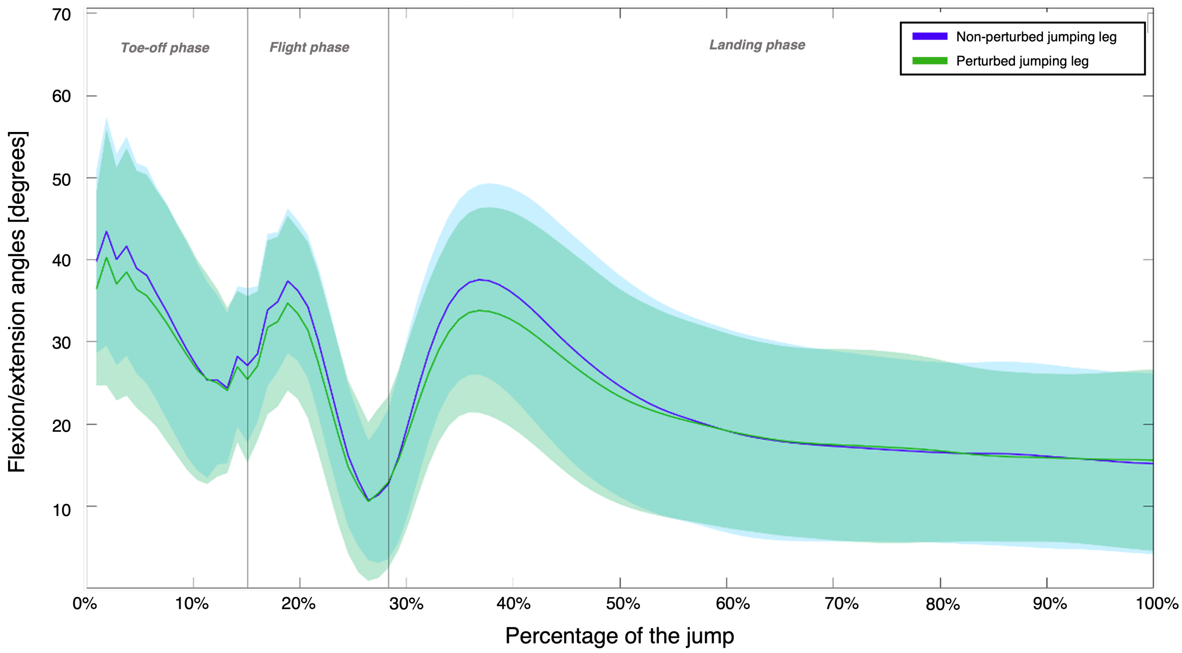


Figure 16: Predicted value plots of the significant predictors of the linear mixed effects model of toe-off data on knee (top two rows), hip (third row) and torso (bottom two rows) range of flexion.

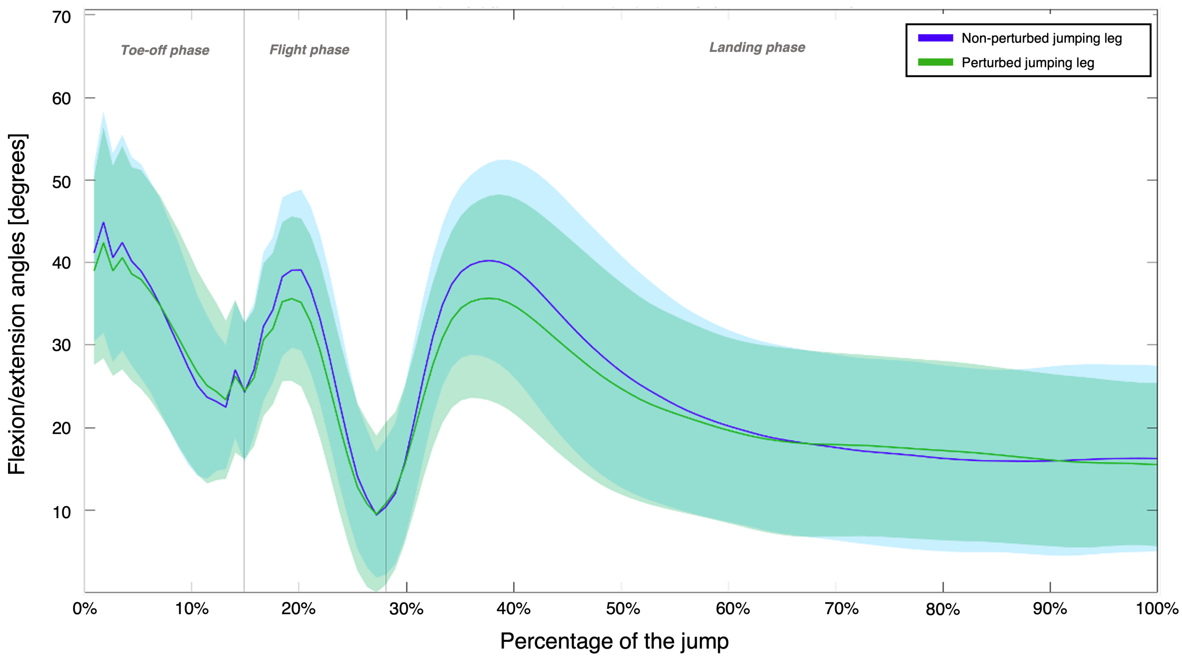


(a) Jump type: 20% of maximum.

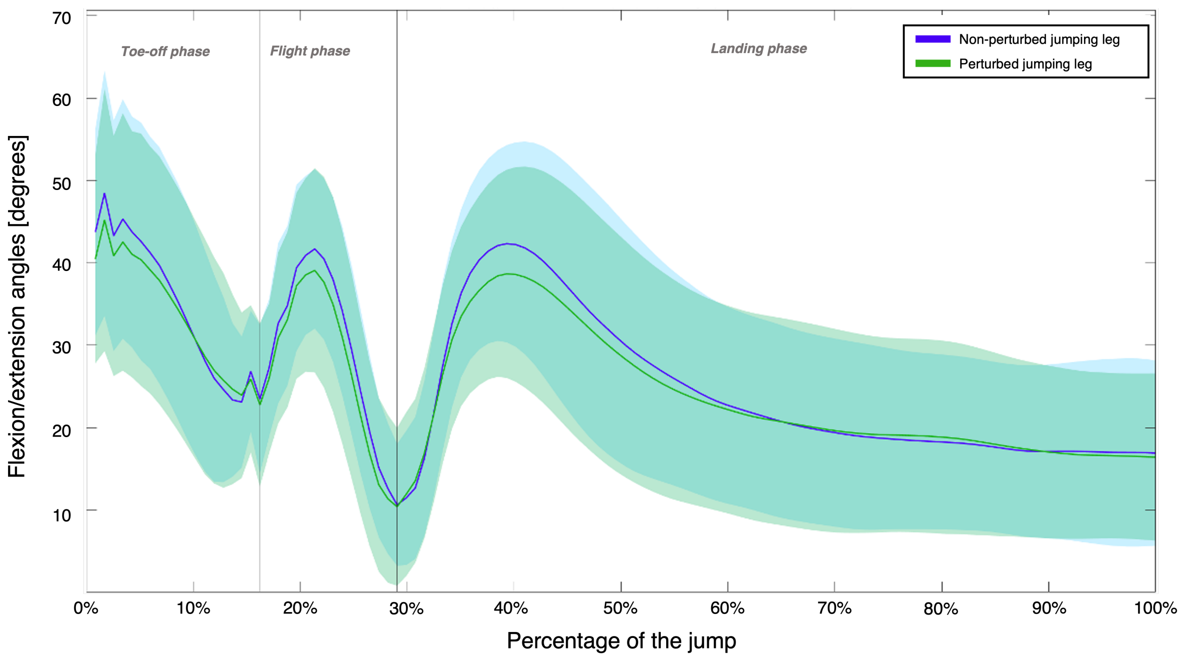


(b) Jump type: 40% of maximum.

Figure 17: Summary visual plot of knee angles for non-perturbed (dominant, shown in blue) and perturbed (non-dominant, shown in green) legs as jumping legs for the six jump types with the full participant dataset included. Phases of the jump (as determined by the indicators in Figure 41) are separated by vertical lines, with each phase indicated in the text.

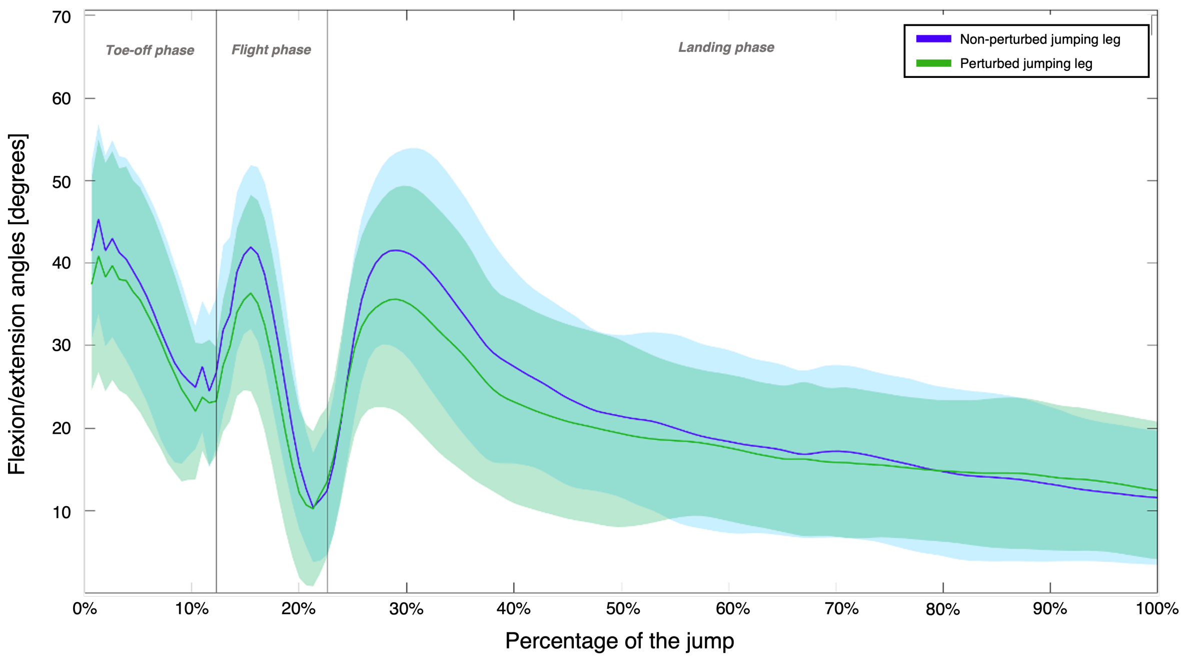


(c) Jump type: 60% of maximum.

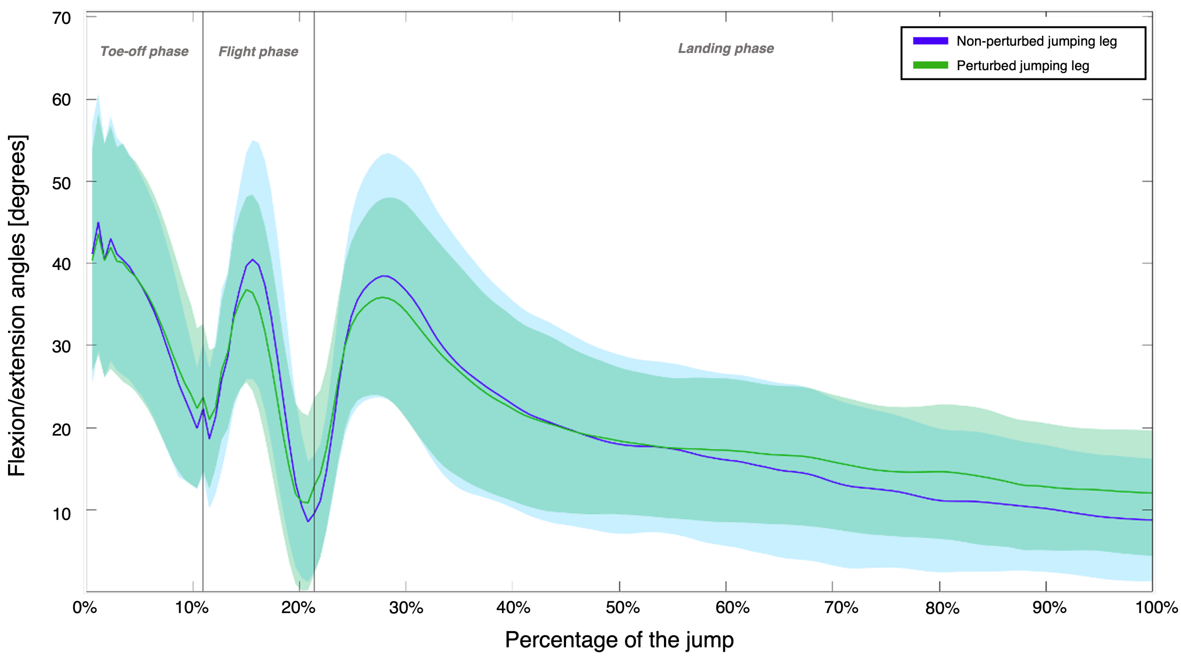


(d) Jump type: 80% of maximum.

Figure 17 - *Continued from previous page.*



(e) Jump type: single-leg VR.



(f) Jump type: single-leg real-world.

Figure 17 - *Continued from previous page.*

Within Figure 17, it can be seen that, on average, for all jump types the non-perturbed dominant leg shows more flexion throughout the jump than the perturbed non-dominant leg. During the initial contact of the leg with the ground (indicated by the vertical line separating the flight and landing phases), the mean knee flexion of the non-perturbed dominant and the perturbed non-dominant legs are similar, while the peak flexion during the landing phase is higher for the non-perturbed dominant leg, as was also found in the significantly higher RoF of this leg for the landing phase. Similarly, a higher range of flexion is found for the non-perturbed dominant leg from the moment of toe-off (indicated by the vertical line separating the toe-off and the flight phase) and the peak flexion during the flight phase, which was again also found within the statistical analysis. This trend was, however, not the case for each participant, see for example the summative graph of P16 in Figure 44. For the increased jumping distance of the jump types, the overall flexion of both legs also shows the same increase found in the previous analyses. Between the single-leg jumps of the real world and the VR condition, a higher flexion of the non-perturbed dominant leg seems to occur in the VR condition. No extreme differences seem to appear in the size standard deviation between both jumping legs for any jump type. When including the knee angles of the swinging legs as well (see Figure 45), it can be seen that there is also a higher flexion in the non-perturbed dominant leg than the perturbed non-dominant leg when swinging.

For the hip, shown for both sides when jumping and swinging in Figure 46 in Appendix J, the flexion at the side of the non-perturbed dominant leg gave a higher peak in the landing phase when jumping as compared to the flexion during jumping at the perturbed non-dominant side (although the statistical analysis did not find this difference to be significant). When looking at the hip flexion of each side during the swinging of the corresponding leg, the maximum peak surrounding the moment of toe-off is shown to be higher for the non-perturbed dominant leg with an increasing margin for further jump distances. In addition, the non-perturbed dominant swing leg shows more range in flexion throughout the entire jump cycle compared to its perturbed counterpart. Between the single-leg jumps in the real world and the VR condition, more flexion seems to appear on the swinging side in the VR condition.

For the torso flexion, the summative plot comparing the flexion for jumps made with the non-perturbed dominant leg and the perturbed non-dominant leg is provided in Figure 47 in Appendix J. The torso flexion does not seem to consistently differ between the two sides throughout the jump. Similar ranges of flexion appear between the two legs throughout the jump and the standard deviation in flexion also does not seem to differ between sides. No further trends were found to occur for the different jump types.

Quick review - graphical presentation of MVN data from the VR-ACL system evaluation

For all jump types, the non-perturbed dominant leg shows a higher mean knee flexion than the perturbed non-dominant leg, both as the jumping and as the swinging leg. For the hip, a higher flexion peak was found for the non-perturbed dominant leg in the landing phase during jumping, while this leg also showed a higher range of flexion throughout the jump as a swinging leg. For the torso flexion, no apparent trends were found differentiating the two legs.

The leg dominance influence measurement resulted in 98 jumps from the $n = 6$ participants, divided between the three conditions of no perturbation (32 jumps), perturbation on the dominant leg (27 jumps) and perturbation on the non-dominant leg (37 jumps). For both P03 and P19, files containing parts of the jumps made with the dominant leg perturbation were corrupted during recording and therefore removed. Based on the data simplification described in subsection 5.7.1, the dataset used for the LME models consisted of 35 jumps.

Only for the knee were perturbance and dominance found to significantly affect the landing RoF, see Table 6. The perturbation was found to decrease the knee RoF ($t(26) = -2,35p < 0,05$), while the dominant leg was found to give a higher knee RoF compared to the non-dominant leg ($t(26) = 2,25p < 0,05$), see also the model plots in Figure 18. The relative effect of dominance and perturbance can also be found in Figure 50 in Appendix J.4. Here, it can be seen that for the knee RoF, the biggest difference is found when the dominant leg is non-perturbed and the non-dominant leg is perturbed, as was also the case for the evaluation measurements. For the hip RoF, no significant fixed effect was found. For the torso, only the age group was found to significantly increase the RoF ($t(26) = 3,57p < 0,05$, see Figure 48 in Appendix J.4). For the torso model, Table 6 furthermore shows that the random slope had a positive ΔAIC, which was kept in the model on a theoretical basis to avoid categorisation effects of the data to violate the linearity assumptions of the model.

For the RoF around the toe-off, there was only a significant fixed effect found for the torso segment, as the jumping leg dominance was found to increase the RoF ($t(27) = 2,54p < 0,05$, see Figure 49 in Appendix J.4). No other discerning patterns were found for the RoF of the toe-off of any of the segments, see also Figure 51 and an overview of the outcomes of the RoF toe-off analysis for the dominance measurement in Table 16 (Appendix J.4).

Figure 18: Predicted value of perturbance and dominance interaction for knee RoF during the landing phase of the dominance measurement.

Table 6: Fixed and random effects structure of linear fixed effects and linear mixed effects models for predicting the knee, hip and torso RoF during landing within the dominance measurement. Note, the estimate consists of log odds; standard errors are denoted by SE; confidence intervals are denoted by CI; standard deviation is denoted by std. dev.

Knee range of flexion

Fixed effects	**Estimate**	**SE**	**T-value**	**P-value**	**Lower 95%-CI**	**Upper 95%-CI**
Intercept	27,04	2,07	13,08	<0,001	23,72	30,34
Perturbance	-5,37	2,28	-2,35	<0,05	-9,09	1,67
Jumping leg dominance	4,93	2,19	2,25	<0,05	1,36	8,46
Random effects	**Variance**	**Std. dev.**	**ΔAIC**			
1 | Participant	5,94	2,44	-8,06			

Hip range of flexion

Fixed effects	**Estimate**	**SE**	**T-value**	**P-value**	**Lower 95%-CI**	**Upper 95%-CI**
Intercept	7,49	1,15	6,48	<0,01	5,43	9,67
Random effects	**Variance**	**Std. dev.**	**ΔAIC**			
1 + Jumping leg dominance | Participant *Jumping leg dominance*	16,44	4,05	-3,81			
1 + Jumping leg dominance | Participant *Full slope*	4,31	2,08	-3,81			

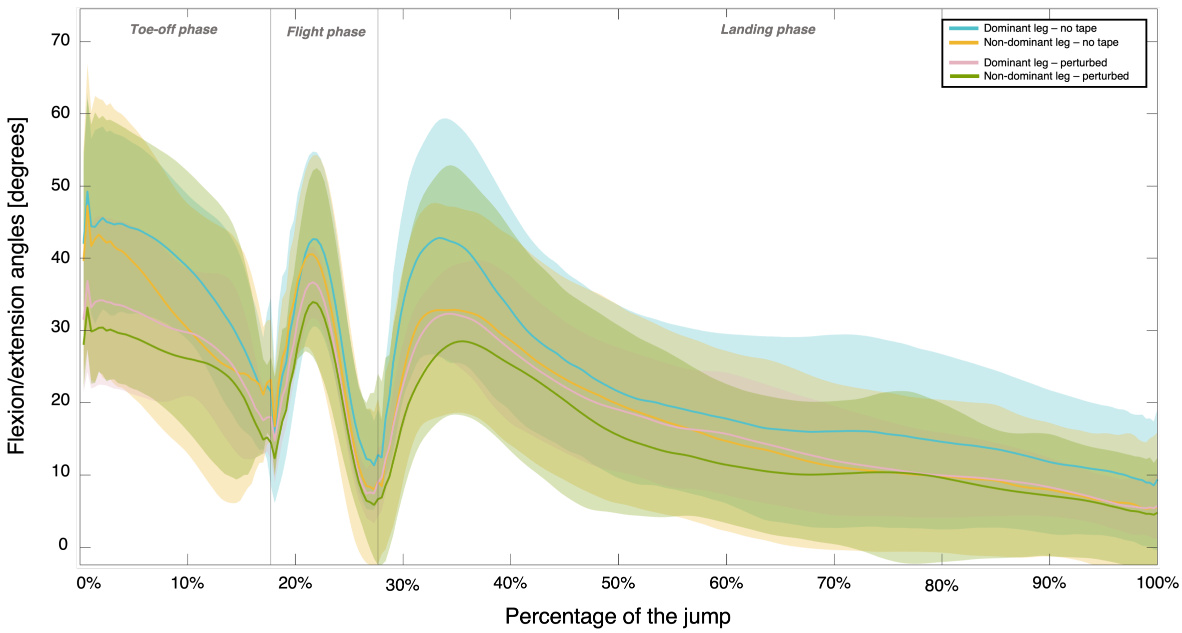
Torso range of flexion

Fixed effects	**Estimate**	**SE**	**T-value**	**P-value**	**Lower 95%-CI**	**Upper 95%-CI**
Intercept	-0,64	0,59	-1,09	0,32	-1,67	0,38
Age group	1,01	0,28	3,57	<0,05	0,52	1,52
Random effects	**Variance**	**Std. dev.**	**ΔAIC**			
1 + Jumping leg dominance | Participant *Jumping leg dominance*	0,09	0,30	3,09			
1 + Jumping leg dominance | Participant *Full slope*	0,20	0,45	7,91			

A graphical comparison between the no tape condition and the perturbed condition for the dominant/non-dominant is presented in Figure 19 for all three segments, with additional visuals showing the knee, hip and torso flexion angles of the jumping and swinging legs during the three taping conditions individually being provided in Figure 52 in Appendix J.4. In Figure 19, it can be seen that for the knee, the highest peak angle values in the flight and landing phases, as well as the highest overall flexion can be found for the dominant leg in the no-tape condition. The perturbed non-dominant leg has the smallest flexion and range of flexion throughout the entire jump. For the hip, the highest peak flexion during landing is for the perturbed dominant leg, followed by the no-tape condition of the dominant leg, while the perturbed non-dominant leg has the lowest peak flexion. For the torso, both perturbation conditions provide the highest flexion, with the dominant leg giving a higher peak during landing than the non-dominant leg. Figure 52 shows additionally that for the knee angles, the biggest differences can be found between the no-tape condition of the dominant leg and the perturbed condition of the non-dominant leg, both for the RoF in toe-off and during landing.

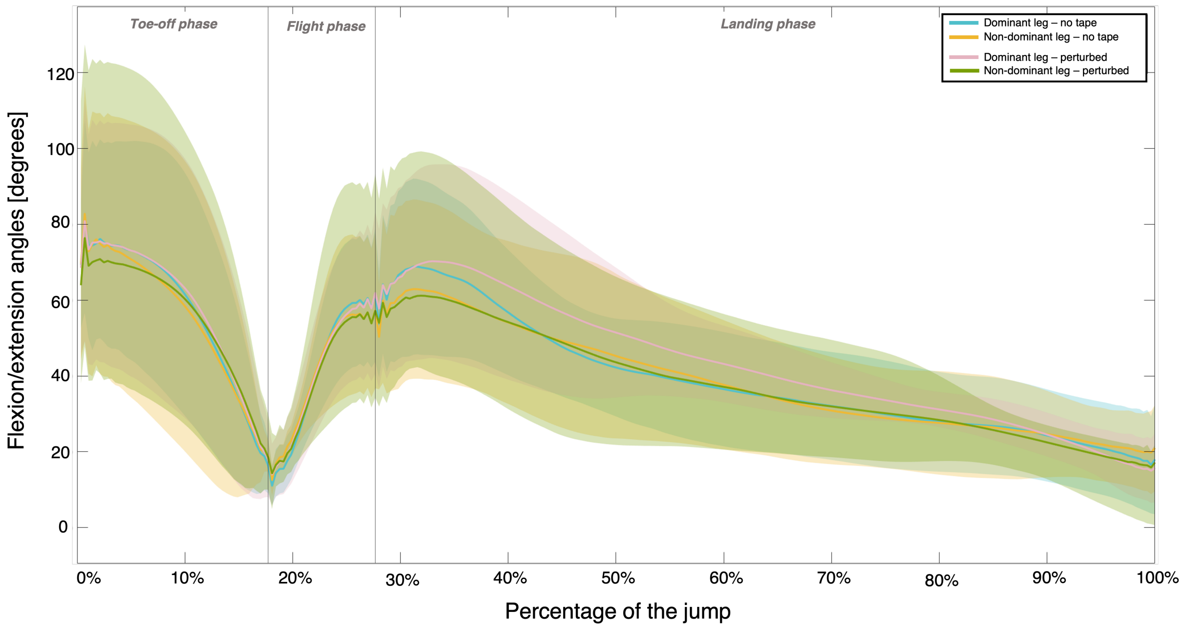
Quick review - dominance influence

For the knee, it was found that both perturbance and leg dominance affect the RoF in landing, with adding a perturbation lowering the RoF and the dominant leg having a higher RoF compared to the non-dominant leg. The biggest difference in knee RoF is found when the dominant leg is not perturbed and the non-dominant leg is perturbed, as was done during the evaluation study.

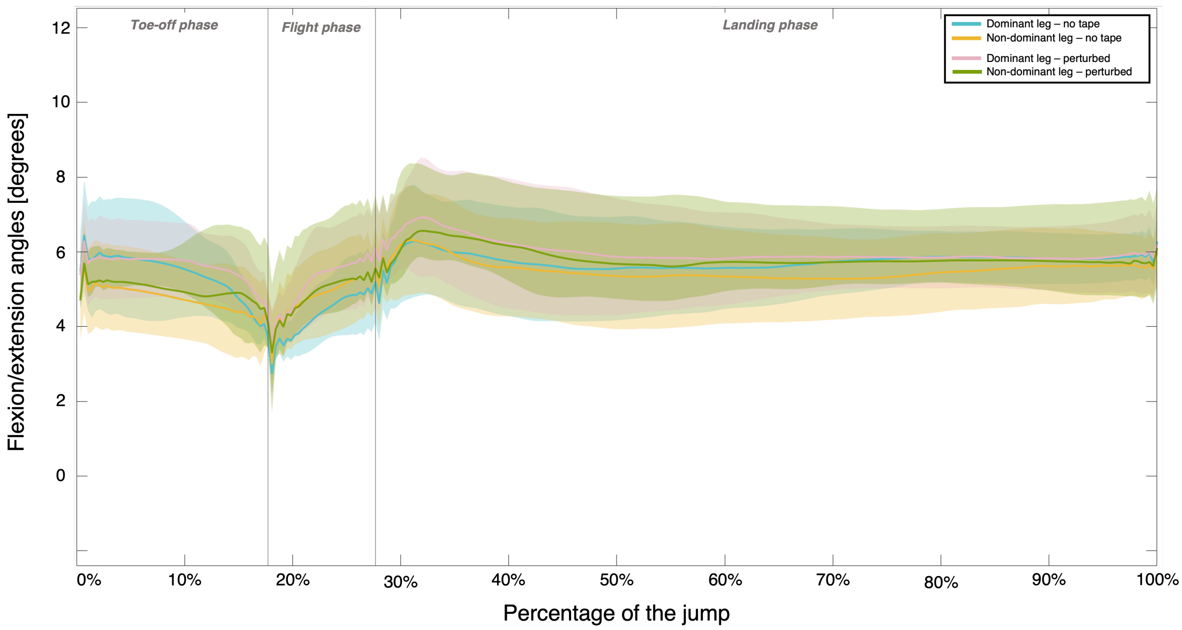


(a) Knee angles.

Figure 19: Summary visual plot of dominance influence measurement per condition for the knee, hip and torso segments.



(b) Hip angles.



(c) Torso angles.

Figure 19 - *Continued from previous page.*

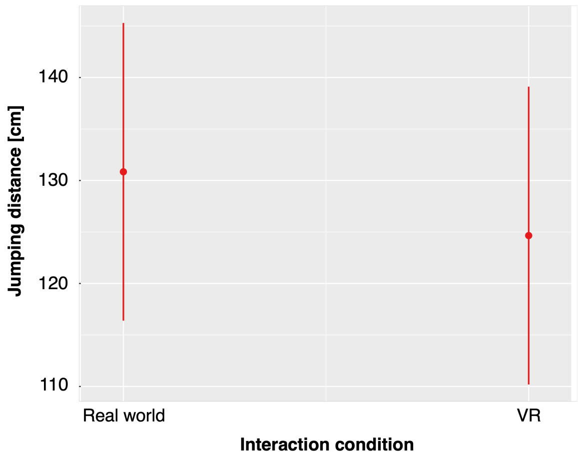
6.5 ANALYSES OF SINGLE-LEG JUMPS DISTANCES

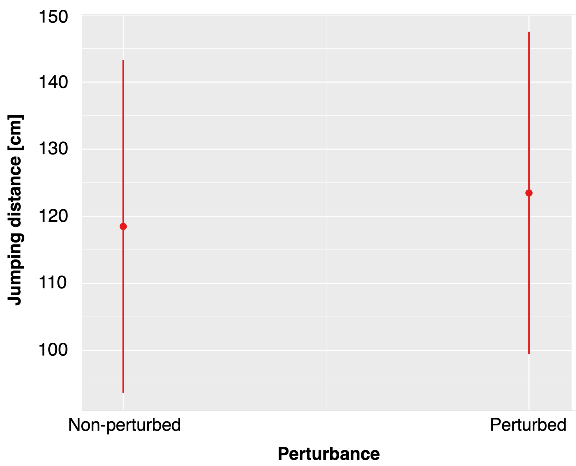
An overview of the outcomes of the LME of the single-leg jump distances is provided in Table 17 in Appendix J.5. For the single-leg jump distances recorded during the main evaluation session, only the interaction condition (for the single-leg jumps only comparing the real world and VR condition as single-leg jumps were not included in the VR game condition) was found to significantly decrease the jumping distance ($t(17) = -3,05, p < 0,01$), see Figure 20. No effect on the jumping distance was found for the perturbance of the jumping leg. With regards to the distances jumped, the average jump distance (with standard deviation) was 139,56 (±34,79) cm for the non-perturbed dominant leg and 136,54 (±35,25) cm for the perturbed non-dominant in the real-world condition; and 128,66 (±36,69) for the non-perturbed dominant leg and 133,21 (±35,22) cm for the perturbed non-dominant leg in the VR condition, see also the boxplot comparison in Figure 53 in Appendix J.5. The average LSI (comparing the maximum jumping distance of both legs) was at 100,31% for the real-world condition, with $n = 4$ participants having an LSI below 90% (i.e. jumping further with their non-perturbed dominant leg) and $n = 4$ participants above 110% (i.e. jumping further with their perturbed non-dominant leg). For the VR condition, the average LSI was 98,78%, with $n = 1$ participants having an LSI below 90% and $n = 3$ participants above 110%. A full overview of the LSI found per participant per condition has been added in Table 18 in Appendix J.5.

For the single-leg jumps made during the dominance effect measurement, a significant increase in jumping distance was found for the perturbance ($t(5) = 3,99, p < 0,05$) and the trial number ($t(47) = 3,71, p < 0,001$), see Figure 20. No significant effect was found for the leg dominance. The mean distance (with standard deviation) jumped in the no-tape condition was 139,83 (±28,74) for the dominant leg and 132,94 (±25,37) cm for the non-dominant leg. When perturbed, the mean distance jumped was 132,81 (±32,87) for the dominant leg and 126,92 (±29,00) cm for the non-dominant leg. The average LSI (here determined by dividing the non-dominant leg by the dominant leg rather than the affected by the unaffected leg) was found to be 97,64% for the no tape condition (with $n = 2$ participants having an LSI below 90% and $n = 2$ with an LSI above 110%); 94,14 for the dominant leg taped condition (with $n = 2$ participants having an LSI below 90%) and 100,35 for the non-dominant leg taped condition (with $n = 1$ participants having an LSI below 90% and $n = 2$ with an LSI above 110%). A full overview of the LSI for the dominance influence measurement has been added in Table 19 in Appendix J.5.

Quick review - single-leg jumping distances

The single-leg jump distances were not significantly affected by the perturbation during the VR-ACL system evaluation measurement, but a significant increase in jumping distance was found for perturbance during the dominance measurement. For the VR-ACL system evaluation, a decrease was found in the jumping distance for the VR condition compared to the real-world condition.





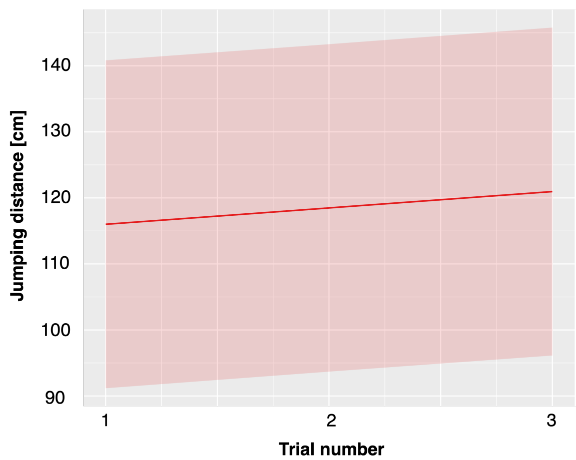


Figure 20: Predicted value of fixed effects for single-leg distance analyses, showing the analysis for the main evaluation dataset (top plot) and the dominance effect measurement (bottom plots).

6.6 ANALYSES OF JUMP ACCURACY, LAVABALL HIT ACCURACY, JUMP TIMES AND PERCEIVED FATIGUENESS

Based on the LME for the jumping accuracy (presented in Table 20 in Appendix J.5), the distance between the landing and the target location significantly increased as the round number increases ($t(931) = 2,34, p < 0,05$), indicating a decrease in jumping accuracy). The perturbance and jump type were not found to be significant predictors for the jumping accuracy, see also Figure 54 in Appendix J.5).

For the lavaball hits (see Table 21 in Appendix J.5), the accuracy increased over the rounds ($t(60) = 2,63, p < 0,05$).

For the round times (presented in Table 22 in Appendix J.5), it was found that the time spent on each jump decreases as the round number increases ($t(789) = -2,20, p < 0,01$) and increases as the jumping distance increases ($t(784) = 9,47, p < 0,001$). The average time per round was 274 seconds.

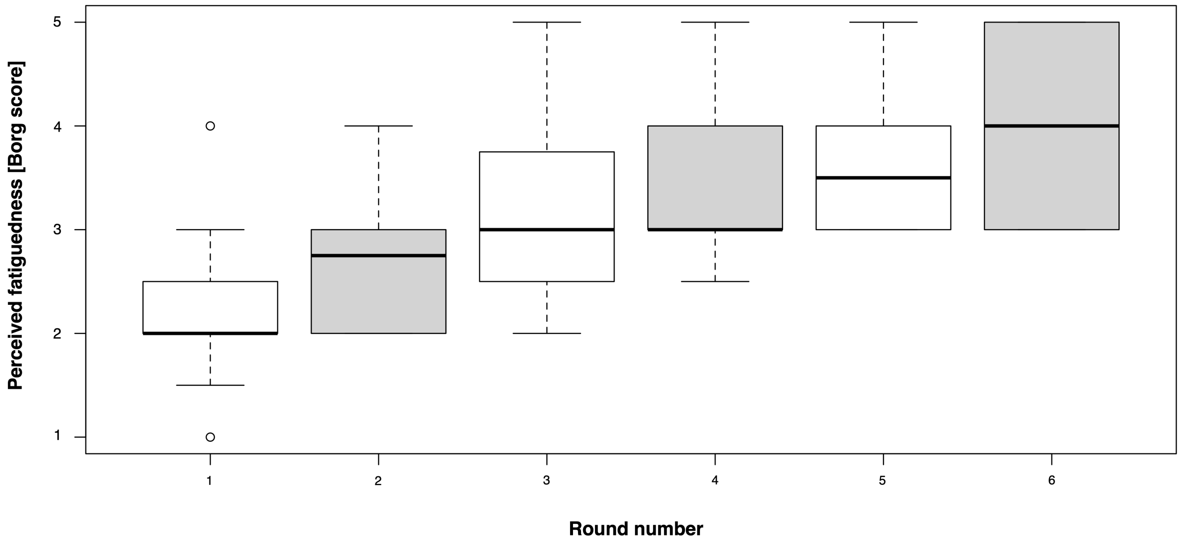


Figure 21: Boxplot of perceived fatigueness (as determined by the Borg score value) over the played interaction rounds. Scores were based on the following distribution of participants, with round 1 including $n = 18$ participants; round 2: $n = 18$ participants; round 3: $n = 16$ participants; round 4: $n = 10$ participants; round 5: $n = 6$ participants and round 6: $n = 2$ participants.

The predicted effects of the jumping accuracy, lavaball hit accuracy and jump time have been added in Figure 22, with additional boxplots having been added in Appendix J.5.

For the perceived fatigueness of participants throughout the rounds, while an increase was seen in the scores over the rounds, the values remained below 5 (to be interpreted as 'hard'). This means that according to the perceived fatigueness, the tasks were not fatiguing enough that this would have interfered with the kinematic data. The Borg score values are added as boxplots in Figure 22.

Quick review - jump accuracy, lavaball hit accuracy and jump times

The jumping accuracy was found to decrease over the rounds played, while the lavaball hit accuracy increased over the rounds and the jump time decreased. For the perceived fatigueness, no values higher than 5 ('hard') were reported.

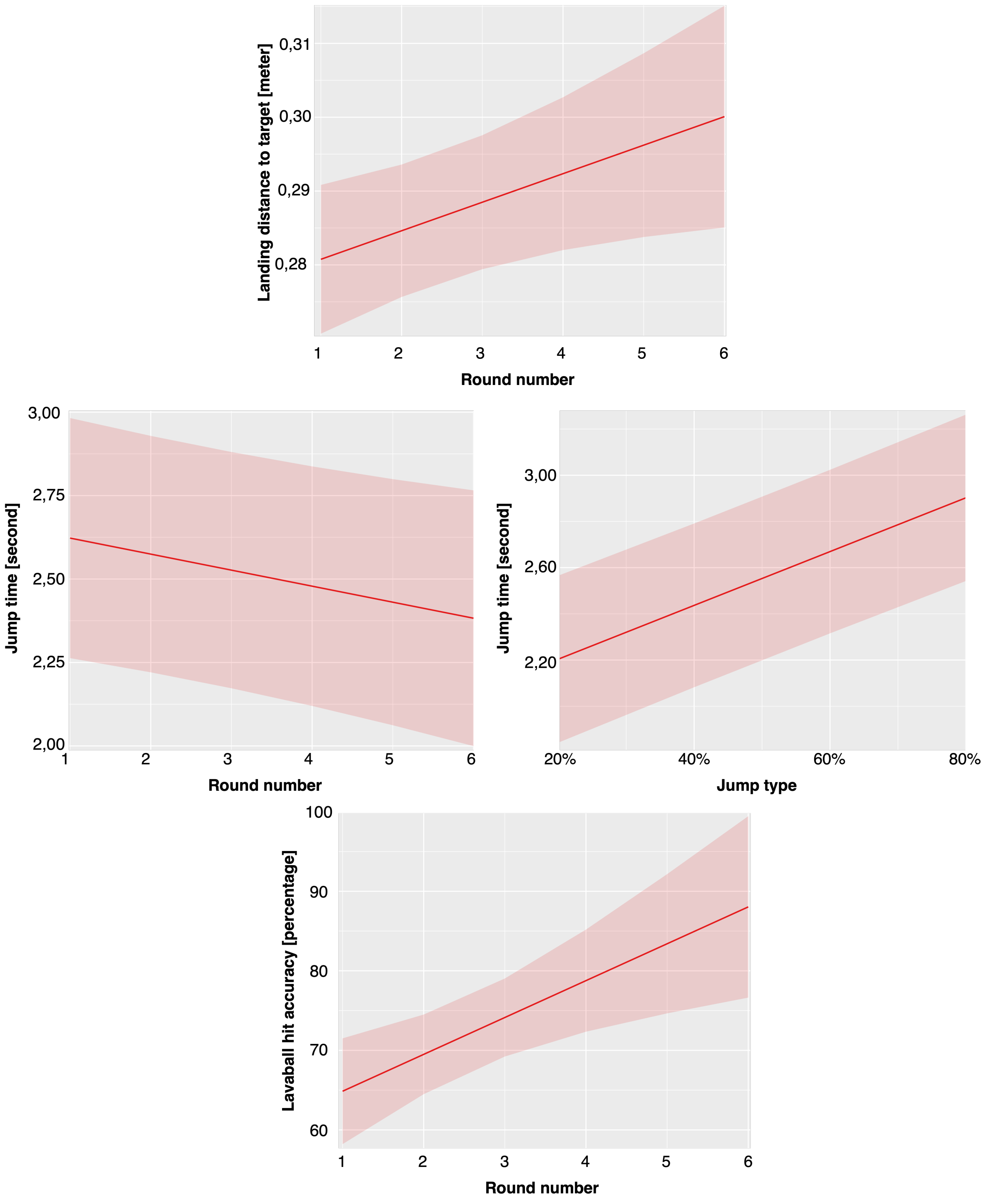


Figure 22: Predicted value plots of the significant predictors of the linear mixed effects models for the jump accuracy (top row), timing (middle row) and lavaball hit accuracy (bottom row).

6.7 PARTICIPANT EXPERIENCES OF THE INTERACTION

Within this section, the findings from the post-session surveys and interviews are included supported by notes made throughout the sessions and a review of the video recordings to

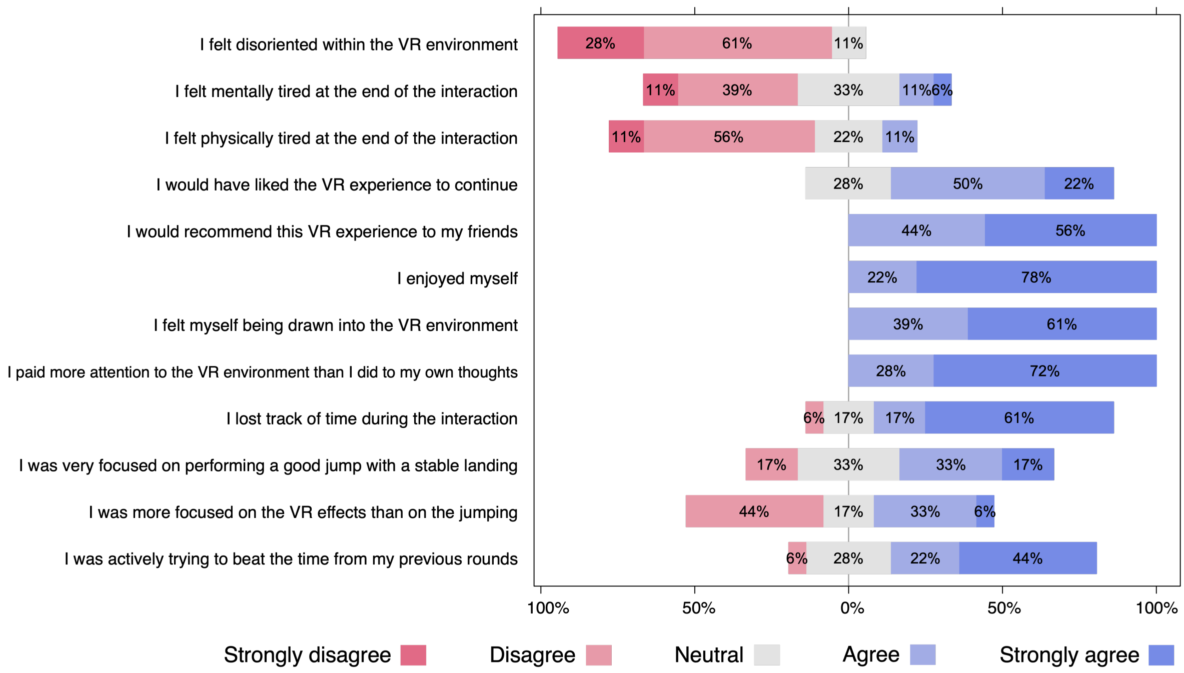


Figure 23: Outcome to the closing questionnaire Likert scale questions.

find specific behaviours. In addition, the evaluation done with the two patient participants is included.

6.7.1 *Post-evaluation survey outcomes*

The first part of the post-evaluation survey was used to form an understanding of the experience participants had with physiotherapy and (VR) gaming, as well as their (general) activity level. The outcomes of this have been presented as part of the participant demographics and characteristics in Section 5.1. In this section, the second part of the survey outcomes concerning the participants' experiences with VR and the interaction is presented.

The Likert scale question outcomes of these questions are presented in Figure 23. From these outcomes, it can be seen that questions related to disorientation and mental tiredness received a mean and standard deviation outcome of $1,83 \pm 0,60$ and $2,61 \pm 1,01$ respectively. The physical tiredness of participants was rated at $2,33 \pm 0,82$. For the questions on whether participants would have liked the interaction to have continued and whether they would recommend it to their friends, mean scores of $3,94 \pm 0,70$ and $4,65 \pm 0,50$ were found, while enjoyment of the overall experience was rated with $4,78 \pm 0,42$. Several questions were related to the participant's immersion, which focused on whether the participants felt like they were drawn into the VR environment (resulting in a score of $4,61 \pm 0,49$), whether they paid more attention to the VR environment than their own thoughts ($4,72 \pm 0,45$), whether they lost track of time ($4,33 \pm 0,94$) and how their focus on jumping related to their focus on the VR effects (which resulted in a score of $3,5 \pm 0,96$ on being focused on performing a good and stable jump; and a score of $3,00 \pm 1,00$ on being more focused on the VR effects than on the jumping). Participants responded to actively trying to beat their previous round times with a score of $4,06 \pm 0,97$.

6.7.2 *Participant interview and comments on interaction behaviours*

Throughout the interaction, several interesting participant behaviours were noted down. Most notably, participants showed different forms of playful behaviour, as both during the VR introduction and the interaction itself, participants were very happily keeping themselves engaged with the interaction. Specific behaviours that were found were laughter, striking poses, skipping and running away from or trying to physically slap lavaballs away once they ran out of shots. This behaviour was often accompanied by exclamations or cheers. Participants also often cheered or frustratedly called out when they hit or missed a lavaball. Additional interesting movements that occurred were looking away from where they were walking or running to, walking and jogging backwards, and making fast spinning movements while in the VR. Several participants also showed competitive behaviours, sprinting from jumping plane to jumping plane. Throughout rounds, participants often indicated of their own volition that they were attempting to beat their high score or that they had found a method to improve their gameplay (e.g. by finding a central place to continuously be on the lookout for new jumping planes or by waiting until the final moment to shoot the lavaball to increase their accuracy). In individual cases, participants took time in between rounds to analyse their own performance and where they had won or lost significant amounts of time. Participants also generally considered their own performance to improve over time, often relating it to how fast they were completing the rounds or how many lavaballs they hit. After the interaction was completed, several participants asked whether they had received a high score in the game based on their time, lavaballs hit or distance covered during the single-leg jumps.

> "*In the last round I was eager to beat my previous times and I definitely saw an improvement in how fast I was. I think it was because I understood the game dynamics better.*" – Participant P18.

Regarding the general game elements and overall performance, participants seemed to grasp the concept very easily. Some participants indicated that they used the first round to get familiar with the gaming elements and controls. Because they were able to practice shooting the lavaballs during the introduction of the game, they indicated to feel confident in performing this action during the interaction. The yogaball shot with the controllers was modelled as a standard ball with physics laws applying to it, shooting the ball spawned it with a force ejecting it directly from the controller and letting it return to the ground with an arc (where it bounced and rolled away to eventually be removed from the virtual environment). Some participants had expected the ball to behave more like a laser or bullet, in which they could directly aim at the target and hit it from far away without it curving back to the ground after being shot. This meant that participants had to focus more on their aim and shooting than they had expected to hit the ball correctly. Two participants discovered that they could aim and wait to shoot until the last second because they were guaranteed to hit the lavaball. The shooting of lavaballs was further considered to be the focus of the game by participants.

> *"From the player's perspective, it seems as if the lavaballs were the main game element in this interaction."* – Participant P04.

The experience of jumping within the virtual environment was generally positive. Participants seemed to estimate the jumping distances well and were happy to have a target to jump towards, especially because they helped to give a more clear and stable jumping experience. Participants did generally think that they had jumped further in the real-world single-leg jump condition than with the VR single-leg jumps, as this was the known and 'safer' condition to them, although the fact that they were unable to translate the VR distance they jumped to the real world did also lead some believe they were able to jump further in VR.

> *"I felt like I could take bigger risks when jumping in the real-world condition because I knew I would be able to catch myself and I did not think I would be able to do that in the VR. For example, with the longer jumping distances in the interaction, I was also first checking if it was still within the virtual guardian."* – Participant P03.

Participants also seemed to think that jumping became easier in the VR environment over time. Several participants indicated an initial hesitancy to jump (larger) distances because they were afraid to hit anything in the real world, but they became more secure in their moving and working with the virtual guardian over time.

> *"It was really fun to make jumps in a VR environment! At the start, I didn't expect it to be this fun, but it really was! In the first round, I was a little afraid to hit something but in later rounds, I was able to work better with the virtual guardian, so I also thought less about the real world around me."* – Participant P18.

The gaming elements, specifically the lavaball dual-task, seemed to move the focus of the participants away from the jump itself. Participants indicated that they were less focused on executing the jumps once they were doing the interaction as compared to their initial single-leg jumps in real-world and VR conditions. Participants also seemed less hesitant to jump, with some participants even running up to the jumping planes and jumping in one go as a tactic to improve their time and to be ready on time for the lavaballs when they would appear. Participants also indicated that they enjoyed the lavaballs as a method to stay alert in the game, especially because different speeds and angles were used and the lavaball would not always appear.

> *"In the real world condition I was overthinking the jumps and in the VR I just jumped without overthinking it at all. I tried to complete jumps as fast as possible so I could be on the lookout for lavaballs. I wasn't as focused on the jumps as I otherwise would be, I had to divide my mental capacity."* – Participant P20.

The use of the time bonuses and deductions was very motivating for some participants, while others were not as focused on this element but rather on the shooting itself. Several participants indicated that, especially for their final round, they were very eager to beat their previous times and were frustrated when they were unable to, which increased their motivation to be even faster still.

> "*I really wanted to beat my time in the last round, so the time bonuses got very important. I think I could have happily kept playing this for the rest of the evening. It's really too bad I didn't beat my time that final round, but that's the game and that also makes it fun!*" – Participant P06.

The experience of the MVN legs varied between participants, but most indicated that they got used to working with them and that it helped them to make the jumps and estimate the target distance correctly. Some participants also experienced issues with the legs in which they moved or turned relative to the participant and several participants indicated that resetting them to be below the HMD by looking up took some getting used to, but they were able to adapt to them well. None of the participants experienced strong delays or required significant repeats of jumps due to the MVN legs.

> "*I quite liked it! It was nice that I could just easily reset the position of the MVN avatar legs by standing up straight. I'm not sure if they were really located where my actual legs were - they maybe were a little bit off - but otherwise, it was very nice and they were very responsive to my actual movements.*" – Participant P10.

An interesting remark that was made by three separate participants at the start of their session was that they felt that they were bad at keeping balance and would, therefore, not do well with the single-leg jumps. For these participants, an initial hesitancy was seen in their jumps, which for all seemed to improve over time. One participant who had indicated a bad balance noted that, while he was very hesitant in his first jumps in the real-world condition, he started to be much faster in the interaction itself because he was engaged in the game. For some of the participants, incorrect jumping behaviour was noted throughout the interaction (e.g. jumping or landing with two legs rather than one or running and leaping over the jumping plane rather than making a correct single-leg jump). Where possible, participants were then reminded of the correct jumping technique in between rounds, but during the rounds themselves, no corrections were made or indicated to the participant.

At the end of the testing session, participants were also asked whether they encountered any physical or mental difficulties in completing the interaction. None of the participants actively noticed a strong increase in their physical fatigue. Some indicated that they got a bit warmer over time, especially on their head when wearing the HMD, but none of the participants found the interaction to fatiguing and no participant was unable to complete at least three rounds of gameplay due to any fatiguing complaint. Two participants did not complete all rounds due to time constraints and their inclusion in the additional VR effect measurement (see Table 14 for an overview of the number of correct jumps gathered per participant). The sports tape that was used to perturb the non-dominant leg was also not considered to be too restrictive by participants. They did notice the rigidness of the tape especially at the start, but most indicated that, either due to the tape stretching because of the jumps or due to the VR immersion, they noticed the tape less as the session went on. Some participants thought that the tape had diminished their ability to use it as the jumping leg, while others said that they were especially affected when it was the swinging leg and that it may have even helped them to generate a stable jump when the perturbed leg was jumping.

Overall, participants were positive about the VR experience and the game itself. Participants indicated that they felt very immersed in the game. Many also stated that, even though they knew at the start that the measurement was related to movement and jumping, they were so focused on the game that they lost sight of this objective. Participants were very enthusiastic and were often eager to provide ideas for continued development. All participants indicated that they found the interaction to have been a positive experience.

> *"I was positively surprised! I did not expect I would ever be making such jumps with a VR setup. I honestly thought I would be much more careful, but you just get used to it. I also liked that I got to be on the lookout for the jumping planes and had to quickly respond when I spotted them."* – Participant P03.

6.7.3 *Analysis of VR-ACL system with patient participants*

After completing their walk-through of the VR-ACL interaction, both patient participants were asked to relate the interaction with their experiences with ACL rehabilitation. Both participants were interested in the VR environment but also considered that making jumps in this condition, especially when they were still rehabilitating, might require some practice and gaining confidence in doing the interaction. Participant P01 indicated that this might also be more trusting in one's own abilities rather than the VR environment. Both participants further indicated that the VR environment would likely be very beneficial in keeping the focus away from the jump and the knee performance and, especially around the end of the rehabilitation when a patient would have confidence in their own movement ability, the VR environment might be useful to make a standard jump more interesting.

> *"It seems like less pressure, you are more doing the game than thinking of your rehabilitation. You also have a lot of openness in the virtual environment, so that gives a lot of security. If I would still be injured, I wouldn't know if I would do it well though, because maybe wearing the HMD would give some insecurity when you'd actually have to make these movements, but I wouldn't know that right now."* – Participant P01.

The participants indicated that knowing what the real-world environment looked like before entering the VR environment helped provide more security, especially when participants could still see the real-world boundary shown in the VR environment with the virtual guardian. Still, making sideways or backwards movements was considered more daunting, as this would require movements completely out of the (virtual) angle of view. In addition, because the exact feedback of the feet is missing (even though the MVN avatar is present), making longer or more difficult jumps was considered more daunting, as it would require trust in one's own ability to correct movements if needed.

Regarding the other gaming elements, the participants indicated that the lavaballs would be a good way to move the focus away from the jumps. This could also be a risk when applied earlier in rehabilitation because especially at that stage the focus on the movement is still needed. The further in the rehabilitation the more the competitive element of time bonuses may become relevant and interesting. It also depends on where the importance is placed, as patients would likely be aware that their jumping performance is more important than their shooting accuracy or round times. Physiotherapists might play a role to help shift the focus away from the jumping performance and onto other gaming elements.

> "*When you are doing this interaction as part of evaluating your rehabilitation process, you know that it really is about the jumps you are making. That might make the timing element less persuasive because you might already realise that this is not the actual performance measure.*" – Participant P01.

Participant P01 put further emphasis on patients not being able to see their own knees while in the VR, with attention being further moved from the knee to the VR world by the lavaball dual-task and visual distractions. Because of this, patients cannot check how their (MVN avatar's) knee performed in the jump. Patients would have to use their proprioception to regain their sense of movement quality in their knees, as is also trained during their rehabilitation. Participant P01 did indicate that, when removing the ability to see the knee performance, some external method of feedback would be beneficial to help create the proprioceptive sense. For the use of the MVN avatar, both participants saw the benefit of seeing the movement of the knee, while P02 again added that this might be a good middle way for still providing some visual feedback without directly showing the real-world knee performance.

> "*When you are visually restricted in seeing your knee move, I think you would start to jump more based on your proprioception. During my rehabilitation, I tended to constantly look at my knee during exercises, so my physiotherapist told me to turn away from the mirror to see if I could also feel whether the knee was making the right movement or not. The feeling in your knee really changes after the ACL surgery, so you need to build that feeling back up. I think using VR could have a similar effect, you start to use your proprioception to feel rather than constantly look at whether you are moving correctly.*" – Participant P01.

Overall, both participants could envision the use of VR as part of their rehabilitation. The unpredictability of the interaction, which forces the patient to make quick decisions and draws the focus from the jump itself, was noted by both participants as a positive way that relates to the rapid decisions made within a sports context. However, it was also considered by the participants that patients might want to have their focus on the jump if they are being evaluated since this is a critical moment in their rehabilitation. The empty virtual environment, coupled with the virtual guardian, gave a sense of security to move around. The participants indicated that the use of a lava plane to jump over, but also the competitive element was considered to be very motivating, especially for patients who might not already have a strong internal motivation to rehabilitate or who might not be rehabilitating to return to sport (and so might not have a clear goal in their rehabilitation). Because rehabilitation exercises are often repetitive, adding such an external motivator was considered to be beneficial. As final remarks on the interaction, the participants both indicated that some familiarity with the VR system would be beneficial for a patient's confidence in their performance during the RTS evaluation. Both also saw possibilities for adding more varied jumps to the interaction rather than only the single-leg jumps.

> *"I thought the VR interaction was very immersive and would draw the focus away from the jumps. I do wonder if I would have wanted this during my rehabilitation because you know that your focus is removed from the main measurement metric of your movement performance evaluation. Especially the RTS evaluation is so critical for a patient wanting to get back to playing sports, so I definitely would have liked to practice with the system during my appointments with my physiotherapist, so that if I had to do it for the RTS evaluation your scores would not be limited by just having to get used to the VR."* – Participant P02.

6.8 ANALYSIS OF VR-ACL SYSTEM AND DATA WITH PHYSIOTHERAPISTS

During the first focus group held with the physiotherapists at OCON, the main focus was to determine how the VR-ACL evaluation system in its totality (i.e. the VR environment as well as the physical constrictions of the sensors, HMD and controllers) affected the movement behaviour of the participants. For participant P06, the physiotherapists considered his natural jumping behaviour, both in the real world and the VR conditions to show significant compensatory movements during the landing. Specifically, the physiotherapists considered the arm movements, torso flexion and the participant's necessity to immediately put his swing leg down after landing as indicators for his unbalanced jump. When jumping in the real-world condition with his perturbed non-dominant leg, P06 was considered to show less peak torso flexion and a more rigid landing compared to the VR single-leg jumps, although he did seem to increase the flexion in the non-perturbed knee during landing in VR. This behaviour was later confirmed with a kinematic analysis. The physiotherapists did express their surprise at the participant's ability to reach similar jumping distances during the VR single-leg jumps compared to those made in the real-world condition, as the maximum single-leg jump distances of P06 were 193, 6 cm for the non-perturbed dominant leg and 189, 1 cm for the perturbed non-dominant leg in the real-world condition, compared to 190, 6 cm for the non-perturbed dominant leg and 194, 1 cm for the perturbed non-dominant leg in the VR condition.

> *"I am surprised at how little difference I see [between the real world and VR single-leg jumps of P06]. To be honest, I had expected that just wearing the HMD itself would give issues for the participants in jumping, not only with the distance but certainly with the execution of it. What we see [for participant P06] does show that doing jumping tasks in VR is at least trainable."* - Physiotherapist PT01.

For P04, the physiotherapists note the stiffness with which the participant carries their perturbed leg. Because the participant did not show a lot of knee flexion before the jump, the jumping distances were also found to be less than for participant P06 (for P04, the maximum single-leg jump distances were 100, 0 cm for the non-perturbed dominant leg and 110, 0 cm for the perturbed non-dominant leg in the real-world condition, compared to 99, 0 cm for the non-perturbed dominant leg and 107, 5 cm for the perturbed non-dominant leg in the VR condition). During the VR game interaction, the participant showed similar behaviours for the smaller jumps as for the larger jumps. Specifically, the limited flexion in the landing pattern and in the knee itself, compensatory movements and the immediate placing of the swing leg on the ground upon landing.

For both participants, different notes were made on their ability to make controlled and stable jumps within each of the three conditions (real world, VR and VR game interaction). In general, when analysing the videos, the physiotherapists considered three main factors aside from the general movement characteristics of the jump. First, compensatory movements were considered, such as late flexion of the torso or significant arm movements that could signify an imbalance. Second was the amount of valgisation when landing (i.e. strong valgus movement of the knee in the frontal plane), which could be considered to be a sign of instability within the knee. While somewhat debated amongst physiotherapists, the 'uncertain' side-to-side movement of the knee in the frontal plane could again signify an inability of the patient's knee to correctly catch the landing of the jump. However, if a patient is able to land stably, even in a valgus orientation, this could still be seen as a stable landing and possibly inherent to the jumping characteristics of that person. Finally, the knee flexion angle was analysed to determine whether any noticeable discrepancies occurred between the affected and unaffected leg, although the initial contact flexion could often be too fast to be considered in practice or with video recordings.

> "*When viewing the landing, it is over so quickly, so only the major things are noticeable when visually analysing. When a patient has a lot of arm movements or shows a deep flexion, those are clear signs that the landing was less stable.*" - Physiotherapist PT01.
>
> "*Of course, context is everything for these cases. There is always a preferred leg or the sport someone plays which can affect their movement. Maybe some things affected their movement development during childhood that no therapy could 'correct'. Even if we now see a good quantitative result with the jumping distance they cover, there are qualitative notes to make to the jump. However, you should also consider what is reasonable. If someone lands stably but there is too much valgus compared to the norm, you might frighten a patient unnecessarily when saying that they are not jumping correctly. Depending on the sports or context of a patient, it might even be functionally fine to jump in such a way.*" - Physiotherapist PT02.

When analysing the movements in the VR game condition, the sudden appearance of the lavaball showed to unbalance both participants. The physiotherapists related this to a sports scenario, where even when unexpected scenarios occur (e.g. having to make a jump to perform a sudden header opportunity in football), the movements should remain controlled and stable for that specific context. ACL re-ruptures can often occur when an athlete is attempting to react to an unexpected scenario, so the response to an unexpected interaction is valuable to analyse. However, physiotherapists can differ on which risk factor in that unexpected interaction is most relevant for each patient to prepare for, so a measure of individuality might be warranted in evaluating their response.

During the second session with the physiotherapists, the main focus was to determine whether the quantitative data could be meaningfully interpreted by the physiotherapists within the given context (as well as possibly translated to the ACL rehabilitation context); whether (relevant) patterns could be found; and to determine what the added value of the data was compared to the standard RTS evaluation.

For the knee flexion throughout the jump (Figure 45), the physiotherapists indicated that both the jumping and the swinging legs could provide interesting information about the movement characteristics of both legs. For instance, when the perturbed non-dominant leg jumps, the swing leg (i.e. the non-perturbed dominant leg) shows more flexion than when the jumping is vice versa. The physiotherapists interpreted this as that more swing might be needed to propel someone forward when the jumping leg is perturbed, thus resulting in higher swing flexion. Of course, it could also be possible that because the perturbation stiffens the knee, less flexion is to be expected when the perturbed non-dominant leg is swinging. For the jumping legs, the flexion at the moment of initial contact seems to be similar for both legs, with differences in the flexion mostly occurring during the landing phase. The physiotherapists, therefore, considered the RoF in the landing to be most relevant, with the RoF in the toe-off to be of secondary interest. For the physiotherapist, the entire chain of knee, hip and torso data is relevant to determine movement behaviours. For each patient, the compensation strategy that they may resort to with their affected leg can be different. Within the current study, it was seen that there was a significant difference between the knee flexion of the two jumping legs, which may have led to compensation strategies using hip and torso flexion when the knee flexion was limited. The hip and torso RoF were not found to differ significantly for the perturbance, however, although it is also not known whether the perturbation might have limited hip flexion and to what degree the arm movements may have contributed as a compensation strategy for both legs.

Based on the proof of concept in this study, the physiotherapists saw added value in evaluating the designed system and setup with ACL-rehabilitating patients. They were, furthermore, interested in tracking the flexion of the three selected segments over the course of an ACL rehabilitation to determine whether the affected leg can behave more similarly to the unaffected leg.

> "*The swing legs can be very interesting, but we would have to test that with ACL patients. If they would also show these patterns, that would be very interesting.*" - Physiotherapist PT03.
>
> "*If ACL patients would show strong differences in swing leg behaviour compared to the normal population and we could track this towards a higher risk of re-injury over time, then that would be a parameter that has not yet been considered as relevant to ACL rehabilitation.*" - Physiotherapist PT01.

Regarding the influence of the VR and VR game compared to the real-world condition (see the trends of the interaction condition in Figure 15), the physiotherapists hypothesised that the VR alone might give some hesitance to the participants, which could make their jumping movements a little uncertain and stiffer, whereas the addition of the game elements could shift their attention or remove their fear of movement, thus changing their movement behaviour again.

As for additional considerations regarding the system made during the focus groups, the addition of the controllers was considered by the physiotherapists to possibly give a false feeling of security, as it can allow for better sideways balancing (similar to a tightrope walker with a pole). While very light, the tactile sensation of the controller may provide this additional balance to the participants during the jump.

Furthermore, the effect of the tape perturbation was still considered to give a relevant simulation of the ACL-affected leg when reviewing the outcomes. While for some participants the effect of stiffness may have been stronger than what would be seen in a rehabilitation patient (such as for P04), the perturbation provided a good proof of concept that differences between the jumping leg kinematics can be identified with this method. An issue that occurred during testing was that the tape got looser throughout the testing, which was decided to not be re-done or adapted throughout the session to avoid tampering with the perturbation (but rather be corrected for in the statistical analysis by determining whether differences occurred over the trial number, see subsection 5.7.1). This was also considered to be the right procedure by the physiotherapists, as continuously changing the tape would continuously manipulate the perturbation and affect the participant's focus on their movement.

Interestingly, while the smaller jumps were not considered to be qualitatively valuable by the physiotherapists based on the video data analysis by appearing too simple, the outcomes of the data analysis that showed the significant difference between the two legs led the physiotherapist consider the use of creating specific targets as a unique benefit of the VR that has not yet been applied in practice.

In general, the physiotherapists indicated that the designed system has a lot of potential and serves as a proof of concept to continue testing in patients. The physiotherapists were positive about the ability of participants to walk, run and jump easily in the VR environment and that participants were positive about the interaction. For the setting itself, especially the ability to control the exact conditions in which a patient would do a task was considered valuable and would allow for the specific evaluation of relevant segments or parameters, or to coerce them into showing their movement behaviours. Furthermore, the VR setting itself can be adapted to a patient's sports context, which could let a patient return to a virtual setting of their sport to be evaluated on their ability to engage with the elements of their sport in the VR. The chosen measures of knee, hip and torso flexion are relevant factors to ACL rehabilitation and connect well with the chosen sensor setup. It should, however, still be considered whether similar trends can be found in ACL rehabilitating patients as were found in this study. In this study, there was an external perturbation, for which participants were not given time to get used to, whereas an ACL patient would have an internal perturbation that they also already had time to relearn their movements with their altered biomechanics and coordination.

"The current single-leg jump tests are essentially a minimal requirement that someone has to meet in order to RTS, but right now we still see a lot of patients come back with re-injuries, so these tests might not tell us enough to determine whether a patient is ready or not to return to sport. There have been publications showing that when you disturb patients who already have a good enough LSI to return, for instance by letting them do a jump with a turn, you suddenly see differences between the affected and unaffected leg again. So something unpredictable removes the learning effect that they have gained with the single-leg jump throughout their rehabilitation. The cognitive aspect of rehabilitation is only added when they start building up their sports training at their sports club again because before that it is hard to add them in a safe and reproducible setting. That's why I think that this VR setup could be very valuable: you can present stimuli to a patient that is similar to a sports game and repeat the same conditions over time, but it is still in the safe lab environment of our clinic and we can be around in case there are problems. So this system is a good starting point to see how we could do these tests differently and how it might affect the re-injury of patients." - Physiotherapist PT02.

"The advantage of VR for me is that we would be able to control the environment. You want to give a neurocognitive challenge to your patients by, for example, catching something mid-jump like the lavaballs in this study, but you can never exactly control the parameters like speed and delay in our current practice. You can do that in VR, and you can further translate that control to another setting, like having virtual opponents that move around the patient at a specific speed or who might pass balls with a certain unpredictability. Those are things you would do during sports training, but then there would always be a human variation that we cannot control. With this type of VR system, we could always be exact in what we are presenting to our patients and repeat our previous exercises exactly as we executed them before." - Physiotherapist PT01.

A repeated study with ACL patients was considered to be very interesting to determine how they would respond to the added perceptual-cognitive pressure and how the measured kinematics would change over the time of their rehabilitation. Aside from this population, the physiotherapists had an interest in repeating the study with elite athletes to determine how patients might relate to individuals who are able to perform under high cognitive-perceptual pressure and what parameters might be relevant in this comparison. In addition, the chosen virtual environment could be adapted to be more targeted to the sport of the patient, for example by letting a footballer be on a football field with virtual opponents around them. Finally, with this proof of concept of the standard single-leg jump, additional jumps could be considered to give more varied insights into the jumping behaviour. Particularly relevant additions were considered to be adding a rotation or a jump to the side after landing or on a cue. Since cutting movements may often result in injury, such unpredictable jumps could add neurocognitive complexity that can prevent the patient from preparing themselves and instead puts them in a task that is similar to the sports-specific context.

7
DISCUSSION AND CONCLUSION

At the beginning of this work, the following research question was posed: "*What is a design for a meaningful functional movement evaluation system based on* ***objective measurement*** *and utilising a* ***sports-specific context*** *that supports RTS decision-making in patients during an* ***anterior cruciate ligament*** *rupture rehabilitation?*". This question resulted in the two objectives of this thesis.

- **Objective 1**: to objectively evaluate the movement performance of a simulated ACL-affected leg compared to the unaffected leg in a single-leg jumping task to aid the diagnostics of physiotherapists during the RTS decision.
- **Objective 2**: to provide a rich evaluation context that allows and triggers an ACL patient to show more sport-specific behaviours and aids the physiotherapist in making a more meaningful consideration of the patient's functional movement performance during an RTS evaluation.

To evaluate these two objectives, the results of Chapter 6 are interpreted in Sections 7.1 and 7.2, after which the study limitations (Section 7.3) are presented. In Chapter 8, the practical implications of this work (Section 8.1) and an overview of possible future work (Section 8.2) are given.

7.1 OUTCOMES OF OBJECTIVE 1 – OBJECTIVELY EVALUATE SIMULATED ACL-AFFECTED MOVEMENT PERFORMANCE

This study gathered a dataset of 1482 targeted single-leg jumps on which kinematic and jump characteristic analyses were completed to determine the discriminability between the non-perturbed dominant leg and perturbed non-dominant leg. Based on these analyses, the specific features that allow for such discriminability with our chosen measurement setup can be given alongside an overview of how these outcomes might transfer to the RTS evaluation with ACL patients.

In this study, we were able to identify significant differences in the kinematics of a non-perturbed dominant and a perturbed non-dominant leg during a targeted single-leg jump. With our perturbation, a decrease in the knee RoF was found during the toe-off and during the landing. For the hip segment, the perturbation resulted in a decrease in toe-off RoF. The torso segment did not show any changes for the perturbation. Aside from the perturbation itself, it was found that, while the dominance of the leg does significantly affect the knee RoF during landing, the perturbance effect is independent of the leg dominance. This means that the findings of the VR-ACL system evaluation are not solely the result of natural differences in jumping characteristics due to leg dominance but also of the perturbation that was applied. While these initial outcomes only provide a binary distinction between the two legs (as either non-perturbed and dominant or perturbed and non-dominant), they give way to an objective functional movement assessment in which the relative outcomes of the noted kinematic features could help describe changes in the functioning of either leg at specific phases of the rehabilitation process (following the ICF format of evaluation). Our ability to identify discriminable features between a perturbed and healthy leg in this study, therefore, gives hope for finding such features that can objectively evaluate the functional movement performance of an ACL-affected leg compared to its healthy counterpart.

It should be noted, however, that the chosen perturbation in this study was not fully representative of the biomechanical and kinematic adaptations of an ACL-affected single-leg jump as found in literature. Using the sports tape perturbation, an external restriction to leg flexing was applied, whereas ACL injuries create an internal restriction due to a change in neuromuscular control (alongside cognitive effects such as fear of movement). The main effect of the external perturbation was to create a stiffer knee, which was found in the kinematic data as a decrease in knee peak flexion during the toe-off and landing. Compared to an unaffected leg, an ACL-affected leg is expected to show more knee and hip flexion during the toe-off phase, while the landing is expected to show less knee flexion but more hip and torso flexion to compensate for the stiffer knee landing [54], [58], see subsection 3.1.2. While the stiffer landing pattern of the knee observed in ACL patients was achieved with the perturbation, the characteristics during the toe-off phase and the kinematic outcomes of the hip and torso during the landing do not transfer to the known adaptations in the single-leg jump of an ACL-affected leg. The stiffer knee itself even made several participants indicate that they felt more supported in their jump, which led them to jump further (as opposed to ACL-affected legs having a typical decrease in jumping ability due to muscular diminishing in that leg). In addition, the use of VR may have further affected the overall kinematics found for the single-leg jump, as was also found for vertical drop tasks performed in VR [59], [96]. Given the differences from ACL-affected kinematics, it seems that the chosen study setup (be it in perturbation, use of VR or otherwise) may have affected the participants' reliance on hip and torso flexion to stabilise and stop their forward movement during landing in a way that differs from ACL patients. Therefore, it should still be determined which features allow for the objective evaluation of an ACL-affected leg compared to its unaffected counterpart and how the use of VR may affect the discriminability of such features.

Aside from the perturbance effect, the jumping target distance significantly affected the kinematics of the knee, hip and torso segments. For an increasing jumping distance, all three segments showed a significantly higher RoF (as well as a visual increase in peak flexion) in landing. While the dominant strategy for slowing down the landing may differ per participant, the overall trend is that all three segments are increasingly contributing to decelerating and stabilising the landing movement as the jumping distance increases.

In addition, no interaction effect was found between the perturbance and the jump type for any of the segments. The additional analysis of the knee RoF during landing for the three smallest jump types furthermore showed that the perturbance was significantly discriminatory. Therefore, jumps made at targeted distances well below the maximum jumping ability are still able to generate the kinematic data on which meaningful comparisons between the two legs can be made.

When comparing the discriminatory ability of the sensor-based targeted single-leg jumps to the standard practice of maximum jump distance LSI comparison, it can be seen that the kinematic data provides a deeper insight into the different movement functionalities of the two legs. While the kinematic data analyses of the VR-ACL system evaluation study were able to differentiate between the non-perturbed dominant and the perturbed non-dominant leg, the comparison of the single-leg distances reached between the two legs yielded mixed results. Within the VR-ACL system evaluation, no significant difference was found for the maximum distance jumped based on the perturbance. However, the jumping distance comparison from the dominance effect measurement did find a significant influence for perturbance. When considering the LSI, no condition during either measurement session resulted in an average LSI between the two legs of lower than 94% (with only a few individual participants reaching LSI outcomes below 90%). This standard method of comparison was, therefore, not able to consistently identify the affected movement caused by the perturbation that could be identified with the kinematic analyses. This deficit in the LSI measurement compared to kinematic analysis was also found for ACL patients by Kotsifaki et al. (2022) [54] and Janssen et al. (2023) [114], both of which comparing LSI evaluations with kinematic analysis on maximum single-leg jumps. Based on the results from this study, it seems that the kinematic analysis is able to identify an (artificial) perturbation in jumping behaviour on a group level, even with jumps below the maximum ability, that the LSI method does not.

The use of VR did not seem to significantly affect the validity of the single-leg jumping task. When determining the effect of the VR environment (subsection 6.2.2), no significant effects were found in the landing RoF of the knee and torso between the three interaction conditions. Interestingly, however, a non-significant trend was shown between the three interaction conditions for the landing RoF of the knee (see Figure 15), in which the RoF seems to decrease between the real-world and VR condition and increase (even above the real-world condition) for the VR condition with game elements. In addition, the single-leg jump was significantly further in the real-world compared to the VR condition, an outcome which was also reported by Cochran et al. (2021) [86] in their distance comparison between VR and real-world single-leg jumps. It was hypothesised that these results might occur due to an initial hesitancy when jumping within the VR as compared to the real-world setting, which would lead to a more unsure and stiffer jumping landing. When adding game elements to the interaction condition, a shift in focus on these elements might remove the hesitancy and result in a higher landing RoF. This hypothesis seems to be further supported by the results of the jump hesitancy, timing and lavaball accuracy analyses (Section 6.6). Here, a decrease in playing time and an improvement in lavaball hit accuracy were found for increased gameplay, showing improvement in the game performance over time. A decrease in jumping accuracy found over the round times may further highlight that participants became less focused on successfully completing the jumping task. Combined with the participant experiences, these results seem to indicate that participants became more drawn to the game and focused strongly on the competitive elements it provided. By using the VR gaming elements, participants may have shifted their focus away from the jumping task and fully onto the gamification, which diminished jumping hesitancy and created higher perceptual-cognitive pressure during the jumping task.

Summary of outcomes - Objective 1

The sensor measurement and subsequent kinematic analyses utilised in this study allow for an in-depth evaluation of the jumping behaviours of the knee, which can provide an objective comparison of the performance of a perturbed non-dominant leg with its unaffected counterpart. The chosen perturbation was not found to be fully representative of the ACL-affected jumping performance (both in kinematics and LSI), but the analyses used were suitably discriminatory for the given methodology. The targeted jump distances all contributed to the overall kinematic comparison and were able to provide a stronger discriminatory ability as compared to the LSI method. The single-leg jumping task was furthermore not altered in its validity by the use of VR, while the use of game elements seems to decrease the hesitancy participants may show when performing jump tasks in VR. Future research is needed to determine how the outcomes of this study translate to the ACL-affected functional movement evaluation.

7.2 OUTCOMES OF OBJECTIVE 2 – PROVIDING A RICH SPORT-SPECIFIC CONTEXT FOR RTS EVALUATION

As a part of creating a sport-specific context, it was found from this study that participants were able to interact comfortably and easily with the VR game and perform the single-leg jumping tasks presented to them during the interaction, without knowing where they would land in the physical world. All participants were able to complete the interaction without any safety-related issues. Only one participant experienced some disorientation in the VR setting due to a software crash, no other instances of disorientation or cybersickness were observed. Moreover, throughout the interaction, participants frequently showed complex movements such as dodging lavaballs, running, moving backwards and making turns and pivoting movements. While vertical drop tasks have been previously integrated within VR environments for various studies (see [59], [96], [98], [99]), this study is, to the best of our knowledge, the first which has evaluated participant willingness to perform a horizontal single-leg jump within a (dual-task) gamified VR environment and in which their movement has been externally perturbed. While the safety risks were mitigated by using a virtual guardian and a soft physical boundary, this study does show a willingness of participants to perform a horizontal jump task without awareness of the physical world. None of the participants noted feeling unsafe throughout the interaction due to their ability to see whether the jump target was within the virtual guardian, while some preferred to walk to each jumping plane rather than run. Based on the participants' experiences and behaviours, a willingness was found to perform targeted single-leg jumps with increased perceptual-cognitive pressure and while adapting their jumping strategy to the provided perturbation.

Within the interaction, participants were drawn into the virtual environment and their focus was shifted from the jumping task to the VR effects. This was found both in the competitive behaviours shown by participants as well as their post-session survey and interviews. As was also described for objective 1, participants seemed to improve at performing the game throughout the interaction. This was also noted by the participants themselves, who frequently described feeling more secure within the VR after gaining some initial experience. Participants also indicated to lose track of time during the interaction and were often actively trying to beat their previous game times. The VR environment was able to distract the participants from the movement task and trigger single-leg jumps while keeping an external focus. This points towards the VR being able to provide a more sport-specific context for the jumping task.

Aside from the behaviours that were shown, the post-evaluation survey showed a high engagement with the virtual environment and the presented tasks. Especially noteworthy are the high scores of enjoyment, the willingness to recommend the experience to their friends and the wish for the VR experience to have continued. The overall participant experiences from the test sessions show that the study population was positively engaged in the virtual environment and the jumping and game tasks as they were provided to them. Because the VR game was found to be challenging and interesting, it may, therefore, be considered more sport-specific (and therefore more ecologically valid [52]) in nature compared to the standard practice.

Throughout the interaction, no significant effects of self-perceived fatigue were noted. The Borg scores showed an increase over the rounds played but did not become higher than 5. After completing the session, the majority indicated that they were more but not exceedingly mentally or physically tired. However, while the Borg scores were all below the limit of fatiguing effects to appear, the perceived fatigueness was found to be a significant predictor of knee RoF increase during landing. In addition, the increasing trial number was shown to increase the knee RoF during toe-off and the perceived fatigueness scores decreased the torso RoF during toe-off. These effects indicate that the duration of the session did affect the jumping performance.

As a second part of this objective, it was found that physiotherapists were able to meaningfully interpret the behaviours and kinematic data output from this study within a diagnostic context. Based on the qualitative and quantitative data gathered in this study, the physiotherapists were able to understand how the functional movement evaluation in the interaction would relate to and the role this system might take in the current practice of RTS evaluation. Within the video data of the participants, the physiotherapists were able to see the sport-specificity of the movements that the VR game triggered, which were frequently related to training and sports game scenarios. Especially the use of the dual-task allowed the physiotherapists to see sport-specific behaviours appear and give a deeper insight into the movement patterns. The game interaction allowed the physiotherapist to evaluate more jumps, both in video and in data, to highlight trends and characteristics, which often sparked discussions on whether these were indicative of the perturbation (and how such characteristics might transfer to the ACL patient). The quantitative data presented to the physiotherapists provided physiotherapists with a higher dimensionality of viewing the jumping movement as opposed to their current practice. While the data could not be directly translated onto an ACL patient's profile, the ability to measure differences within this study methodology did provide the physiotherapists with a good sense of what the data outcomes of their patients could be and how this might be analysed over time and compared to a normal population or a normal progression of ACL rehabilitation. The use of this sensor and gamified system might provide insights into the risks of re-injury as well as possible gains that could still be achieved with further rehabilitation. The chosen segments and focus points in the kinematic data were found to be individually relevant for the RTS diagnosis of an ACL patient but especially valuable when considered as a whole. The physiotherapists furthermore indicated that this system would be beneficial to create personalised and reproducible evaluation contexts for ACL patients within a safe setting. The use of VR was considered to give a higher ecological validity to the jumping task which could help physiotherapists give more meaningful insights into the movement performance of an ACL patient at the RTS evaluation.

Summary of outcomes - Objective 2

The study design was able to provide a rich context in which participants were able to make the single-leg jump movements while displaying more sport-specific behaviours. Participants showed a willingness to make such movements and indicated a focus on the game elements over the jumping tasks, as well as overall enjoyment of the interaction. The physiotherapists were able to interpret the data and provide meaningful considerations to the presented qualitative and quantitative outcomes as they related to the chosen perturbation. Through this initial proof-of-concept, a gamified rich environment was created that can trigger participants to perform the single-leg jump task in a more holistic, ecologically valid way for a more meaningful functional movement evaluation.

7.3 STUDY LIMITATIONS

Through testing, different issues were noted for the system. Where possible, small issues were resolved in between testing sessions, but larger issues are reported here for future development.

As a logistical issue, the available testing location was smaller than what was intended during development. Initially, there was no restriction made for letting jumping planes spawn within the available physical space. Participants had to, therefore, work with the virtual guardian and teleportation functionality to see whether or not they were able to make a jump within the physical space. Three participants (P06, P07 and P17) ended up jumping against the physical boundary but all indicated afterwards that they had seen the virtual guardian before making the jump but that they were so immersed in the game that they willingly jumped against the barrier. Participant P07 noted afterwards "*I saw that I was nearing the guardian and that I had to jump out of it to get to the target, but I just wanted to make the jump*", and participant P17 indicated that he had wanted to make the jump to "*not lose my precious time*".

A second issue relating to location is that, while the system was designed to let its jumping planes always appear right in front of the participant, this feature malfunctioned due to an apparent disconnect in orientation between the HMD and the virtual camera rig on which the spawning location was based. Therefore, planes appeared somewhat more randomly (albeit still rotated towards the participant) and could, on occasion, spawn outside of the virtual playing field or under virtual objects, thus making them inaccessible to participants without teleportation and, where needed, back-end interventions. While participants were instructed to limit their use of the teleportation feature, it became commonly used in the interaction. The planes being spawned more randomly than designed was not considered bothersome by participants, with participant P06 indicating that "*the jumping planes appearing everywhere rather than just in front of you seems to be more a feature than a bug, it is actually more fun that you have to constantly look for them in the game and to have to be on the lookout*.".

One significant issue that occurred within the data gathering was that several MVN recordings crashed, became corrupted or stopped midway through the measurement. While a complete crash of the MVN Record software only occurred for three participants and was quickly resolved with a restart and recalibration, corrupted files could only be identified after the measurement and could not in all cases be replaced with new measurements. In addition, the continued use of MVN within the virtual environment led to a shift of the virtual legs relative to the HMD position. When this became inconvenient to the participant, the interaction was paused and the axes of the MVN and the virtual environment were reset (as was also done between each round). For a few participants, the issues persisted and required recalibrations.

In general, the hardware attached to the participants did not cause major issues or delays. Depending on their clothing choice, the sensors occasionally slid down for some participants, which led to a stop and recalibration, during which the participant was kept, if possible, in the VR environment through Oculus' passthrough functionality. For one participant, the HMD fell off after the first jump in the interaction, which was the only occurrence of this issue. Other participants remarked that the HMD was quite warm, but most did not note any issues with the added weight around their heads or with having to hold the controllers throughout the interaction. The sports tape stayed on for all participants, although some noted that it stretched out as the interaction continued and that it may not have been as effective at the end as at the start.

With regard to the study methodology, additional limitations can be identified. First, the chosen recruitment technique (convenience sample and snowballing at a technical university) likely resulted in a population with a higher-than-average affinity with technology, which may not resemble the attitude of an ACL population. This was partly mitigated by the observation moments and focus groups at the OCON Orthopaedic Centre as well as the patient participant interviews and system walk-throughs, but should be considered for future development. Additional social desirability effects should be considered when evaluating the participant experiences and were, where possible, mitigated by welcoming all feedback from the participants.

8
PRACTICAL IMPLICATIONS AND FUTURE WORK

Within this study, we have created and analysed a system that combines objective measurement of the functional movement during single-leg jumps of specified target distances with a rich VR-based evaluation context. The resulting design incorporated a sensor setup within a gamified VR environment that triggered healthy participants to make sport-specific movements and provided kinematic data to determine which parameters would allow for a distinction between a non-perturbed dominant and a perturbed non-dominant leg. This study methodology and setup were used as a proof-of-concept for the use of sensor-integrated VR gamification within the single-leg jump within the context of RTS evaluations for ACL patients.

8.1 PRACTICAL IMPLICATIONS OF THIS WORK

This study served as a proof-of-concept of improving the RTS evaluation through the use of healthy and perturbed participants. While the results of this study cannot be translated directly to ACL patients, this study was able to take a first step towards the development of an objective movement analysis method in a sport-specific context for this population. Given the outcomes of this study, two main recommendations for the consideration of physiotherapists and future research in this field can be put forward.

1. The use of sensor-based measurements of knee stability during smaller, targeted single-leg jumps may be preferred over the standard practice of LSI measurements for maximum distance single-leg jumps in ACL rehabilitation.

While this study does not provide direct evidence for kinematic differences occurring in shorter single-leg jumps for the ACL patient population, its outcomes for the perturbed participants do give hope that kinematic features with discriminatory ability may be found in short-distance jumps for this purpose. The use of sensor measurement of such shorter interval jumps could provide a new and beneficial method of determining the functional movement performance of an affected leg compared to the unaffected leg over the standard practice of single-leg jumps for distance. By relying on multiple smaller jumps, a larger dataset can be used to find trends within the jumping characteristics without overfatiguing the patient and while utilising external focus for a more sport-specific movement. This could provide deeper and more varied insights into the jumping performance. In addition, by relying on kinematic evaluations of LSI, patients would not be able to (subconsciously) affect their RTS outcomes by adjusting their unaffected leg's performance to their affected leg. Finally, as was also considered by Janssen et al. (2023) [114], all jumps in the test battery could be considered for a more holistic consideration of the jump performance, rather than the current practice which evaluates only the distance achieved with the best jump (and often neglects characteristics of the failed jumps).

An additional outcome from the sensor-based study methodology that may merit consideration for practice is the inclusion of the swinging leg behaviours in the functional movement test. Based on the current study, the swinging leg shows different behaviours between the non-perturbed dominant and the perturbed dominant leg. While it is uncertain whether this is the result of the chosen (external) perturbation and how these results may translate to ACL patients, the behaviour of the swinging leg as a possible force-generating or balancing strategy might be considered to be studied as an indicator for re-injury risks.

2. The use of VR can provide a more ecologically valid, controlled and interesting evaluation context for the RTS functional movement test of ACL patients.

Within this study, positive effects and experiences were found using VR and an initial proof-of-concept was given for its safe and effective use with healthy but externally perturbed participants. The use of VR allows for controlled and reproducible stimuli to be presented to a patient of which responses can be monitored and compared over time. Individual progress in the rehabilitation can be tracked, which might (based on initial patient input) increase confidence in movement and reduce frustration. By using a VR setup, the environment and scenario in which a functional movement test is done can be further tailored to the patient and their sport-specific needs. The perceptual-cognitive pressure of the VR environment can, therefore, match what a patient will encounter after returning to their sport while still in the safe physical testing environment of their physiotherapy clinic.

To conclude, the potential of this thesis is to create a more meaningful and objective evaluation of the functional movement test of an ACL patient, taking their sport-specific context and individual jumping strategy into consideration. The resulting system allows for providing an objective and deeper insight into the jumping movement performance for physiotherapists and can create a patient-specific evaluation context that simulates the perceptual-cognitive pressure of their sport-specific context with controlled, targeted and reproducible stimuli.

8.2 FUTURE WORK

As future work for this study, additional research, design and evaluations can be considered. As the most important recommendation, the current study should be repeated with ACL patients to determine whether the objectives of the system can still be met with the target population. For this, both the patient experiences and willingness to move in VR as well as the meaningfulness of the kinematic outcomes need to be re-evaluated with this population. The safe use of the VR environment for this patient population was shown and evaluated within the context of this study. As a part of this future research, the validity of the MVN sensors for their use in this system (which was considered valid and appropriate for evaluating ACL-affected functional movement but which still requires careful consideration of the outcomes [52]) should be determined. Such validation was not within the scope of this work but should be considered in order to provide certainty to the objective outcomes of this method. To interpret the quantitative outcomes of ACL patients with this system, additional measurements with a normal population or a population of elite athletes may be utilised to further highlight how specific parameters and characteristics within the kinematic data can indicate risks of re-injury or high adaptability to a sports context. Additional analysis methods for the kinematic data, such as machine learning or statistical parameter mapping may be further considered to provide depth and meaningfulness to the outcomes. Finally, additional parameters, such as arm waving after landing or swing leg behaviour, could be considered to give a more in-depth analysis of relevant (compensatory) movements.

With regard to the continued design of the VR game, several main considerations can be made. First, the virtual environment can be changed from a generic multi-purpose setting (the volcanic adventure style used in this study) to a sport-specific setting. This would allow patients to receive similar stimuli as they would encounter after returning to their sport but would require a targeted evaluation by ACL patients of that sport. Possible game elements that could be used to facilitate this sport-specific dual-tasks and stimulation could be the use of virtual opponents; adding ball catching or ball throwing movements; adding game artefacts like bats, rackets or hockey sticks; and using bystanders or audience with audio or visual distractions. The use of cognitive load may warrant evaluation upon continued development, see for example the guidelines of Skulmowski et al. (2023) [112].

A second consideration is to integrate more sport-specific and complex movements in the game, such as sideways jumps, cross-over or triple hops, jumps with a vertical component, turns or other dual-tasks. Especially the use of vertical jumps is frequently utilised in RTS test batteries to create a more biomechanically demanding task and increase evaluation test-retest reliability [41], [128], [129]. However, while previously applied in a drop-down task in VR [59], incorporation of such tasks within a gamified VR setting may give difficulties as it would likely require the use of objects in the real world. While possible with a mixed reality setup or a virtual object to jump over, this should be considered in terms of safety. A further increase in perceptual-cognitive pressure could be to give the landing target location after getting ready to jump (thus making the jumping leg and target distance unpredictable until the moment of the jump start). Especially when presented unexpectedly, a patient would have to rely on their movement ability to perform the jumping task correctly, thus being an interesting evaluation method for RTS.

Thirdly, the use of meaningful feedback to correct patients when not completing the jumping tasks correctly may be considered (see Appendix B.4.3). For this, additional modalities could be utilised, such as providing sound cues. As the safe use of the VR system was shown, the use of sound could also be further applied to provide additional stimuli, such as for the spawning of jumping planes and lavaballs.

Finally, the ability of the system to adapt to the performance of a patient throughout the interaction could be beneficial. By automatically adapting task difficulty or perceptual-cognitive pressure, the familiarisation effects of VR may be mitigated and frustration or fatiguing effects could be avoided. Systematic and incrementally changing variables could have coaxing effects that could give a better understanding of patient performance.

[1] Lam, M. H., Fong, D. T., Yung, P. S., Ho, E. P., Chan, W.-Y., and Chan, K.-M., "Knee stability assessment on anterior cruciate ligament injury: Clinical and biomechanical approaches," *BMC Sports Science, Medicine and Rehabilitation*, vol. 1, no. 1, p. 20, Dec. 2009, ISSN: 2052-1847. DOI: 10.1186/1758-2555-1-20. [Online]. Available: https://bmcsportsscimedrehabil.biomedcentral.com/articles/10.1186/1758-2555-1-20.

[2] Van Melick, N., Hullegie, W., Brooijmans, F., *et al.*, "Revalidatie na voorste- kruisbandreconstructie KNGF Evidence Statement," Koninklijk Nederlands Genootschap voor Fysiotherapie, Tech. Rep., 2019. [Online]. Available: www.kngf.nl/kennisplatform..

[3] Della Villa, F., Buckthorpe, M., Grassi, A., *et al.*, "Systematic video analysis of ACL injuries in professional male football (soccer): injury mechanisms, situational patterns and biomechanics study on 134 consecutive cases.," *British journal of sports medicine*, vol. 54, no. 23, pp. 1423–1432, Dec. 2020, ISSN: 1473-0480. DOI: 10.1136/bjsports-2019-101247. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/32561515.

[4] Marieb, E. N. and Hoehn, K., "Covering, Support, and Movement of the Body," in *Human Anatomy & Physiology*, Beauparlant, S., Ed., 10th ed., Pearson Education Limited, 2016, ch. 8, pp. 271–297, ISBN: 978-1-292-10042-5.

[5] Platzer, W., "Onderste extermiteit," in *Sesam Atlas van de anatomie deel 1 - Bewegingsapparaat*, 1st ed., ThiemeMeulenhoff, 2015, pp. 185–280, ISBN: 9789006951981.

[6] Schoenfeld, B. J., "Squatting Kinematics and Kinetics and Their Application to Exercise Performance," *Journal of Strength and Conditioning Research*, vol. 24, no. 12, pp. 3497–3506, Dec. 2010, ISSN: 1064-8011. DOI: 10.1519/JSC.0b013e3181bac2d7. [Online]. Available: https://journals.lww.com/00124278-201012000-00040.

[7] Zeng, C., Lei, G., Gao, S., and Luo, W., "Methods and devices for graft fixation in anterior cruciate ligament reconstruction," *Cochrane Database of Systematic Reviews*, vol. 2018, no. 6, Jun. 2018, ISSN: 14651858. DOI: 10.1002/14651858.CD010730.pub2. [Online]. Available: https://doi.wiley.com/10.1002/14651858.CD010730.pub2.

[8] Boden, B. P., Sheehan, F. T., Torg, J. S., and Hewett, T. E., "Noncontact anterior cruciate ligament injuries: mechanisms and risk factors.," *The Journal of the American Academy of Orthopaedic Surgeons*, vol. 18, no. 9, pp. 520–7, Sep. 2010, ISSN: 1067-151X. DOI: 10.5435/00124635-201009000-00003. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/20810933%20http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC3625971.

[9] Shelburne, K. B., Torry, M. R., and Pandy, M. G., "Contributions of muscles, ligaments, and the ground-reaction force to tibiofemoral joint loading during normal gait," *Journal of Orthopaedic Research*, vol. 24, no. 10, pp. 1983–1990, Oct. 2006, ISSN: 0736-0266. DOI: 10.1002/jor.20255. [Online]. Available: https://onlinelibrary.wiley.com/doi/10.1002/jor.20255.

[10] Palmitier, R. A., An, K.-N., Scott, S. G., and Chao, E. Y., "Kinetic Chain Exercise in Knee Rehabilitation," *Sports Medicine*, vol. 11, no. 6, pp. 402–413, Jun. 1991, ISSN: 0112-1642. DOI: 10.2165/00007256-199111060-00005. [Online]. Available: http://link.springer.com/10.2165/00007256-199111060-00005.

[11] Georgoulis, A. D., Moraiti, C., Ristanis, S., and Stergiou, N., "A novel approach to measure variability in the anterior cruciate ligament deficient knee during walking: the use of the approximate entropy in orthopaedics.," *Journal of clinical monitoring and computing*, vol. 20, no. 1, pp. 11–8, Feb. 2006, ISSN: 1387-1307. DOI: 10.1007/s10877-006-1032-7. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/16523229.

[12] Decker, L. M., Moraiti, C., Stergiou, N., and Georgoulis, A. D., "New insights into anterior cruciate ligament deficiency and reconstruction through the assessment of knee kinematic variability in terms of nonlinear dynamics.," *Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA*, vol. 19, no. 10, pp. 1620–33, Oct. 2011, ISSN: 1433-7347. DOI: 10.1007/s00167-011-1484-2. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/21445594.

[13] Paterno, M. V., "Incidence and Predictors of Second Anterior Cruciate Ligament Injury After Primary Reconstruction and Return to Sport.," *Journal of athletic training*, vol. 50, no. 10, pp. 1097–9, Oct. 2015, ISSN: 1938-162X. DOI: 10.4085/1062-6050-50.10.07. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/26509777%20http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC4641548.

[14] Ng, A. W. H., Griffith, J. F., Hung, E. H. Y., Law, K. Y., and Yung, P. S. H., "MRI diagnosis of ACL bundle tears: value of oblique axial imaging," *Skeletal Radiology*, vol. 42, no. 2, pp. 209–217, Feb. 2013, ISSN: 0364-2348. DOI: 10.1007/s00256-012-1372-y. [Online]. Available: http://link.springer.com/10.1007/s00256-012-1372-y.

[15] Zhang, Y., Liu, G., and Xie, S. Q., "Biomechanical simulation of anterior cruciate ligament strain for sports injury prevention," *Computers in Biology and Medicine*, vol. 41, no. 3, pp. 159–163, Mar. 2011, ISSN: 0010-4825. DOI: 10.1016/J.COMPBIOMED.2011.01.006. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0010482511000151?casa_token=MiXHGVymhOoAAAAA:S8EScZqVX2szdvXTET7CnRb-IMffF0mjk6ArMEVnvLO2nHEGPdeBjW0ptu6-P-limDovOB4Wn7U.

[16] LaBella, C. R., Hennrikus, W., and Hewett, T. E., "Anterior Cruciate Ligament Injuries: Diagnosis, Treatment, and Prevention," *Pediatrics*, vol. 133, no. 5, pp. 1437–1450, 2014. DOI: 10.1542/peds.2014-0623. [Online]. Available: www.pediatrics.org/cgi/doi/10.1542/peds.2014-0623.

[17] Andriolo, L., Filardo, G., Kon, E., *et al.*, "Revision anterior cruciate ligament reconstruction: clinical outcome and evidence for return to sport," *Knee Surgery, Sports Traumatology, Arthroscopy*, vol. 23, no. 10, pp. 2825–2845, Oct. 2015, ISSN: 0942-2056. DOI: 10.1007/s00167-015-3702-9. [Online]. Available: http://link.springer.com/10.1007/s00167-015-3702-9.

[18] Kline, P. W., Burnham, J., Yonz, M., Johnson, D., Ireland, M. L., and Noehren, B., "Hip external rotation strength predicts hop performance after anterior cruciate ligament reconstruction.," *Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA*, vol. 26, no. 4, pp. 1137–1144, Apr. 2018, ISSN: 1433-7347. DOI: 10.1007/s00167-

017-4534-6. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/28378137%20http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC5628096.

[19] Feller, J. and Webster, K. E., "Return to sport following anterior cruciate ligament reconstruction.," *International orthopaedics*, vol. 37, no. 2, pp. 285–90, Feb. 2013, ISSN: 1432-5195. DOI: 10.1007/s00264-012-1690-7. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/23138966%20http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC3560893.

[20] Sadigursky, D., Braid, J. A., De Lira, D. N. L., Machado, B. A. B., Carneiro, R. J. F., and Colavolpe, P. O., "The FIFA 11+ injury prevention program for soccer players: a systematic review," *BMC Sports Science, Medicine and Rehabilitation*, vol. 9, no. 1, p. 18, Dec. 2017, ISSN: 2052-1847. DOI: 10.1186/s13102-017-0083-z. [Online]. Available: https://bmcsportsscimedrehabil.biomedcentral.com/articles/10.1186/s13102-017-0083-z.

[21] Paterno, M. V., Rauh, M. J., Schmitt, L. C., Ford, K. R., and Hewett, T. E., "Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport.," *Clinical journal of sport medicine : official journal of the Canadian Academy of Sport Medicine*, vol. 22, no. 2, pp. 116–21, Mar. 2012, ISSN: 1536-3724. DOI: 10.1097/JSM.0b013e318246ef9e. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/22343967%20http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC4168893.

[22] Melick, N. van, Rijn, L. van, Nijhuis-van der Sanden, M. W. G., Hoogeboom, T. J., and Cingel, R. E. H. van, "Fatigue affects quality of movement more in ACL-reconstructed soccer players than in healthy soccer players," *Knee Surgery Sports Traumatology Arthroscopy*, vol. 27, no. 2, pp. 549–555, Feb. 2019, ISSN: 0942-2056. DOI: 10.1007/s00167-018-5149-2. [Online]. Available: http://link.springer.com/10.1007/s00167-018-5149-2.

[23] Harris, J. D., Abrams, G. D., Bach, B. R., *et al.*, "Return to Sport After ACL Reconstruction," *Orthopedics*, vol. 37, no. 2, Feb. 2014, ISSN: 0147-7447. DOI: 10.3928/01477447-20140124-10. [Online]. Available: http://journals.healio.com/doi/10.3928/01477447-20140124-10.

[24] Paterno, M. V., Schmitt, L. C., Ford, K. R., *et al.*, "Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport.," *The American journal of sports medicine*, vol. 38, no. 10, pp. 1968–78, Oct. 2010, ISSN: 1552-3365. DOI: 10.1177/0363546510376053. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/20702858%20http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC4920967.

[25] Dingenen, B., Billiet, B., De Baets, L., Bellemans, J., Truijen, J., and Gokeler, A., "Rehabilitation strategies of Flemish physical therapists before and after anterior cruciate ligament reconstruction: An online survey," *Physical Therapy in Sport*, vol. 49, pp. 68–76, May 2021, ISSN: 1466-853X. DOI: 10.1016/J.PTSP.2021.02.003. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S1466853X21000316.

[26] Cheney, S., Chiaia, T. A., Mille, P. de, Boyle, C., and Ling, D., "Readiness to Return to Sport After ACL Reconstruction: A Combination of Physical and Psychological Factors," *Sports Medicine and Arthroscopy Review*, vol. 28, no. 2, pp. 66–70, Jun. 2020,

ISSN: 1062-8592. DOI: 10.1097/JSA.0000000000000263. [Online]. Available: https://journals.lww.com/10.1097/JSA.0000000000000263.

[27] Makhmalbaf, H., Moradi, A., Ganji, S., and Omidi-Kashani, F., "Accuracy of lachman and anterior drawer tests for anterior cruciate ligament injuries.," *The archives of bone and joint surgery*, vol. 1, no. 2, pp. 94–7, Dec. 2013, ISSN: 2345-4644. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/25207297%20http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC4151408.

[28] Prins, M., "The Lachman test is the most sensitive and the pivot shift the most specific test for the diagnosis of ACL rupture," *Australian Journal of Physiotherapy*, vol. 52, no. 1, p. 66, Jan. 2006, ISSN: 0004-9514. DOI: 10.1016/S0004-9514(06)70069-1. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0004951406700691.

[29] Meuffels, D., Diercks, R., Hoogeslag, R., *et al.*, "Diagnostiek bij Voorste Kruisbandletsel," *Federatie Medisch Specialisten Richtlijnendatabase*, 2018.

[30] Center for Health Statistics, N., "The ICF: An Overview Introducing the ICF," Tech. Rep. [Online]. Available: https://www.cdc.gov/nchs/data/icd/icfoverview_finalforwho10sept.pdf.

[31] Zebis, M. K., Warming, S., Pedersen, M. B., *et al.*, "Outcome Measures After ACL Injury in Pediatric Patients: A Scoping Review," *Orthopaedic Journal of Sports Medicine*, vol. 7, no. 7, p. 232 596 711 986 180, Jul. 2019. DOI: 10.1177/2325967119861803. [Online]. Available: http://journals.sagepub.com/doi/10.1177/2325967119861803.

[32] Malempati, C., Jurjans, J., Noehren, B., Ireland, M. L., and Johnson, D. L., "Current Rehabilitation Concepts for Anterior Cruciate Ligament Surgery in Athletes.," *Orthopedics*, vol. 38, no. 11, pp. 689–96, Nov. 2015, ISSN: 1938-2367. DOI: 10.3928/01477447-20151016-07. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/26558662.

[33] Doege, J., Ayres, J. M., Mackay, M. J., *et al.*, "Defining Return to Sport: A Systematic Review.," *Orthopaedic journal of sports medicine*, vol. 9, no. 7, p. 23 259 671 211 009 589, Jul. 2021, ISSN: 2325-9671. DOI: 10.1177/23259671211009589. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/34377709%20http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC8320574.

[34] Buckthorpe, M., Della Villa, F., Della Villa, S., and Roi, G. S., "On-field Rehabilitation Part 1: 4 Pillars of High-Quality On-field Rehabilitation Are Restoring Movement Quality, Physical Conditioning, Restoring Sport-Specific Skills, and Progressively Developing Chronic Training Load.," *The Journal of orthopaedic and sports physical therapy*, vol. 49, no. 8, pp. 565–569, 2019, ISSN: 1938-1344. DOI: 10.2519/jospt.2019.8954. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/31291553.

[35] ——, "On-field Rehabilitation Part 2: A 5-Stage Program for the Soccer Player Focused on Linear Movements, Multidirectional Movements, Soccer-Specific Skills, Soccer-Specific Movements, and Modified Practice.," *The Journal of orthopaedic and sports physical therapy*, vol. 49, no. 8, pp. 570–575, 2019, ISSN: 1938-1344. DOI: 10.2519/jospt.2019.8952. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/31291556.

[36] Kaplan, Y. and Witvrouw, E., "When Is It Safe to Return to Sport After ACL Reconstruction? Reviewing the Criteria.," *Sports health*, vol. 11, no. 4, pp. 301–305, Jul. 2019, ISSN: 1941-0921. DOI: 10.1177/1941738119846502. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6600576/.

[37] Paterno, M. V., "Non-operative Care of the Patient with an ACL-Deficient Knee," *Current Reviews in Musculoskeletal Medicine*, vol. 10, no. 3, pp. 322–327, Sep. 2017, ISSN: 1935-973X. DOI: 10.1007/s12178-017-9431-6. [Online]. Available: http://link.springer.com/10.1007/s12178-017-9431-6.

[38] Davies, G. J., McCarty, E., Provencher, M., and Manske, R. C., "ACL Return to Sport Guidelines and Criteria," *Current Reviews in Musculoskeletal Medicine*, vol. 10, no. 3, pp. 307–314, Sep. 2017, ISSN: 1935-973X. DOI: 10.1007/s12178-017-9420-9. [Online]. Available: http://link.springer.com/10.1007/s12178-017-9420-9.

[39] Melick, N. van, Cingel, R. E. H. van, Brooijmans, F., *et al.*, "Evidence-based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus.," *British journal of sports medicine*, vol. 50, no. 24, pp. 1506–1515, Dec. 2016, ISSN: 1473-0480. DOI: 10.1136/bjsports-2015-095898. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/27539507.

[40] Gokeler, A., Welling, W., Zaffagnini, S., Seil, R., and Padua, D., "Development of a test battery to enhance safe return to sports after anterior cruciate ligament reconstruction," *Knee Surgery, Sports Traumatology, Arthroscopy*, vol. 25, no. 1, pp. 192–199, Jan. 2017, ISSN: 0942-2056. DOI: 10.1007/s00167-016-4246-3. [Online]. Available: http://link.springer.com/10.1007/s00167-016-4246-3.

[41] Gustavsson, A., Neeter, C., Thomeé, P., *et al.*, "A test battery for evaluating hop performance in patients with an ACL injury and patients who have undergone ACL reconstruction," *Knee Surgery, Sports Traumatology, Arthroscopy*, vol. 14, no. 8, pp. 778–788, Aug. 2006, ISSN: 0942-2056. DOI: 10.1007/s00167-006-0045-6. [Online]. Available: http://link.springer.com/10.1007/s00167-006-0045-6.

[42] Zaffagnini, S., Grassi, A., Serra, M., and Marcacci, M., "Return to sport after ACL reconstruction: how, when and why? A narrative review of current evidence.," *Joints*, vol. 3, no. 1, pp. 25–30, 2015, ISSN: 2282-4324. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/26151036%20http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC4469040.

[43] Schmitt, L. C., Paterno, M. V., Ford, K. R., Myer, G. D., and Hewett, T. E., "Strength Asymmetry and Landing Mechanics at Return to Sport after Anterior Cruciate Ligament Reconstruction.," *Medicine and science in sports and exercise*, vol. 47, no. 7, pp. 1426–34, Jul. 2015, ISSN: 1530-0315. DOI: 10.1249/MSS.0000000000000560. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/25373481%20http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC4418954.

[44] Scott, S. M., Perry, M. A., and Sole, G., ""Not always a straight path": patients' perspectives following anterior cruciate ligament rupture and reconstruction," *Disability and Rehabilitation*, vol. 40, no. 19, pp. 2311–2317, Sep. 2018, ISSN: 0963-8288. DOI: 10.1080/09638288.2017.1335803. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/09638288.2017.1335803.

[45] Devita, P., Hortobagyi, T., and Barrier, J., “Gait biomechanics are not normal after anterior cruciate ligament reconstruction and accelerated rehabilitation,” *Medicine & Science in Sports & Exercise*, vol. 30, no. 10, pp. 1481–1488, 1998.

[46] Samé, A., Oukhellou, L., Kong, K., and Huo, W., “Recognition of gait cycle phases using wearable sensors,” *Robotics and Autonomous Systems*, vol. 75, pp. 50–59, Jan. 2016, ISSN: 0921-8890. DOI: 10.1016/J.ROBOT.2014.10.012. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0921889014002334.

[47] Gokeler, A., Hof, A. L., Arnold, M. P., Dijkstra, P. U., Postema, K., and Otten, E., “Abnormal landing strategies after ACL reconstruction,” *Scandinavian Journal of Medicine & Science in Sports*, vol. 20, no. 1, e12–e19, Feb. 2010, ISSN: 09057188. DOI: 10.1111/j.1600-0838.2008.00873.x. [Online]. Available: https://onlinelibrary.wiley.com/doi/10.1111/j.1600-0838.2008.00873.x.

[48] Kharb, A., Saini, V., Jain, Y. K., and Dhiman, S., “A Review of Gait Cycle and its Parameters,” Tech. Rep., 2011, pp. 2230–7893. [Online]. Available: www.IJCEM.orgIJCEMwww.ijcem.org.

[49] Deneweth, J. M., Bey, M. J., McLean, S. G., Lock, T. R., Kolowich, P. A., and Tashman, S., “Tibiofemoral joint kinematics of the anterior cruciate ligament-reconstructed knee during a single-legged hop landing.,” *The American journal of sports medicine*, vol. 38, no. 9, pp. 1820–8, Sep. 2010, ISSN: 1552-3365. DOI: 10.1177/0363546510365531. [Online]. Available: http://journals.sagepub.com/doi/10.1177/0363546510365531%20http://www.ncbi.nlm.nih.gov/pubmed/20472756.

[50] Ristanis, S., Stergiou, N., Patras, K., Vasiliadis, H. S., Giakas, G., and Georgoulis, A. D., “Excessive Tibial Rotation During High-Demand Activities Is Not Restored by Anterior Cruciate Ligament Reconstruction,” *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, vol. 21, no. 11, pp. 1323–1329, Nov. 2005, ISSN: 07498063. DOI: 10.1016/j.arthro.2005.08.032. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0749806305011953.

[51] Decker, M., Torry, M., Noonan, T., Riviere, A., and Sterett, W., “Landing adaptations after ACL reconstruction,” *Medicine & Science in Sports & Exercise*, vol. 34, no. 9, pp. 1408–1413, 2002. [Online]. Available: https://journals.lww.com/acsm-msse/Fulltext/2002/09000/Landing_adaptations_after_ACL_reconstruction.2.aspx.

[52] Janssen, I., Streefkerk, A., and Linders, M., “Comparing an Inertial Sensor System to Video for ACL Injury Risk Screening,” in *ISBS Proceedings Archive*, 2019, pp. 292–295. [Online]. Available: https://commons.nmu.edu/isbs/vol37/iss1/71.

[53] Laughlin, W. A., Weinhandl, J. T., Kernozek, T. W., Cobb, S. C., Keenan, K. G., and O'Connor, K. M., “The effects of single-leg landing technique on ACL loading,” *Journal of Biomechanics*, vol. 44, no. 10, pp. 1845–1851, Jul. 2011, ISSN: 0021-9290. DOI: 10.1016/J.JBIOMECH.2011.04.010. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0021929011003150.

[54] Kotsifaki, A., Whiteley, R., Van Rossom, S., *et al.*, “Single leg hop for distance symmetry masks lower limb biomechanics: time to discuss hop distance as decision criterion for return to sport after ACL reconstruction?” *British journal of sports medicine*, vol. 56, no. 5, pp. 249–256, Mar. 2022, ISSN: 1473-0480. DOI: 10.1136/bjsports-2020-103677. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/33687928.

[55] Gokeler, A., Welling, W., Benjaminse, A., Lemmink, K., Seil, R., and Zaffagnini, S., "A critical analysis of limb symmetry indices of hop tests in athletes after anterior cruciate ligament reconstruction: A case control study.," *Orthopaedics & traumatology, surgery & research : OTSR*, vol. 103, no. 6, pp. 947–951, 2017, ISSN: 1877-0568. DOI: 10.1016/j.otsr.2017.02.015. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/28428033.

[56] Johnston, P. T., McClelland, J. A., and Webster, K. E., "Lower Limb Biomechanics During Single-Leg Landings Following Anterior Cruciate Ligament Reconstruction: A Systematic Review and Meta-Analysis," *Sports Medicine*, vol. 48, no. 9, pp. 2103–2126, Sep. 2018, ISSN: 0112-1642. DOI: 10.1007/s40279-018-0942-0. [Online]. Available: http://link.springer.com/10.1007/s40279-018-0942-0.

[57] Kotsifaki, A., Korakakis, V., Whiteley, R., Van Rossom, S., and Jonkers, I., "Measuring only hop distance during single leg hop testing is insufficient to detect deficits in knee function after ACL reconstruction: a systematic review and meta-analysis.," *British journal of sports medicine*, vol. 54, no. 3, pp. 139–153, Feb. 2020, ISSN: 1473-0480. DOI: 10.1136/bjsports-2018-099918. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/31142471.

[58] Orishimo, K. F., Kremenic, I. J., Mullaney, M. J., McHugh, M. P., and Nicholas, S. J., "Adaptations in single-leg hop biomechanics following anterior cruciate ligament reconstruction," *Knee Surgery, Sports Traumatology, Arthroscopy*, vol. 18, no. 11, pp. 1587–1593, Nov. 2010, ISSN: 0942-2056. DOI: 10.1007/s00167-010-1185-2. [Online]. Available: http://link.springer.com/10.1007/s00167-010-1185-2.

[59] Brazalovich, P., Simon, J. E., Criss, C. R., Yom, J. P., and Grooms, D. R., "The effects of virtual reality immersion on drop landing mechanics," *Sports Biomechanics*, pp. 1–17, Feb. 2022, ISSN: 1476-3141. DOI: 10.1080/14763141.2022.2035427. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/14763141.2022.2035427.

[60] Podraza, J. T. and White, S. C., "Effect of knee flexion angle on ground reaction forces, knee moments and muscle co-contraction during an impact-like deceleration landing: Implications for the non-contact mechanism of ACL injury," *The Knee*, vol. 17, no. 4, pp. 291–295, Aug. 2010, ISSN: 0968-0160. DOI: 10.1016/J.KNEE.2010.02.013. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/20303276/.

[61] Tate, J., Suckut, T., Wages, J., Lyles, H., and Perrin, B., "The Associations Between Hip Strength and Hip Kinematics During a Single Leg Hop in Recreational Athletes Post ACL Reconstruction Compared to Healthy Controls," *International journal of sports physical therapy*, vol. 12, no. 3, pp. 341–351, Jun. 2017. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/28593088%20http://www.ncbi.nlm.nih.gov/pubmed/28593088.

[62] Gokeler, A., Eppinga, P., Dijkstra, P. U., *et al.*, "Effect of fatigue on landing performance assessed with the landing error scoring system (less) in patients after ACL reconstruction. A pilot study.," *International journal of sports physical therapy*, vol. 9, no. 3, pp. 302–11, May 2014, ISSN: 2159-2896. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/24944848%20http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC4060307.

[63] Huis 't Veld, R., Hoven, C. van den, Maartens, E., *et al.*, "The Influence of Sport-Specific Fatigue on Neuromuscular Activation and Joint Angles in ACL Reconstructed Knees," *Medicine & Science in Sports & Exercise*, vol. 48, p. 336, May 2016, ISSN: 0195-9131. DOI: 10.1249/01.mss.0000486018.00698.34. [Online]. Available: http://journals.lww.com/00005768-201605001-01012.

[64] Thomas, A. C., Lepley, L. K., Wojtys, E. M., McLean, S. G., and Palmieri-Smith, R. M., "Effects of Neuromuscular Fatigue on Quadriceps Strength and Activation and Knee Biomechanics in Individuals Post–Anterior Cruciate Ligament Reconstruction and Healthy Adults," *Journal of Orthopaedic & Sports Physical Therapy*, vol. 45, no. 12, pp. 1042–1050, Dec. 2015, ISSN: 0190-6011. DOI: 10.2519/jospt.2015.5785. [Online]. Available: http://www.jospt.org/doi/10.2519/jospt.2015.5785.

[65] Chappell, J. D., Herman, D. C., Knight, B. S., Kirkendall, D. T., Garrett, W. E., and Yu, B., "Effect of Fatigue on Knee Kinetics and Kinematics in Stop-Jump Tasks," *The American Journal of Sports Medicine*, vol. 33, no. 7, pp. 1022–1029, Jul. 2005, ISSN: 0363-5465. DOI: 10.1177/0363546504273047. [Online]. Available: http://journals.sagepub.com/doi/10.1177/0363546504273047.

[66] Marotta, L., Buurke, J. H., Beijnum, B.-J. F. van, Stoel, M., and Reenalda, J., "Identification Of Physical Fatigue In Interval Training: A Machine Learning Approach," *Medicine & Science in Sports & Exercise*, vol. 54, no. 9S, pp. 6–6, Sep. 2022, ISSN: 1530-0315. DOI: 10.1249/01.mss.0000875120.01654.33. [Online]. Available: https://journals.lww.com/10.1249/01.mss.0000875120.01654.33.

[67] Borg, G. A., "Psychophysical bases of perceived exertion.," *Medicine and science in sports and exercise*, vol. 14, no. 5, pp. 377–81, 1982, ISSN: 0195-9131. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/7154893.

[68] Delden, R. W. van, Janssen, J., Ter Stal, S., and Deenik, W., *Personalization of Gait Rehabilitation Games on a Pressure Sensitive Interactive LED Floor*, 2016. [Online]. Available: https://www.researchgate.net/publication/301289010_Personalization_of_Gait_Rehabilitation_Games_on_a_Pressure_Sensitive_Interactive_LED_Floor.

[69] Taylor, M., Goubran, R., and Knoefel, F., "Patient standing stability measurements using pressure sensitive floor sensors," in *2012 IEEE International Instrumentation and Measurement Technology Conference Proceedings*, IEEE, May 2012, pp. 1275–1279, ISBN: 978-1-4577-1772-7. DOI: 10.1109/I2MTC.2012.6229355. [Online]. Available: http://ieeexplore.ieee.org/document/6229355/.

[70] Peebles, A. T., Ford, K. R., Taylor, J. B., Hart, J. M., Sands, L. P., and Queen, R. M., "Using force sensing insoles to predict kinetic knee symmetry during a stop jump," *Journal of Biomechanics*, vol. 95, p. 109 293, Oct. 2019, ISSN: 0021-9290. DOI: 10.1016/J.JBIOMECH.2019.07.037. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/31455500/.

[71] Xu, H., Gao, L., Zhao, H., *et al.*, "Stretchable and anti-impact iontronic pressure sensor with an ultrabroad linear range for biophysical monitoring and deep learning-aided knee rehabilitation," *Microsystems & Nanoengineering*, vol. 7, no. 1, p. 92, Dec. 2021, ISSN: 2055-7434. DOI: 10.1038/s41378-021-00318-2. [Online]. Available: https://www.nature.com/articles/s41378-021-00318-2.

[72] Butt, H. T., Pancholi, M., Musahl, M., Sanchez, M. A., and Stricker, D., "Development of High Rate Wearable MIMU Tracking System Robust to Magnetic Disturbances and Body Acceleration," in Springer, Cham, 2020, pp. 1178–1198. DOI: 10.1007/978-3-030-29516-5{_}87. [Online]. Available: http://link.springer.com/10.1007/978-3-030-29516-5_87.

[73] Gustafsson, F., *Statistical Sensor Fusion*, 3rd. Studentlitteratur Ab, 2012, ISBN: 978-91-44-12724-8. [Online]. Available: https://www.studentlitteratur.se/kurslitteratur/teknik-datorer-it-och-bygg/signalbehandling/statistical-sensor-fusion-a44f04ba.

[74] Camomilla, V., Bergamini, E., Fantozzi, S., and Vannozzi, G., "Trends Supporting the In-Field Use of Wearable Inertial Sensors for Sport Performance Evaluation: A Systematic Review," *Sensors*, vol. 18, no. 3, p. 873, Mar. 2018, ISSN: 1424-8220. DOI: 10.3390/s18030873. [Online]. Available: http://www.mdpi.com/1424-8220/18/3/873.

[75] Middelaar, R. P. van, Zandbergen, M. A., Gruber, A. H., and Reenalda, J., "Shock Attenuation Wavelet Transform Of Dominant Leg During A Fatiguing Run," *Medicine & Science in Sports & Exercise*, vol. 53, no. 8S, pp. 147–148, Aug. 2021, ISSN: 1530-0315. DOI: 10.1249/01.mss.0000760832.04495.f7. [Online]. Available: https://journals.lww.com/10.1249/01.mss.0000760832.04495.f7.

[76] Haitjema, A., Marotta, L., Backx, F. J., and Reenalda, J., "Objectifying Biomechanical Parameters Related To Chronic Low Back Pain In Competitive Horseback Riders Using IMUs," *Medicine & Science in Sports & Exercise*, vol. 54, no. 9S, pp. 562–562, Sep. 2022, ISSN: 1530-0315. DOI: 10.1249/01.mss.0000882116.68363.3a. [Online]. Available: https://journals.lww.com/10.1249/01.mss.0000882116.68363.3a.

[77] Stetter, B. J., Ringhof, S., Krafft, F. C., Sell, S., and Stein, T., "Estimation of Knee Joint Forces in Sport Movements Using Wearable Sensors and Machine Learning," *Sensors*, vol. 19, no. 17, p. 3690, Aug. 2019, ISSN: 1424-8220. DOI: 10.3390/s19173690. [Online]. Available: https://www.mdpi.com/1424-8220/19/17/3690.

[78] Rawashdeh, S. A., Rafeldt, D. A., and Uhl, T. L., "Wearable IMU for Shoulder Injury Prevention in Overhead Sports.," *Sensors (Basel, Switzerland)*, vol. 16, no. 11, Nov. 2016, ISSN: 1424-8220. DOI: 10.3390/s16111847. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/27827880%20http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC5134506.

[79] Beenhakker, L., Salim, F., Postma, D., Delden, R. van, Reidsma, D., and Beijnum, B.-J. van, "How Good is Good Enough?" In *Proceedings of the 2020 International Conference on Multimodal Interaction*, New York, NY, USA: ACM, Oct. 2020, pp. 278–286, ISBN: 9781450375818. DOI: 10.1145/3382507.3418846. [Online]. Available: https://dl.acm.org/doi/10.1145/3382507.3418846.

[80] Yin, Z.-X. and Xu, H.-M., "A wearable rehabilitation game controller using IMU sensor," in *2018 IEEE International Conference on Applied System Invention (ICASI)*, IEEE, Apr. 2018, pp. 1060–1062, ISBN: 978-1-5386-4342-6. DOI: 10.1109/ICASI.2018.8394459. [Online]. Available: https://ieeexplore.ieee.org/document/8394459/.

[81] Zhao, H., Wang, Z., Qiu, S., Shen, Y., and Wang, J., "IMU-based gait analysis for rehabilitation assessment of patients with gait disorders," in *2017 4th International Conference on Systems and Informatics (ICSAI)*, IEEE, Nov. 2017, pp. 622–626, ISBN: 978-1-5386-1107-4. DOI: 10.1109/ICSAI.2017.8248364. [Online]. Available: http://ieeexplore.ieee.org/document/8248364/.

[82] Bravo-Illanes, G., Halvorson, R., Matthew, R., Lansdown, D., Ma, C., and Bajcsy, R., "IMU Sensor Fusion Algorithm for Monitoring Knee Kinematics in ACL Reconstructed Patients," in *2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, IEEE, Jul. 2019, pp. 5877–5881, ISBN: 978-1-5386-1311-5. DOI: 10.1109/EMBC.2019.8857431. [Online]. Available: https://ieeexplore.ieee.org/document/8857431/.

[83] Postma, D. B., Groeneveld, J., Van Dijk, L., *et al.*, "From Theory to Practice: Designing SportsHCI to Promote Motor Learning in Sports," in *Hamburg '23: The ACM CHI Conference on Human Factors in Computing Systems*, Hamburg, Germany: Association for Computing Machinery, 2023.

[84] Postma, D. B., Delden, R. W. van, Koekoek, J. H., *et al.*, "Sports, Data, and Interaction – Taxonomy of a Design Space of Science and Technology," 2021.

[85] Weichenberger, M., Schilling-Kästle, V., Mentz, L., Engleder, T., and Hessling, M., "A fencing robot for performance testing in elite fencers," *Sports Technology*, vol. 8, no. 3-4, pp. 95–99, Oct. 2015, ISSN: 1934-6182. DOI: 10.1080/19346182.2015.1108326. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/19346182.2015.1108326.

[86] Cochran, S. M., Aiken, C. A., Rhea, C. K., and Raisbeck, L. D., "Effects of an external focus of attention and target occlusion on performance in virtual reality," *Human Movement Science*, vol. 76, p. 102 753, Apr. 2021, ISSN: 0167-9457. DOI: 10.1016/J.HUMOV.2021.102753. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0167945721000014.

[87] Wulf, G., "Attentional focus and motor learning: a review of 15 years," 2013. DOI: 10.1080/1750984X.2012.723728. [Online]. Available: http://dx.doi.org/10.1080/1750984X.2012.723728.

[88] Bonnette, S., DiCesare, C. A., Kiefer, A. W., *et al.*, "Injury Risk Factors Integrated Into Self-Guided Real-Time Biofeedback Improves High-Risk Biomechanics," *Journal of Sport Rehabilitation*, vol. 28, no. 8, pp. 831–839, Nov. 2019, ISSN: 1056-6716. DOI: 10.1123/jsr.2017-0391. [Online]. Available: https://journals.humankinetics.com/view/journals/jsr/28/8/article-p831.xml.

[89] Damgrave, R., *Virtual Reality Mastercourse lecture handouts*, Enschede, The Netherlands, 2022.

[90] Tripathi, S., "Integration of Virtual Reality and Augmented Reality for Immersive Gaming and Learning," in *2019 2nd International Conference on Power Energy, Environment and Intelligent Control (PEEIC)*, IEEE, Oct. 2019, pp. 63–66, ISBN: 978-1-7281-1793-5. DOI: 10.1109/PEEIC47157.2019.8976608. [Online]. Available: https://ieeexplore.ieee.org/document/8976608/.

[91] Hern, A., *Meta's virtual reality project will finally have legs – literally*, Oct. 2022. [Online]. Available: https://www.theguardian.com/technology/2022/oct/12/meta-virtual-reality-legs-mark-zuckerberg-facebook.

[92] Du, Y., Kips, R., Pumarola, A., *et al.*, "Avatars Grow Legs: Generating Smooth Human Motion from Sparse Tracking Inputs with Diffusion Model," Tech. Rep. [Online]. Available: https://arxiv.org/pdf/2304.08577.pdf.

[93] Faure, C., Limballe, A., Bideau, B., and Kulpa, R., "Virtual reality to assess and train team ball sports performance: A scoping review," *Journal of Sports Sciences*, vol. 38, no. 2, pp. 192–205, Jan. 2020, ISSN: 0264-0414. DOI: 10.1080/02640414.2019.1689807. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/02640414.2019.1689807.

[94] Levin, M. F., Weiss, P. L., and Keshner, E. A., "Emergence of Virtual Reality as a Tool for Upper Limb Rehabilitation: Incorporation of Motor Control and Motor Learning Principles," *Physical Therapy*, vol. 95, no. 3, pp. 415–425, Mar. 2015, ISSN: 0031-9023. DOI: 10.2522/ptj.20130579. [Online]. Available: https://academic.oup.com/ptj/article/95/3/415/2686558.

[95] Pasco, D., "The Potential of Using Virtual Reality Technology in Physical Activity Settings," *Quest*, vol. 65, no. 4, pp. 429–441, Oct. 2013, ISSN: 0033-6297. DOI: 10.1080/00336297.2013.795906. [Online]. Available: http://www.tandfonline.com/doi/abs/10.1080/00336297.2013.795906.

[96] Gokeler, A., Bisschop, M., Myer, G. D., *et al.*, "Immersive virtual reality improves movement patterns in patients after ACL reconstruction: implications for enhanced criteria-based return-to-sport rehabilitation," *Knee Surgery, Sports Traumatology, Arthroscopy*, vol. 24, no. 7, pp. 2280–2286, Jul. 2016, ISSN: 0942-2056. DOI: 10.1007/s00167-014-3374-x. [Online]. Available: http://link.springer.com/10.1007/s00167-014-3374-x.

[97] Cannell, J., Jovic, E., Rathjen, A., *et al.*, "The efficacy of interactive, motion capture-based rehabilitation on functional outcomes in an inpatient stroke population: a randomized controlled trial.," *Clinical rehabilitation*, vol. 32, no. 2, pp. 191–200, Feb. 2018, ISSN: 1477-0873. DOI: 10.1177/0269215517720790. [Online]. Available: http://journals.sagepub.com/doi/10.1177/0269215517720790%20http://www.ncbi.nlm.nih.gov/pubmed/28719977%20http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC5777543.

[98] Cmentowski, S. and Krueger, J., "Exploring the Potential of Vertical Jump Training in Virtual Reality," in *Extended Abstracts of the 2021 Annual Symposium on Computer-Human Interaction in Play*, New York, NY, USA: ACM, Oct. 2021, pp. 179–185, ISBN: 9781450383561. DOI: 10.1145/3450337.3483503. [Online]. Available: https://dl.acm.org/doi/10.1145/3450337.3483503.

[99] Cmentowski, S., Karaosmanoglu, S., Nacke, L. E., Steinicke, F., and Krüger, J., "Never Skip Leg Day Again: Training the Lower Body with Vertical Jumps in a Virtual Reality Exergame," 2023. DOI: 10.1145/3544548.3580973. [Online]. Available: https://doi.org/10.1145/3544548.3580973.

[100] He Huang, Ingalls, T., Olson, L., Ganley, K., Rikakis, T., and Jiping He, "Interactive Multimodal Biofeedback for Task-Oriented Neural Rehabilitation," in *2005 IEEE Engineering in Medicine and Biology 27th Annual Conference*, IEEE, 2005, pp. 2547–2550, ISBN: 0-7803-8741-4. DOI: 10.1109/IEMBS.2005.1616988. [Online]. Available: http://ieeexplore.ieee.org/document/1616988/.

[101] Rausch, M., Simon, J. E., Starkey, C., and Grooms, D. R., "Smartphone virtual reality to increase clinical balance assessment responsiveness," *Physical Therapy in Sport*, vol. 32, pp. 207–211, Jul. 2018, ISSN: 1466-853X. DOI: 10.1016/J.PTSP.2018.05.017. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S1466853X17306880?via%3Dihub.

[102] Peebles, A. T., Veen, S. van der, Stamenkovic, A., France, C. R., Pidcoe, P. E., and Thomas, J. S., "A Virtual Reality Game Suite for Graded Rehabilitation in Patients With Low Back Pain and a High Fear of Movement: Within-Subject Comparative Study.," *JMIR serious games*, vol. 10, no. 1, e32027, Mar. 2022, ISSN: 2291-9279. DOI: 10.2196/32027. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/35319471%20http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC8987950.

[103] Tremmel, C. and Krusienski, D. J., "EEG Spectral Conditioning for Cognitive-state Classification in Interactive Virtual Reality," in *2019 IEEE International Conference on Systems, Man and Cybernetics (SMC)*, IEEE, Oct. 2019, pp. 2806–2811, ISBN: 978-1-7281-4569-3. DOI: 10.1109/SMC.2019.8914264. [Online]. Available: https://ieeexplore.ieee.org/document/8914264/.

[104] Gokeler, A., McKeon, P. O., and Hoch, M. C., "Shaping the Functional Task Environment in Sports Injury Rehabilitation: A Framework to Integrate Perceptual-Cognitive Training in Rehabilitation," *Athletic Training & Sports Health Care*, vol. 12, no. 6, pp. 283–292, Nov. 2020, ISSN: 1942-5864. DOI: 10.3928/19425864-20201016-01. [Online]. Available: http://journals.healio.com/doi/10.3928/19425864-20201016-01.

[105] Bolt, R., Heuvelmans, P., Benjaminse, A., Robinson, M. A., and Gokeler, A., "An ecological dynamics approach to ACL injury risk research: a current opinion," *Sports Biomechanics*, pp. 1–14, Aug. 2021, ISSN: 1476-3141. DOI: 10.1080/14763141.2021.1960419. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/14763141.2021.1960419.

[106] Gokeler, A., Grassi, A., Hoogeslag, R., *et al.*, "Return to sports after ACL injury 5 years from now: 10 things we must do," *Journal of Experimental Orthopaedics*, vol. 9, no. 1, p. 73, Jul. 2022, ISSN: 2197-1153. DOI: 10.1186/s40634-022-00514-7. [Online]. Available: https://jeo-esska.springeropen.com/articles/10.1186/s40634-022-00514-7.

[107] Zentgraf, K., Heppe, H., and Fleddermann, M.-T., "Training in interactive sports," *German Journal of Exercise and Sport Research*, vol. 47, no. 1, pp. 2–14, Mar. 2017, ISSN: 2509-3142. DOI: 10.1007/s12662-017-0441-8. [Online]. Available: http://link.springer.com/10.1007/s12662-017-0441-8.

[108] Plummer, P. and Eskes, G., "Measuring treatment effects on dual-task performance: a framework for research and clinical practice," *Frontiers in Human Neuroscience*, vol. 9, p. 225, Apr. 2015, ISSN: 1662-5161. DOI: 10.3389/fnhum.2015.00225. [Online]. Avail-

able: http://journal.frontiersin.org/article/10.3389/fnhum.2015.00225/abstract.

[109] TG, A., T, K., S, C., B, S., J, W., and W, H., "Cognitive Demands Influence Lower Extremity Mechanics During a Drop Vertical Jump Task in Female Athletes," *The Journal of orthopaedic and sports physical therapy*, vol. 48, no. 5, 2018, ISSN: 1938-1344. DOI: 10.2519/JOSPT.2018.7739. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/29320946/.

[110] Ford, K. R., Myer, G. D., Smith, R. L., Byrnes, R. N., Dopirak, S. E., and Hewett, T. E., "Use of an overhead goal alters vertical jump performance and biomechanics.," *Journal of strength and conditioning research*, vol. 19, no. 2, pp. 394–9, May 2005, ISSN: 1064-8011. DOI: 10.1519/15834.1. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/15903381.

[111] Zijlstra, F. R. H., Roe, R. A., Leonora, A. B., and Krediet, I., "Temporal factors in mental work: Effects of interrupted activities," *Journal of Occupational and Organizational Psychology*, vol. 72, no. 2, pp. 163–185, Jun. 1999, ISSN: 09631798. DOI: 10.1348/096317999166581. [Online]. Available: http://doi.wiley.com/10.1348/096317999166581.

[112] Skulmowski, A., "Guidelines for Choosing Cognitive Load Measures in Perceptually Rich Environments," *Mind, Brain, and Education*, vol. 17, no. 1, pp. 20–28, Feb. 2023, ISSN: 1751-2271. DOI: 10.1111/mbe.12342. [Online]. Available: https://onlinelibrary.wiley.com/doi/10.1111/mbe.12342.

[113] Tedesco, S., Belcastro, M., Torre, O. M., *et al.*, "A Multi-Sensors Wearable System for Remote Assessment of Physiotherapy Exercises during ACL Rehabilitation," in *2019 26th IEEE International Conference on Electronics, Circuits and Systems (ICECS)*, IEEE, Nov. 2019, pp. 237–240, ISBN: 978-1-7281-0996-1. DOI: 10.1109/ICECS46596.2019.8965214. [Online]. Available: https://ieeexplore.ieee.org/document/8965214/.

[114] Janssen, I., Hunen, M. v., and Tijssen, M., "Landing Kinematics after ACL Reconstruction; Do the Biomechanist and Physiotherapist See Different Things?" *ISBS Proceedings Archive*, vol. 41, no. 1, Jul. 2023. [Online]. Available: https://commons.nmu.edu/isbs/vol41/iss1/56.

[115] Schepers, M., Giuberti, M., and Bellusci, G., "Xsens MVN: Consistent Tracking of Human Motion Using Inertial Sensing," 2018. DOI: 10.13140/RG.2.2.22099.07205. [Online]. Available: https://www.researchgate.net/publication/324007368.

[116] Schwarz, A., Al-Haj Husain, A., Einaudi, L., *et al.*, "Reliability and Validity of a Wearable Sensing System and Online Gait Analysis Report in Persons after Stroke.," *Sensors (Basel, Switzerland)*, vol. 23, no. 2, Jan. 2023, ISSN: 1424-8220. DOI: 10.3390/s23020624. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/36679424%20http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC9862973.

[117] Zhang, J.-T., Novak, A. C., Brouwer, B., and Li, Q., "Concurrent validation of Xsens MVN measurement of lower limb joint angular kinematics," *Physiological Measurement*, vol. 34, no. 8, N63–N69, Aug. 2013, ISSN: 0967-3334. DOI: 10.1088/0967-3334/34/8/N63. [Online]. Available: https://iopscience.iop.org/article/10.1088/0967-3334/34/8/N63.

[118] Robert-Lachaine, X., Mecheri, H., Larue, C., and Plamondon, A., "Validation of inertial measurement units with an optoelectronic system for whole-body motion analysis," *Medical & Biological Engineering & Computing*, vol. 55, no. 4, pp. 609–619, Apr. 2017, ISSN: 0140-0118. DOI: 10.1007/s11517-016-1537-2. [Online]. Available: http://link.springer.com/10.1007/s11517-016-1537-2.

[119] Movella, *XSens MVN pricing*, 2022. [Online]. Available: https://www.xsens.com/news/xsens-motion-capture-pricing.

[120] *Virtual Reality Headset Market Share & Growth Report, 2030*, 2021. DOI: GVR-4-68038-030-9. [Online]. Available: https://www.grandviewresearch.com/industry-analysis/virtual-reality-vr-headset-market.

[121] Baker, A., *Getting Started with VR for Your Architecture & Design Team in 2022*, 2022. [Online]. Available: https://thewild.com/blog/architect-getting-started-with-vr.

[122] Meta, *Oculus Quest 2 pricing*, 2022. [Online]. Available: https://store.facebook.com/nl/nl/quest/products/quest-2/.

[123] Hocking, J., *Unity in Action*, 3rd. Manning, 2022, pp. 1–53, ISBN: 9781638350576.

[124] Quest-blog, M., *Building Mixed Reality with Presence Platform: A New Dimension for Work and Fun*, 2022. [Online]. Available: https://www.meta.com/nl-nl/blog/quest/building-mixed-reality-with-presence-platform-a-new-dimension-for-work-and-fun/.

[125] Lessiter, J., Freeman, J., Keogh, E., and Davidoff, J., "A Cross-Media Presence Questionnaire: The ITC-Sense of Presence Inventory," *Presence: Teleoperators and Virtual Environments*, vol. 10, no. 3, pp. 282–297, Jun. 2001, ISSN: 1054-7460. DOI: 10.1162/105474601300343612. [Online]. Available: https://direct.mit.edu/pvar/article/10/3/282-297/18311.

[126] Winter, B., "Linear models and linear mixed effects in R with linguistic applications," 2013. [Online]. Available: http://arxiv.org/pdf/1308.5499.pdf.

[127] Greenwood, M., "AICs for model selection," in Montana State University: LibreText Statistics, 2022, ch. 8. [Online]. Available: https://stats.libretexts.org/Bookshelves/Advanced_Statistics/Intermediate_Statistics_with_R_(Greenwood)/08%3A_Multiple_linear_regression/8.13%3A_AICs_for_model_selection.

[128] Cruz, A., Bell, D., McGrath, M., Blackburn, T., Padua, D., and Herman, D., "The Effects of Three Jump Landing Tasks on Kinetic and Kinematic Measures: Implications for ACL Injury Research," *Research in Sports Medicine*, vol. 21, no. 4, pp. 330–342, Oct. 2013, ISSN: 1543-8627. DOI: 10.1080/15438627.2013.825798. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/15438627.2013.825798.

[129] Kotsifaki, A., Van Rossom, S., Whiteley, R., *et al.*, "Single leg vertical jump performance identifies knee function deficits at return to sport after ACL reconstruction in male athletes.," *British journal of sports medicine*, vol. 56, no. 9, pp. 490–498, May 2022, ISSN: 1473-0480. DOI: 10.1136/bjsports-2021-104692. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/35135826%20http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC9016240.

[130] FIFA YouTube, *Anterior Drawer Test | Anterior Cruciate Ligament (ACL) Rupture*, 2019. [Online]. Available: https://www.youtube.com/watch?v=7kS4kFat-Uk.

[131] Rohman, E., Steubs, J. T., and Tompkins, M., "Changes in involved and uninvolved limb function during rehabilitation after anterior cruciate ligament reconstruction: implications for Limb Symmetry Index measures.," *The American journal of sports medicine*, vol. 43, no. 6, pp. 1391–8, Jun. 2015, ISSN: 1552-3365. DOI: 10.1177/0363546515576127. [Online]. Available: http://journals.sagepub.com/doi/10.1177/0363546515576127%20http://www.ncbi.nlm.nih.gov/pubmed/25828078.

[132] Pollen, T., *Why Distance Doesn't Tell the Full Story During Hop Testing*. [Online]. Available: https://www.physio-network.com/blog/why-distance-doesnt-tell-the-full-story-during-hop-testing/.

[133] Webster, K. E., McClelland, J. A., Palazzolo, S. E., Santamaria, L. J., and Feller, J. A., "Gender differences in the knee adduction moment after anterior cruciate ligament reconstruction surgery.," *British journal of sports medicine*, vol. 46, no. 5, pp. 355–9, Apr. 2012, ISSN: 1473-0480. DOI: 10.1136/bjsm.2010.080770. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/21508075.

[134] Clarke, S., Kenny, I., and Harrison, A., "Dynamic Knee Joint Mechanics after Anterior Cruciate Ligament Reconstruction," *Medicine & Science in Sports & Exercise*, vol. 47, no. 1, pp. 120–127, Jan. 2015. DOI: 10.1249/MSS.0000000000000389. [Online]. Available: https://journals.lww.com/00005768-201501000-00016.

[135] Hewett, T. E., Torg, J. S., and Boden, B. P., "Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism.," *British journal of sports medicine*, vol. 43, no. 6, pp. 417–22, Jun. 2009, ISSN: 1473-0480. DOI: 10.1136/bjsm.2009.059162. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/19372088%20http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC4062295.

[136] Zazulak, B. T., Dpt, †. ‡. §., Hewett, T. E., *et al.*, "Deficits in Neuromuscular Control of the Trunk Predict Knee Injury Risk A Prospective Biomechanical-Epidemiologic Study," 2007. DOI: 10.1177/0363546507301585. [Online]. Available: https://journals.sagepub.com/doi/pdf/10.1177/0363546507301585.

[137] Hewett, T. E., Myer, G. D., Ford, K. R., *et al.*, "Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study.," *The American journal of sports medicine*, vol. 33, no. 4, pp. 492–501, Apr. 2005, ISSN: 0363-5465. DOI: 10.1177/0363546504269591. [Online]. Available: http://journals.sagepub.com/doi/10.1177/0363546504269591%20http://www.ncbi.nlm.nih.gov/pubmed/15722287.

[138] Dai, B., Butler, R. J., Garrett, W. E., and Queen, R. M., "Using ground reaction force to predict knee kinetic asymmetry following anterior cruciate ligament reconstruction," *Scandinavian Journal of Medicine & Science in Sports*, vol. 24, no. 6, pp. 974–981, Dec. 2014, ISSN: 09057188. DOI: 10.1111/sms.12118. [Online]. Available: https://onlinelibrary.wiley.com/doi/10.1111/sms.12118.

[139] Fern’ndez-Baena, A., Susin, A., and Lligadas, X., “Biomechanical Validation of Upper-Body and Lower-Body Joint Movements of Kinect Motion Capture Data for Rehabilitation Treatments,” in *2012 Fourth International Conference on Intelligent Networking and Collaborative Systems*, IEEE, Sep. 2012, pp. 656–661, ISBN: 978-1-4673-2281-2. DOI: 10.1109/iNCoS.2012.66. [Online]. Available: http://ieeexplore.ieee.org/document/6338001/.

[140] Naeemabadi, M., Dinesen, B., Andersen, O. K., Najafi, S., and Hansen, J., “Evaluating Accuracy and Usability of Microsoft Kinect Sensors and Wearable Sensor for Tele Knee Rehabilitation after Knee Operation,” in *Proceedings of the 11th International Joint Conference on Biomedical Engineering Systems and Technologies*, SCITEPRESS - Science and Technology Publications, 2018, pp. 128–135, ISBN: 978-989-758-307-0. DOI: 10.5220/0006578201280135. [Online]. Available: https://www.scitepress.org/DigitalLibrary/Link.aspx?doi=10.5220/0006578201280135.

[141] PhaseSpace Motion Capture, *Impulse X2 Motion Capture Solution*. [Online]. Available: https://www.phasespace.com/impulse-motion-capture.html.

[142] Al-Amri, M., Nicholas, K., Button, K., Sparkes, V., Sheeran, L., and Davies, J., “Inertial Measurement Units for Clinical Movement Analysis: Reliability and Concurrent Validity,” *Sensors*, vol. 18, no. 3, p. 719, Feb. 2018, ISSN: 1424-8220. DOI: 10.3390/s18030719. [Online]. Available: http://www.mdpi.com/1424-8220/18/3/719.

[143] Wu, J., Sun, L., and Jafari, R., “A Wearable System for Recognizing American Sign Language in Real-Time Using IMU and Surface EMG Sensors,” *IEEE Journal of Biomedical and Health Informatics*, vol. 20, no. 5, pp. 1281–1290, Sep. 2016, ISSN: 2168-2194. DOI: 10.1109/JBHI.2016.2598302. [Online]. Available: http://ieeexplore.ieee.org/document/7552525/.

[144] Kong, W., Sessa, S., Cosentino, S., *et al.*, “Development of a real-time IMU-based motion capture system for gait rehabilitation,” in *2013 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, IEEE, Dec. 2013, pp. 2100–2105, ISBN: 978-1-4799-2744-9. DOI: 10.1109/ROBIO.2013.6739779. [Online]. Available: http://ieeexplore.ieee.org/document/6739779/.

[145] Sigrist, R., Rauter, G., Riener, R., and Wolf, P., “Augmented visual, auditory, haptic, and multimodal feedback in motor learning: A review,” *Psychonomic Bulletin & Review*, vol. 20, no. 1, pp. 21–53, Feb. 2013, ISSN: 1069-9384. DOI: 10.3758/s13423-012-0333-8. [Online]. Available: http://link.springer.com/10.3758/s13423-012-0333-8.

[146] Postma, D., Delden, R. W. van, Walinga, W., *et al.*, “Towards Smart Sports Exercises: First Designs,” in *Extended Abstracts of the Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts*, New York, NY, USA: ACM, Oct. 2019, pp. 619–630, ISBN: 9781450368711. DOI: 10.1145/3341215.3356306. [Online]. Available: https://dl.acm.org/doi/10.1145/3341215.3356306.

[147] Jensen, M. M., Rasmussen, M. K., Mueller, F. ’., and Grønbæk, K., “Designing training games for soccer,” *Interactions*, vol. 22, no. 2, pp. 36–39, Feb. 2015, ISSN: 1072-5520. DOI: 10.1145/2724582. [Online]. Available: https://dl.acm.org/doi/10.1145/2724582.

[148] Schmidt, R. A. and Wulf, G., "Augmented Concurrent Feedback Degrades Learning: Implications for Training and Simulation," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 40, no. 21, pp. 1051–1054, Oct. 1996, ISSN: 2169-5067. DOI: 10.1177/154193129604002101. [Online]. Available: http://journals.sagepub.com/doi/10.1177/154193129604002101.

[149] Israely, S. and Carmeli, E., "Error augmentation as a possible technique for improving upper extremity motor performance after a stroke - a systematic review.," *Topics in stroke rehabilitation*, vol. 23, no. 2, pp. 116–25, Apr. 2016, ISSN: 1074-9357. DOI: 10.1179/1945511915Y.0000000007. [Online]. Available: http://www.ncbi.nlm.nih.gov/pubmed/26382572.

[150] Givon-Mayo, R., Simons, E., Ohry, A., Karpin, H., Israely, S., and Carmeli, E., "A preliminary investigation of error enhancement of the velocity component in stroke patients' reaching movements," *International Journal of Therapy and Rehabilitation*, vol. 21, no. 4, pp. 160–168, Apr. 2014, ISSN: 1741-1645. DOI: 10.12968/ijtr.2014.21.4.160. [Online]. Available: http://www.magonlinelibrary.com/doi/10.12968/ijtr.2014.21.4.160.

[151] Yejun Wei, Bajaj, P., Scheidt, R., and Patton, J., "Visual Error Augmentation for Enhancing Motor Learning and Rehabilitative Relearning," in *9th International Conference on Rehabilitation Robotics, 2005. ICORR 2005.*, IEEE, pp. 505–510, ISBN: 0-7803-9003-2. DOI: 10.1109/ICORR.2005.1501152. [Online]. Available: http://ieeexplore.ieee.org/document/1501152/.

[152] Zuckerman, O. and Gal-Oz, A., "Deconstructing gamification: evaluating the effectiveness of continuous measurement, virtual rewards, and social comparison for promoting physical activity," *Personal and Ubiquitous Computing*, vol. 18, no. 7, pp. 1705–1719, Oct. 2014, ISSN: 1617-4909. DOI: 10.1007/s00779-014-0783-2. [Online]. Available: http://link.springer.com/10.1007/s00779-014-0783-2.

[153] Burke, J., McNeill, M., Charles, D., Morrow, P., Crosbie, J., and McDonough, S., "Augmented Reality Games for Upper-Limb Stroke Rehabilitation," in *2010 Second International Conference on Games and Virtual Worlds for Serious Applications*, IEEE, Mar. 2010, pp. 75–78, ISBN: 978-1-4244-6331-2. DOI: 10.1109/VS-GAMES.2010.21. [Online]. Available: http://ieeexplore.ieee.org/document/5460103/.

[154] Lange, B., Flynn, S., Proffitt, R., Chang, C.-Y., and "Skip" Rizzo, A., "Development of an Interactive Game-Based Rehabilitation Tool for Dynamic Balance Training," *Topics in Stroke Rehabilitation*, vol. 17, no. 5, pp. 345–352, Sep. 2010, ISSN: 1074-9357. DOI: 10.1310/tsr1705-345. [Online]. Available: http://www.tandfonline.com/doi/full/10.1310/tsr1705-345.

[155] Bower, K. J., Louie, J., Landesrocha, Y., Seedy, P., Gorelik, A., and Bernhardt, J., "Clinical feasibility of interactive motion-controlled games for stroke rehabilitation," *Journal of NeuroEngineering and Rehabilitation*, vol. 12, no. 1, p. 63, Dec. 2015, ISSN: 1743-0003. DOI: 10.1186/s12984-015-0057-x. [Online]. Available: http://www.jneuroengrehab.com/content/12/1/63.

[156] Alahakone, A. U. and Senanayake, A., "A real-time interactive biofeedback system for sports training and rehabilitation," DOI: 10.1243/17543371JSET52. [Online]. Available: https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1001.5398&rep=rep1&type=pdf.

[157] Tsetserukou, D., Sato, K., and Tachi, S., "ExoInterfaces: novel exosceleton haptic interfaces for virtual reality, augmented sport and rehabilitation," in *Proceedings of the 1st Augmented Human International Conference*, New York, NY, USA: ACM, Apr. 2010, pp. 1–6, ISBN: 9781605588254. DOI: 10.1145/1785455.1785456. [Online]. Available: https://dl.acm.org/doi/10.1145/1785455.1785456.

[158] Alamri, A., Cha, J., and El Saddik, A., "AR-REHAB: An Augmented Reality Framework for Poststroke-Patient Rehabilitation," *IEEE Transactions on Instrumentation and Measurement*, vol. 59, no. 10, pp. 2554–2563, Oct. 2010, ISSN: 0018-9456. DOI: 10.1109/TIM.2010.2057750. [Online]. Available: http://ieeexplore.ieee.org/document/5567156/.

[159] Adams, K., Kiefer, A., Panchuk, D., Hunter, A., MacPherson, R., and Spratford, W., "From the field of play to the laboratory: Recreating the demands of competition with augmented reality simulated sport," *Journal of Sports Sciences*, vol. 38, no. 5, pp. 486–493, Mar. 2020, ISSN: 0264-0414. DOI: 10.1080/02640414.2019.1706872. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/02640414.2019.1706872.

[160] Gelder, J.-L. van, Cornet, L. J. M., Zwalua, N. P., Mertens, E. C. A., and Schalk, J. van der, "Interaction with the future self in virtual reality reduces self-defeating behavior in a sample of convicted offenders," *Scientific Reports*, vol. 12, no. 1, p. 2254, Dec. 2022, ISSN: 2045-2322. DOI: 10.1038/s41598-022-06305-5. [Online]. Available: https://www.nature.com/articles/s41598-022-06305-5.

[161] Donker, T., Van Esveld, S., Fischer, N., and Van Straten, A., "0Phobia – towards a virtual cure for acrophobia: study protocol for a randomized controlled trial," *Trials*, vol. 19, no. 1, p. 433, Dec. 2018, ISSN: 1745-6215. DOI: 10.1186/s13063-018-2704-6. [Online]. Available: https://trialsjournal.biomedcentral.com/articles/10.1186/s13063-018-2704-6.

[162] Banakou, D., Kishore, S., and Slater, M., "Virtually Being Einstein Results in an Improvement in Cognitive Task Performance and a Decrease in Age Bias," *Frontiers in Psychology*, vol. 9, p. 917, Jun. 2018, ISSN: 1664-1078. DOI: 10.3389/fpsyg.2018.00917. [Online]. Available: https://www.frontiersin.org/article/10.3389/fpsyg.2018.00917/full.

[163] Yee, N. and Bailenson, J., "The Proteus Effect: The Effect of Transformed Self Representation on Behavior," *Human Communication Research*, vol. 33, pp. 271–290, 2007. DOI: 10.1111/j.1468-2958.2007.00299.x. [Online]. Available: https://stanfordvr.com/mm/2007/yee-proteus-effect.pdf.

A
OVERVIEW OF SUPPLEMENTARY MATERIALS

Table 7: Supplementary materials to this work.

Title	**Description**
Informational brochure	Information document provided to the participant before the VR-ACL evaluation session with a full description of what the study participation entails.
Informed consent template	Informed consent of the VR-ACL evaluation provided to the participant before the session.
Information about VR controls	Information regarding the VR-ACL system's controls provided to the participant before the session.
MVN dataset	All HD reprocessed MVN and MVNX files gathered within this study, alongside an Excel sheet overview identifying and labelling jumps within each MVN file.
MATLAB code	All MATLAB code scripts to extract jumps from the MVN data using the Excel sheet overview and provide graphical presentation as well as gathering RoF overviews for statistical analyses.
Signed informed consents	All informed consents signed by participants for the different aspects of this study.
Guideline of MVN datastream integration into Unity	Step-by-step guide showing how the MVN data stream from the IMU sensors can be integrated within the virtual environment through Unity, alongside C# scripts to account for and correct coordination issues.

B
ADDITIONAL NOTES ON BACKGROUND

B.1 ADDITIONAL NOTES OF ACL INJURY MECHANISM AND REHABILITATION

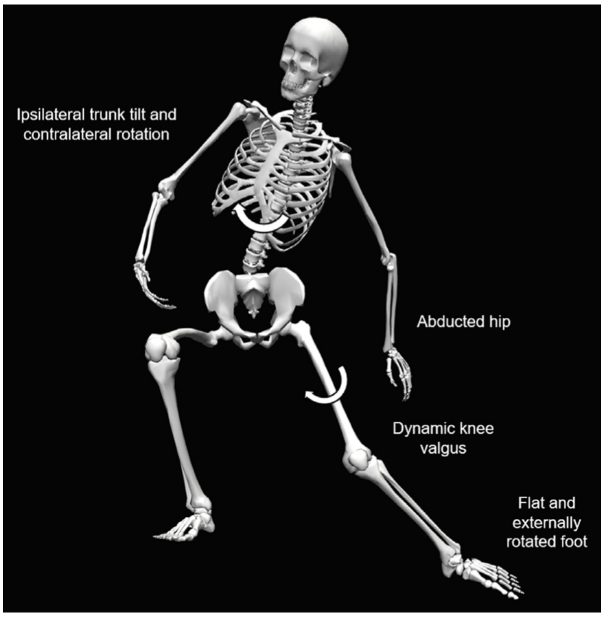


Figure 24: Frequently-observed mechanism of a non-contact ACL injury, from [3].

(a) The anterior drawer test, with the clinician stabilising the foot to the examination table as they apply an antro-posterior force.

(b) The Lachman test, with the clinician pulling with an anterior force on the patient's tibia.

(c) The pivot shift test, with the clinician applying valgus torque and internal rotation to the patient's leg, while slowly flexing the knee.

(d) The KT-1000 test, where the device measures the anterior-posterior laxity of the knee.

Figure 25: The physical examination tests for an ACL rupture diagnosis, from [1], [130].

When ruptured, the anterior drawer phenomenon can be found in the knee, where the lower leg can be moved 2-3 cm forward relative to the upper leg when the knee is in the bent position. When the PCL and the fibular collateral ligament are ruptured, there is a posterior drawer phenomenon and the lower leg can be moved backward. In addition, muscle strength (in particular that of the quadriceps) and the difference between hip external rotation, knee extension strengths and various jump performances have been shown to differ between the ACL-affected and healthy leg (see for example [18]). Such measures are, therefore, often used to evaluate whether an athlete is ready for RTS.

B.1.1 *Specific phases of ACL rehabilitation*

The following phases of ACL rehabilitation can be distinguished, each with its own focus points and frequently-applied exercises [32].

- *Preoperative phase* (before ACLr): establishing a normal gait pattern and an active RoM of the affected leg of at least 0-90°. The RoM of the affected knee during flexion and extension can be used to predict the postoperative RoM of the leg. An additional focus of this phase is to minimise swelling of the affected knee by icing when needed. Exercises used during this phase are prone hangs, heel slides, prone flexion stretching to re-establish the RoM; quadriceps and straight leg raises and neuromuscular electrical stimulation to strengthen the quadriceps. Quadriceps deficits of more than 20% (compared to the healthy leg) are associated with poor outcomes after the ACLr.

- *Early postoperative phase* (first 4 weeks after ACLr): minimising the pain and swelling of the affected knee, establishing a normal gait pattern with (and slowly without) crutches, achieving a 90-degree flexion and full extension of the knee, and strengthening the quadriceps. Immediate weight-bearing after surgery, supported by two crutches is promoted to decrease patellofemoral pain. Patients are recommended to take 2-3 physiotherapy sessions per week, alongside daily home exercises. The exercises used during this phase are prone hangs, heel slides and prone flexion stretching to improve the RoM as in the previous phase, sometimes guided by using a stationary bike with a higher saddle (thus keeping the knee more extended); neuromuscular electrical stimulation, quadriceps sets and straight leg raises for quadriceps strengthening, and patellar mobilisation (i.e. pushing the patella up, down and sideways and holding that position) to improve the active extension mechanics of the knee.

- *Strengthening phase* (4 weeks - 6 months after ACLr): this phase furthermore focuses on further improving the knee RoM to its full extent and strengthening the muscles. Neuromuscular control is further trained by using balance cushions or a wobble board. Cardiopulmonary training is performed by running in a straight line (on a treadmill) and/or cycling exercises. Exercises should only give short-term articular soreness to the patient (for no longer than 6-12 hours) and patients should not take any pain medication anymore (but can, when needed, use cryotherapy). Specific exercises during this phase are mini-squats, mini-lunges, leg presses, hamstring curls, step downs, wall sits, one-legged deadlifts, 4-way hip exercises, hip rotator exercises, shuttle and wall squats.

- *Return to activity phase* (3 months after surgery - until RTS): continue muscle strengthening, neuromuscular control and proprioception. This phase also focuses on jumping, with the patient learning good form and minimising landing impact and rotary forces on the affected knee. Exercises during the phase include squats, lunches, plyometric and agility drills, vertical jumps and running patterns.

Based on existing the Royal Dutch Physiotherapy Society (KNGF) standards [2], similar phases are considered in the Netherlands for ACL rehabilitation. For each phase, different exercises can be recommended, of which an overview is provided in Appendix E. In addition, the KNGF recommends avoiding heavy physical activities in work and sports within at least the first three months after the operation. This also extends to the rehabilitation itself, as heavy physical rehabilitation activities, such as running, fast turns and risk activities that rely on the knee should not be conducted.

Within the last phase of *returning to activity*, a patient can start to slowly integrate their sport into their rehabilitation through exercises and on-field training. The use of on-field rehabilitation has been found to, among others, improve muscle strength and knee function and a reduced risk of re-injury after RTS [34]. This is because the on-field rehabilitation allows for sport-specific performance requirements to be directly addressed and sport-specific skills to be restored with the adapted post-surgical neuromuscular control. By incorporating sport-specific elements within rehabilitation, the reactive nature of movements given the environmental stimuli and perceptual-cognitive pressure can be progressively (re-)trained. To allow for on-field rehabilitation to commence, Buckthorpe et al. (2019) [35] suggest that the patient should not experience knee pain or swelling and no subjective knee instability; and should have negative knee laxity tests; a limb symmetry index (LSI) higher than 80% during isokinetic assessments; a good quality of movement; and the ability to run aerobically for more than 10 minutes at 8 km/h.

B.1.2 *Additional parameters for RTS evaluation*

The following parameters can be utilised to evaluate the performance of the ACL-affected leg during the RTS evaluation.

- Time since surgery in months passed.
- The RoM of the knee.
- The muscle strength and balance of the affected leg required to provide dynamic stability within the patient's sport-specific context. For this, it is important to note that the muscle strength of the unaffected leg may change alongside that of the affected leg over the duration of the rehabilitation. Being unable to maintain the usual activity level, the unaffected leg might decrease in muscle strength before rehabilitation, while, for the affected leg, the rehabilitation exercises themselves have shown to increase muscle strength [131].
- An limb symmetry index during single-leg jumps for distance higher than 90%. This parameter is determined by dividing the jumped distance of the affected with that of the unaffected knee, expressed in percentages.
  - A single-leg jump for distance: a jumping task in which a person balances on one leg and jumps forward as far as possible, landing in a stable and controlled manner

on the same leg. This is the most commonly used jumping task in RTS evaluation. The single-leg jump may also include a vertical evaluation. In this work, the single-leg jump is always considered with respect to its horizontal distance measurement unless indicated otherwise.

  – A triple single-leg jump for distance: three consecutive single-leg jumps forward.
  – A triple crossover jump for distance: combining three single-leg jumps forward while switching legs between jumps.
  – A 6-meter timed jump: jumping 6 meters forward on one leg as fast as possible without losing balance.
  – A single-leg vertical jump: jumping upwards as high as possible.
  – (Timed) sideways hops: jumping sideways on one leg over a set distance for a specific duration of time.

- The ability to perform (single-leg) jumping tasks without experiencing pain or instability in the joint.
- An isokinetic strength assessment of the affected leg as compared to the healthy leg (thus assessing both legs). In particular, the quadriceps femoris strength [43] and the hamstrings [37] can be evaluated as a measure of strength and knee asymmetry (bending/extending in the sagittal plane).
- KT-1000 ligament arthrometry (see Figure 25).

In addition to the general parameters, current rehabilitation has lately placed a stronger focus on patient-specific aspects that influence the RTS [42], such as graft healing (measured by an MRI) or concomitant injuries to the ACL rupture should be evaluated before deciding to complete the RTS. For the latter, the menisci in particular interact closely with the ACL to increase stability in the knee and, when deficient, can add to the stress on the ACL. Furthermore, anatomical features such as the tibial slope, notch width and femoral condyle shape have been shown to correlate with an increased risk of ACL injury and can, therefore, be considered during the RTS evaluation. In addition, sensoric analyses to evaluate biomechanical risk factors [36] and systems such as the Jump Landing System and Landing Error Scoring System have been proposed to quantify neuromuscular recovery.

B.2 ADDITIONAL NOTES ON BIOMECHANICAL PARAMETERS

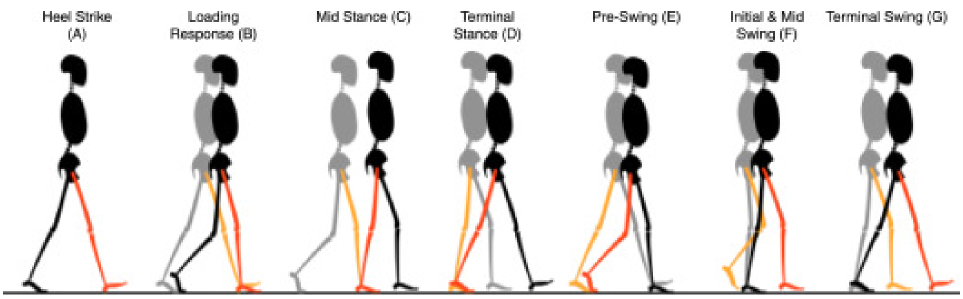


Figure 27: Gait cycle of the leg, from [46].

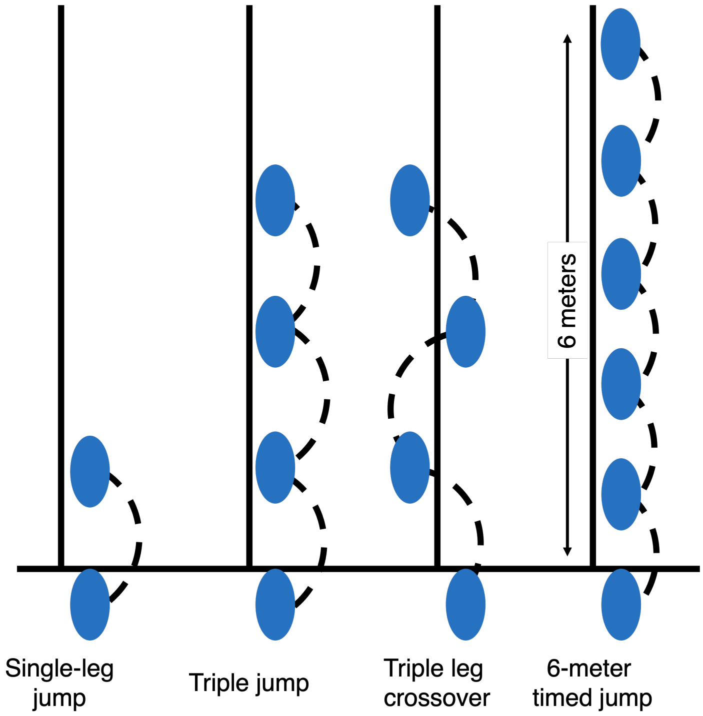


Figure 26: Overview of the four main single-leg horizontal jump tests, adapted from [132]. Each blue oval represents a landing moment, with legs alternating between the vertical line.

The extensor torque of the knee (as a result of the knee being pulled into extension by the patellar tendon) is, for healthy individuals, observed between 10-45% of the stance phase, while individuals suffering from a recent ACL injury have a knee extensor torque that can last almost the entire stance phase of gait [45]. As the ACL patient rehabilitates, the extensor torque becomes more reduced and can become a flexor torque, while the hip extensor torque can increase to 1,5 times that of a healthy individual. The differences between healthy individuals and those with a recent ACL injury are even bigger for more complex actions within the gait (e.g. when making sharp turns and changes in directions). Generally, patients with an ACL reconstruction can regain their normal peak torque at the knee after 10 to 22 months post-surgery. Between genders, differences in gait can also be found for ACL patients, with women having a higher knee adduction moment compared to males [133]. Since ACL stress is higher with increased knee and hip extension and with increased quadriceps force, the adaptations found in the gait of ACLr patients are often considered to reduce the load on the repaired ligament.

In the study by Decker et al. (2002) [51], the kinetic and kinematic landing performances of healthy participants and ACL patients (with hamstring autograft reconstructions) were compared using a GRF plate and a five-camera motion-analysis system. In this study, inverse dynamics was used to calculate internal-joint moments within the knee's sagittal plane during the impact (deceleration) phase of a jump. With the joint moment and angular velocity, the hip, knee and ankle muscle powers were calculated and compared between the healthy and ACLr subject groups. Compared to the healthy participants, ACL patients showed a stiffer landing posture at the moment of initial ground contact and showed less energy absorption of the hip extensors, but greater absorption from the ankle plantar flexors. In addition, the ACLr group had a greater ankle ROM at a higher angular velocity, which is similar to a soft-landing technique. Decker and colleagues hypothesised that ACLr patients utilised this method to avoid the use of the hip extensor muscles (hamstrings and quadriceps). In addition to this landing technique, there was a normal isokinetic knee extension and flexion strength (i.e. keeping the knee angular velocity constant throughout the movement) found for the ACLr group. The increase in the ankle's ROM is hypothesised to provide a more even distribution of muscular force within the ankle, knee and hip kinetic chain throughout the entire landing phase, as well as decelerate the trunk forward flexion by reducing the hip flexion. For energy dissipation, this meant that the knee extensors provided the majority of energy absorption (as was also the case for the healthy subjects), but there was a reduced energy absorption from the hip extensors and an increased contribution from the ankle plantar flexors in the ACLr group.

A reduced knee moment and increased ankle and hip moments were also found in ACLr patients six months after their reconstruction [47]. During the landing of a single-leg jump, there is a greater knee moment and knee power needed to stabilise the body as compared to the takeoff. The landing biomechanics could, therefore, provide important information about the knee performance. The study of Orishimo et al. (2010) [58] asked ACLr patients to perform a maximal-effort single-leg horizontal jump off and onto a force place and compared the affected with the unaffected leg. Here, they found that during the take-off of the jump, the knee ROM was 25% lower for the affected leg compared to the unaffected leg, which resulted in a 40% peak knee moment reduction and a 38% peak knee power reduction at the affected side. The reduction was compensated for with a 38% peak hip moment and a 21% peak hip power increase. There was a 43% lower peak power absorption at the affected knee, which was compensated with a 42% increase in power absorption at the ankle. These results are similar to thigh muscle fatigue and follow a softer landing strategy, as was also indicated by the work of Laughlin et al. (2011) [53].

Aside from the single-leg jump, other jump tasks common in rehabilitation can also be considered in terms of the kinematic adaptations for ACL-affected legs. The work of Cruz et al. (2013) [128] evaluated common jumps in ACL rehabilitation such as the drop landing (i.e. jumping vertically from a specific height and landing), the vertical jump (i.e. jumping from a specific height, landing, and making a vertical jump upward) and the forward vertical jump (i.e. jumping forward from a specific height to a specific distance, landing and then jumping upward), see also Figure 28. In their study, Cruz and colleagues used the peak anterior tibial shear force as a measure for kinematic variables, as the anterior shear force causes a maximal ACL strain, thus showing the moment in which ACL is at its highest likelihood for (re-)injury. Based on this measure, it was found that the forward vertical jump was the most biomechanically demanding and also elicited increased hip and trunk flexion, knee abduction and knee flexion moments. In general, the study found that the biomechanical demands increase from the drop landing to the vertical jump and from the latter to the forward vertical jump. The increased demand within the forward vertical jump was likely due to the added horizontal jumping component, which requires more energy to absorb the higher impact force and to complete the vertical jump after landing. In addition to the work of Cruz and his team, the study by Clarke et al. (2015) [134] saw for a maximum drop jump an increased

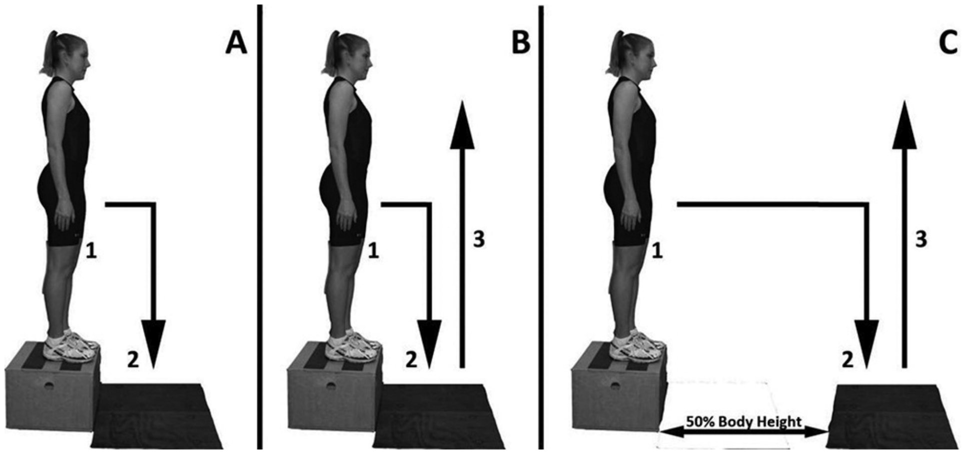


Figure 28: The drop landing (A), vertical jump (B) and forward-vertical jump (C), from [128].

hip flexion and knee ROM in the transverse plane was found for ACLr participants during the landing. Furthermore, an increased internal knee abduction moment was found during an unanticipated cutting task (i.e. a fast switch of direction task).

B.2.1 *Lateral trunk flexion*

The knee abduction load and the neuromuscular control of the trunk can both be used as sensitive and specific predictors of ACL injury risk [135], [136]. Comparing between genders, it has been found that female subjects with an ACL injury show a greater lateral trunk and knee abduction motion at jump landing compared to healthy females and ACL-affected males. This increased trunk flexion can also explain the increase in hip power described in 3.1.2, as the hip is used to control the trunk stability from forces generated by the landing impact, as well as unexpected perturbations. Landing and cutting movements may lead to uncontrolled movement of the trunk, which requires an increase in knee abduction and torque, as well as increased hip adductor torque to compensate. For women, in particular, the hip adductors are activated more during low and high-intensity activities, as well as during cutting movements, as they also have a decrease in active joint stiffness. During the single-leg jump landing (as well as during cutting movements), the entire body mass is balanced over the lower extremity in contact with the ground. As the largest part of the body mass, the trunk motion in the lateral direction during such movements increases the GRFs and the knee abduction load. Through the feedback control loop, the trunk position (and other segment positions and loads) affects the neuromuscular control of the hip, knee and ankle. For female participants, it was shown by Hewett et al. (2009) [135] that the trunk moves laterally to the ACL-affected limb during knee abduction. The study by Zazulak et al. (2007) [136] showed that the factors related to the core stability of an athlete can be used as predictors of an ACL injury for female athletes. As was described in subsection 2.1.3, women also have a higher risk of getting an ACL injury [137].

B.2.2 *Vertical ground reaction forces*

The study by Decker et al. (2002) [51] showed that ACLr subjects had a peak in the vertical GRF in the lower range of values that correspond to a soft landing. The horizontal GRF was found by Gokeler et al. (2010) [47] to be significantly lower for the affected ACL leg compared to the unaffected leg. However, the study by Gokeler and colleagues did not find differences between affected and unaffected legs for the vertical GRF.

The relation between knee kinetic asymmetry and GRF was studied by Dai et al. (2013) [138] using a stop-jump (i.e. an approaching run at the maximal speed that was followed in a 2-legged takeoff maximal vertical jump) and a side-cutting task (i.e. an approaching run at the maximum speed that was followed by a one-legged landing and a 35° cutting manoeuvre). The study found a strong correlation between sagittal plane kinetic and GRF asymmetries. This was especially the case for the stop-jump task, as there was a two-legged takeoff jump, that allowed for compensation of the affected leg by the unaffected one. In addition, the relation between knee kinetic asymmetry and GRF was more prominent for the push-off than the landing phase, as the push-off involves active muscle contraction and the landing is orchestrated by both passive and active structures.

B.3 ADDITIONAL NOTES ON SENSORS AND SENSOR INTEGRATION

B.3.1 *Motion capture markers*

With motion capture (in this case referring to optoelectronic systems), active or reflective markers are attached to the anatomical landmarks of a person to track the movement of individual segments with a camera setup. Within a remarked space, the cameras, often in combination with a force plate on the ground on which the subject moves, enable tracking of functional tasks along multiple planes and determining rotational forces in individual joints [36]. For this, biomechanical models are used to translate the marker and force plate data into kinetic data [139]. Motion capture is commonly used for digital animation (for entertainment and gaming purposes) as well as for biomechanical analysis for clinical and sporting purposes. A typical optical motion capture system (or optoelectronic MoCap system; see also Figure 29) consists of a camera, computer and marker setup. Usually, between 4 to 32 cameras are used (at least two are needed for a 3D visualisation) in a fixed setup, which sends information to the computer for analysis. These cameras can capture between 30 and 2000 frames per second. The markers can either be passive and only reflect light from infrared LEDs around the camera lenses, or be active and emit signals that can be captured by the cameras. For biomechanical analysis, force plates placed into the floor are often used to estimate GRFs. During the measurement, light is reflected or emitted by the markers and captured by the camera lenses. This signal is then cleaned up and analysed. Based on the marker movements captured by the camera, it can then be estimated what the body movements were. Markers should, therefore, be ideally placed on anatomical landmarks (such as bones origins/insertions close to the skin surface) that are relevant for the movement of interest and be attached to the skin directly to avoid movement or skin artefacts (i.e. markers moving because of moving loose-fitting clothes or because of skin movement relative to the skeleton, respectively). After the movement is captured by the camera, the markers need to be identified on the computer by labelling each one (and making sure that no markers

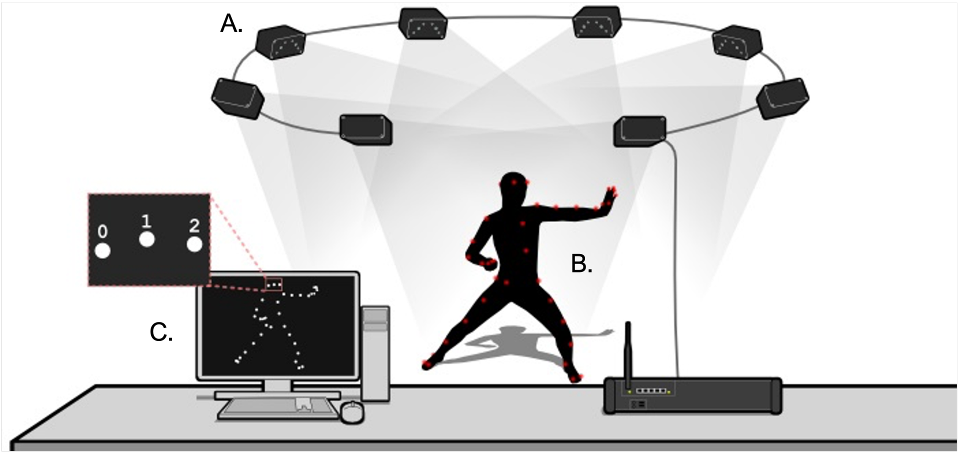


Figure 29: Schematic overview of a motion capture system, adapted from [141]. The cameras are positioned at the top (A.) and film the movements of the red markers on the subject (B.), which is processed by the computer setup (C.).

are missed and that the labelling is not interrupted throughout the movement). In addition, the high-frequency noise should be filtered out of the data. For this, Orishimo et al. (2010) [58] describes the effective use of a fourth-order Butterworth low-pass filter (cutoff of 10 Hz). Once the data is labelled and cleaned up, indirect kinematics can be used to determine the underlying biomechanics of the movement.

Using a marker-based motion capture system is popular in ACL performance literature (see, for example, [1], [47], [58], [88], [134]) and can be used for gait retraining and within ACL prevention training programmes. However, drawbacks of this method are the restricted setup with cameras, the time-intensive and precise preparation of the test subject and a time-intensive data analysis procedure (which often involves re-labelling of markers and various data clean-up steps). Recently, the Microsoft Kinect depth camera has also been applied for MoCap purposes as a more low-effort and markerless method with acceptable accuracy [140].

Motion capture systems for rehabilitation purposes have also been combined with interactive technology [1], [58], [88]. In the study by Bonnette et al. (2019) [88], an abstract visualisation was made of the squatting movement to evaluate knee performance in an interactive setting, see Figure 30. For this, a 3D optical motion capture system with real-time biofeedback was used. The study used a total of 30 retroreflective markers, with a minimum of three markers placed on each segment. In addition to the tracking markers, GRFs and the centre of pressure of either foot were gathered. The general assessment of the participants' squatting performance was visualised by creating a heat map of their movement patterns during the trials. One of the main strengths that this study found with the methodology was that the used biofeedback could be provided over a wide range of biomechanical variables simultaneously. The study was able to provide feedback regarding the knee, trunk and hip in real-time and conveyed within a single visual stimulus that was presented to the participants.

One downside of using motion capture systems and inverse dynamics is that the setup requires high-speed cameras and large processing power. The study by Dai et al. (2014) [138], therefore, also focused on providing a setup in which only a force plate would be needed. While the study was able to correlate the GRFs of the force plate with the knee kinetic asymmetry found with the motion capture, still high prediction errors were found. The 3D motion analysis provided a more accurate and sensitive evaluation of the knee performance.

Another downside to the motion capture method is that the setup with marker placement and post-measurement labelling can be time-intensive and requires correctly and consistently placed markers [139]. A possible solution is the use of markers integrated within a skin-tight suit or the application of the Microsoft Kinect as a sensing device [139], which does not require markers but does give a 3D, simplified skeleton in real-time, made up out of 15 joints.

B.3.2 *Additional notes on IMUs*

The issue of exact marker placement for MoCap systems could be solved more easily with technology such as the MVN Link system by Movella [142], a suit with inertial markers, which can be used in a similar way to the motion capture technique. This system uses a sensor-integrate IMU to estimate body orientation. By using a suit-based system rather than placing markers on the different anatomical landmarks, the preparation for measurement can be significantly decreased as the subject only needs to put on the suit. In addition, the markers will always be positioned in the same place for the subject, so there is less inter-measurement variability. This method also showed a high validity for evaluating hip, knee and ankle joint angles in 3D for different tasks.

For measurement systems, an important aspect is to correctly interpret the gathered data. First, the correct signal processing method is needed to remove noise and artefacts. Depending on the type of measurements used, different modelling methods can be applied. Knee joint forces have been successfully estimated by neural networks within sports contexts (see for instance Setter et al., 2019 [77]). A downside of machine learning may, however, be the accuracy of such a machine learning-based data evaluation, as was evaluated by the work of Beenhakker et al. (2020) [79].

B.3.3 *Sensor integration*

In the study by Gokeler et al. (2010) [47], motion capture biomechanical data was collected and combined with EMG measurements. The biomechanical data was collected through a 3D motion analysis system. This system used two cameras and a set of reflective markers, alongside measuring vertical GRFs and horizontal GRFs. The joint angles, velocities and accelerations were derived from an inverse dynamics simulation. The GRFs were calculated from a forward dynamics simulation. The EMG measurement was conducted with disposable surface electrodes.

The measurements of IMUs can be combined with other sensor data. In the study by Wu et al. (2016) [143], IMU measurements were combined with EMG data to create a system that could automatically detect a wide variety of hand and arm gestures. While this system was for recognising American sign language rather than a rehabilitation purpose, the sensor fusion of these two modalities shows the system's ability to recognise fine movements such as hand gestures. For individual users, 80 signs were classified with over 96%. A downside to this technology is that the accuracy was only significant when the model was trained on a subject. Therefore, inter-subject usage of the system was not yet possible. Within the work of Tedesco et al. (2019) [113], a wearable multi-sensor system was developed for ACL rehabilitation evaluation with three sensors, combining IMUs with EMG and electrical muscle stimulation. While only preliminary results were available, the sensor fusion ability of IMUs and EMG seems to provide an in-depth insight into knee performance.

Aside from EMG data, IMUs and motion capture technology can also be combined to accurately estimate body segment orientations. In the study by Kong et al. (2013) [144], an IMU-based motion capture system was developed for gait rehabilitation after a loss of motor ability. This system was specifically developed to be used by patients themselves in their own homes as part of a treatment to regain their physical mobility. For this purpose, a markerless optical motion capture system should be used, as a marker-based optical motion capture system has a high cost and is dependent on the precise knowledge of marker placement. Marker-less motion capture systems, however, do not have the same accuracy for body segment orientation (as was also found by Fern'ndez-Baena et al., 2012 [139]). The combination of a markerless optical motion capture system with an IMU system was, therefore, very beneficial to the study of Kong et al., as IMUs are low-cost and low-maintenance. The entire system could also be made very compact and easy to wear. The developed system had an accuracy that was comparable to an optical motion capture system.

B.4 ADDITIONAL NOTES ON SPORTS INTERACTION TECHNOLOGY

Motor learning entails a lasting change of motor performance through (repeated) training [145]. For motor learning in the ACL rehabilitation context, several insights are needed, which are discussed in this section. Motor learning consists of the following three key phases.

- Phase 1: rapid learning progression and first movement representation.
- Phase 2: refining of motor presentation and improving error detection and correction (both in real-time or during subsequent movements).
- Phase 3: movements are performed in a highly automatised manner, showing a consistent execution.

B.4.1 *Sense - Think - Act cycle*

Within sports interaction technology, the technological interventions follow the 'sense' - 'think' - 'act' cycle, see Figure 31. Here, the system uses sensor data to measure behaviours, performs data processing to find the correct response, and provides these responses back to the system users, of which the effects can, once again, be measured. Applied to the topic of interactive ACL rehabilitation with a sensor technology setup, the proposed system should iteratively measure objective stability parameters from the subject's knee ('sense'), process the data to evaluate the knee stability and rehabilitation progress ('think') and provide new stimuli to further guide the rehabilitation process ('act'). This cycle will trigger specific movements

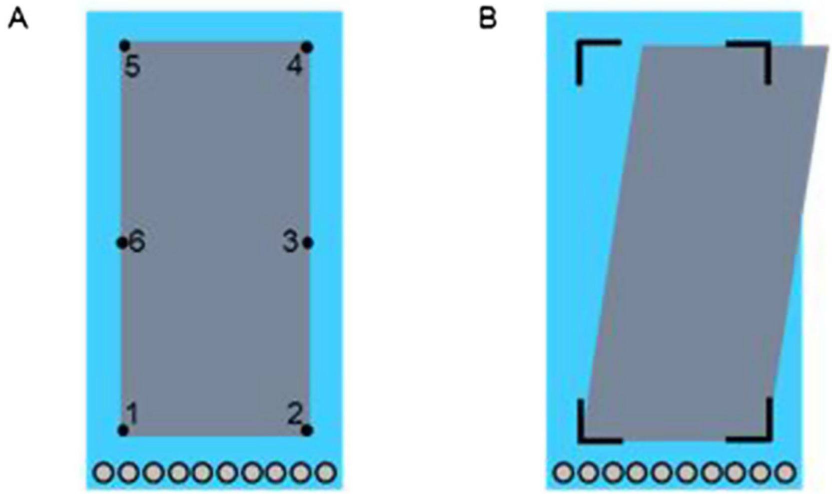


Figure 30: Example of mapping six key biomechanical parameters (denoted 1-6 in A.) onto an abstract rectangle during a squatting task, adapted from [88]. The correct (target) mapping of biomechanical variables onto the shape is shown in A., while B. gives an example of an incorrect squatting movement (too much trunk lean) as visualised by the abstract shape.

from the athlete that will allow for the continuous objective measurement within the relevant sport-specific context.

This 'sense' - 'think' - 'act' cycle can provide the learning-rich environment and the diagnostically relevant situations introduced above. A learning-rich environment is an environment in which the system presents the user with a large variety of situations, which can be adapted to the individual needs and abilities of the user, such that the user receives those situations that give them the opportunities, action possibilities and motivation to learn [146]. An example of such a learning-rich environment is by Jensen et al. (2015) [147], who created a setup that provides football players with different games to train important football skills in rapid succession (e.g. practising a pass and turn movement on average seventeen times within a single minute). For ACL rehabilitation, the learning-rich environment should provide the patient with the opportunities, action possibilities and motivation to perform and learn their rehabilitation exercises as part of their treatment, as could also be applied to the jumping exercises also discussed in subsection 2.2.1.

B.4.2 *Ecological validity of sports interaction technology*

An important differentiation between sports interaction technology is between the idea of representationalism versus ecological dynamicism [83], [84]. Within representationalism, athletes are instructed to behave according to an 'ideal' movement. These movements are then trained in isolation such that the athlete can execute the same ideal movement during an in-context performance as well. In dynamicism, the movement does not need to be ideal but should rather be considered 'adequate'. Movements are trained *in-situ* and movement patterns are found through exploration and variation. The dynamicist views provide a more ecologically valid training scenario than the representationalist ideas. For rehabilitation, a dynamicist viewpoint would be to let athletes play their sport within their actual contexts,

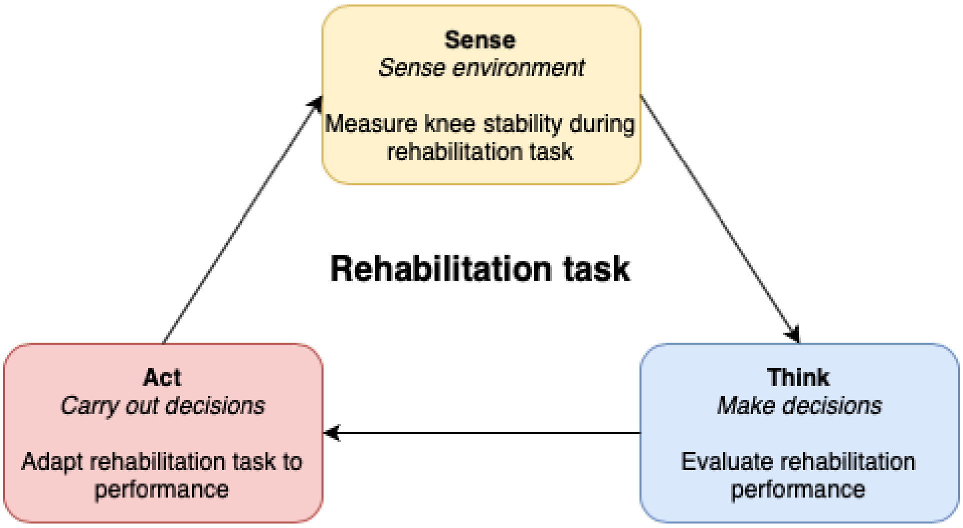


Figure 31: The HMI 'sense' - 'think' - 'act' cycle, centred around a rehabilitation task.

rather than to do exercises that only relate to the movements of the sport. In general, a positive far transfer task (i.e. a task close to the performance context) has been shown to increase in performance and learning of the athlete. The assessment of an ecologically valid task in rehabilitation can, therefore, also aid the understanding of how an athlete would perform after they return to play. An example of an ecologically valid evaluation of performance is by Weichenberger et al. (2015) [85] (also discussed in Section 3.3), whose fencing robot allows users to train within a far transfer task. By replacing an opponent with a fencing robot, the task creates a controlled evaluation of the athlete's performance that can be directly translated to the actual performance context.

As the objective measures for knee stability are inherent to a representationalistic nature, a final system, even one that is ecologically valid, incorporating the measurement systems described in 3.2 will improve the ecological validity of rehabilitation while remaining embedded within the representationalism of sports interaction technology. As the current rehabilitation (described in Section 2.2) relies mostly on standardised tests (with very limited ecological validity) used to determine whether players can return to their sport (i.e. going to the highest ecological validity), the use of such a combination between the sensor and interaction technology will breach this gap of the ecological invalid to the ecologically valid with controlled increments that allow for objective comparison between the performance of the affected and unaffected leg.

B.4.3 *Providing meaningful feedback in sports*

Aside from triggering a movement and controlling the interaction, the interactive system should also provide meaningful feedback to its users. Here, only augmented (or extrinsic) feedback is considered, meaning that this information could not be elaborated upon by the patient without an external source (such as the interactive system itself or a therapist) [145]. For this type of feedback, the timing, frequency, content, modality, form and function need to be considered for an effective design. For an in-depth analysis of possible feedback mechanisms in sports interaction technology see Postma et al. (2021) [84].

Feedback can be provided before ('prospective'), during ('concurrent') or after ('terminal') the execution of a movement [84]. Concurrent feedback during training has been shown to greatly benefit the performance during practice but does not aid the retention and transfer to the actual performance context [148], as it likely forces learners to ignore their proprioceptive feedback, which makes them dependent on the augmented feedback [145]. The negative transfer seems to increase when feedback is provided at higher frequencies and is higher for visual feedback than for other modalities. In contrast with concurrent, terminal feedback is effective for both low and high task complexity [84].

For the modality of feedback, several options are possible, including visual, haptic, auditory or multimodel (i.e. combining the other options) systems [84]. Haptic feedback consists of tactile (e.g. vibrations or pressure) and kinesthetic (e.g. regarding the sensation of body pose) perceptions [145]. Generally, visual feedback (isolated or in a multimodel system) allows for presenting the highest complexity of information. Multimodel feedback provides the most immersive experience to the user. As with the timing, the modality can affect how dependent users can become on the feedback. The use of auditory concurrent feedback seems to have a lesser dependency than visual concurrent feedback. The effectiveness of the different feedback modalities for low and high functional tasks is visualised in Figure 32.

The frequency at which feedback is provided directly affects the performance, especial for tasks with high functional complexity. If the functional task complexity is lowered, the feedback becomes less necessary and it should be decreased to avoid dependency from the user and improve automation of the movement [145]. This can be done by following a fading schedule that structurally reduced feedback over the training. Within rehabilitation, patients need to relearn their motor functions both efficiently and permanently. One possible method for this is self-controlled feedback, where the learner can decide whether they want feedback and can, therefore, adapt the frequency to their learning phase. In addition, this method has been shown to positively involve and motivate the learner in their learning process. A risk for this method is that, because the progress depends on the learners' self-estimation, they might get stuck at a certain skill level. In the case of rehabilitation, this would require either the therapist's expertise or the system's evaluation of the athlete's performance to gradually further increase the task complexity.

The content of the feedback generally focuses on a distinction between the knowledge of results and the knowledge of performance [145]. The former provides feedback about the outcome of an action, while the latter gives information on those behaviours that led to the observed outcomes. Generally, the knowledge of performance is considered more effective than knowledge of results to improve motor learning. In addition, the use of quantitative or quality and the amount of feedback (single or multi-error responses) can be used to adapt the feedback precision [84]. Of course, feedback can be positive or negative. Positive feedback can help to motivate, while awareness of the errors can drive (and are sometimes even considered necessary for) motor learning. Whether the feedback is valid or erroneous can lead to further differentiation in the outcome. Generally speaking, providing correct feedback is considered the most optimal for motor learning and performance. One adaptation to the validity that might prove beneficial is called 'error augmentation', where errors are enhanced to promote motor learning. This has been applied to stroke rehabilitation, finding limited effectiveness [149] or even some potential [150], [151] for the method. Finally, as was discussed in 3.3.2, feedback can be used to direct the athlete's attention towards the movement itself (i.e. having an internal focus of attention) or away from the movement itself but

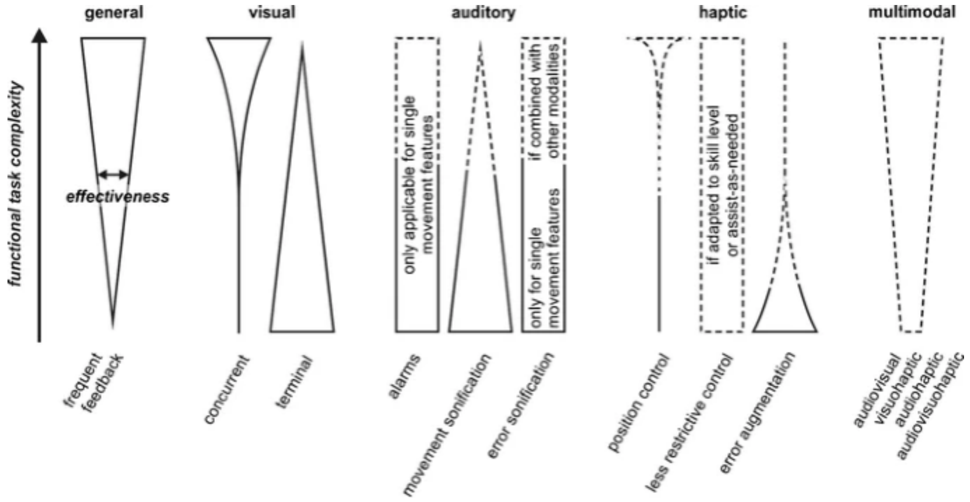


Figure 32: Effectiveness of feedback strategies based on the functional task complexity, from [145].

towards the effect of it (i.e. an external focus of attention). The latter has been shown to be most beneficial to motor learning.

For biofeedback devices (i.e. sensors measuring and analysing body parameters), visual and auditory signals are often used [100]. Within neuromotor rehabilitation, multimodel signals may help draw the patient's attention to the task. Motor learning is supported when the biofeedback system provides information to the patient that can be used to improve subsequent movements. Huang et al. (2005) [100] used a visual feedback system to guide arm movement during a reaching task, while musical presentation would be used to provide spatial-temporal information. The visual feedback consisted of a 3D modelled Augmented Reality animation providing information on the patient's arm position in real-time, alongside an ideal movement trajectory. The auditory feedback was manipulated as a chord transition mapped to the distance of the arm to the target object, with a smooth movement being rewarded with a good performance of the music, while bad movement execution would lead to the musical piece being staggered or incomplete. The multimodality of the setup improved the smooth movement execution of patients and disproved the concern of sensory overloading within an interactive rehabilitation setup.

B.4.4 *Overview of additional gamified systems*

In recent years, different novel interventions have been made with interaction technology for sports rehabilitation. A large variety of possible technologies have been previously studied, such as the SpeedCord (i.e. testing response to light cues), interactive floors/LEDs; augmented or virtual reality, and haptic interventions. Here, a selection of gamified systems are described as they are applied to rehabilitation.

Gamification, or the implementation of game design elements within a non-game context such as physical activity, aims to motivate users to become more active or to perform certain movements [152]. To successfully implement gamification, the theory of self-determination should be considered. This theory states that competence, autonomy and relatedness are needed to increase intrinsic motivation in humans. Especially the autonomy of humans might be influenced by gamification, as virtual rewards and social comparison in the game might remove the voluntary aspect of continued participation. Virtual rewards are points or badges that can be won by the user within the game, aimed to improve motivation. The effectiveness of such rewards was found to be inconclusive by Zuckerman et al. (2014) [152]. Similarly, social comparison (where players can compare their results to others) has achieved mixed results for promoting physical activity. In general, Zuckerman and colleagues found that people interact with gamified systems in different ways, which requires personal tailoring to be used for optimal effectiveness. Burke et al. (2010) [153] determined three design aspects that are important for optimising gamification in a rehabilitation setting, namely meaningful play (i.e. providing clear, consistent and meaningful feedback); dynamically adapt the level of challenge to the patient's performance, and positively handling failure by encouraging and rewarding the engagement with the game.

B.4.4.1 *Interactive floors*

One study that has focused directly on using interaction technology for rehabilitation purposes is by Van Delden et al. (2016) [68]. In this study, an eight-by-one meter gait rehabilitation LED floor with pressure sensors was used to help participants show a more symmetrical walking pattern. By using a gamified setting, participants were motivated to improve in terms of coordination, walking speed, balance, strength and endurance, but also perceptual-cognitive aspects such as their reaction time, attention and focus. Simple game setups were used that could be modified to the individual user requirements. This allowed the therapists to adapt the challenges to meet the rehabilitant's progress, as well as individualising the game to the user's gait characteristics. The games also introduced competitive elements which helped to further motivate users to keep trying to improve their scores and, with it, their gait patterns. One of the main issues that were found with this setup was the lack of space available with the LED floor, which limited for instance the endurance aspect of training. In addition to this, the floor forced users to look down rather than forward during gait.

Another similar method used for balance training during stroke rehabilitation was by Lange et al. (2010), where a Nintendo Wii Fit Balance Board to let users shift their weight from one leg to the other to move a virtual balloon floating upwards [154]. Here, rather than motivating specific movements to improve the gait pattern, users were motivated to strain their affected limb for continuous and controlled periods. Here, the focus was to give users confidence and distract them to overcome their fear of straining the affected limb.

Parallel to the study by Lange et al. focusing on the Nintendo Balance Board is a similar study by Bower et al. (2015) [155], who developed a set of games for the same purpose but in a more low-cost and usable setting with a depth-sensing camera. This study looked at encouraging dynamic balance through weight-shifting movements, and upper limb activities. The software was able to track single or multiple users by computing skeleton joint locations and movements. Participants of this study enjoyed the novelty and competitive aspects of the games. The novelty effect did seem to wear off for participants due to the monotonous setup of the game. Interestingly, this gamified setup also helped participants to perform movements that they were previously hesitant to do. The study also monitored the pain, dizziness and fatigue of participants, which were all found to not change significantly (or outside of reasonable results for a general physiotherapeutic session).

B.4.4.2 *Haptic interventions*

In addition to the aforementioned applications, the development of haptic interfaces for rehabilitation purposes has also previously been demonstrated by Alahakone and Senanayake (2009) [156]. Such haptic interfaces can provide tactile feedback or provide realistic physical interaction with real and virtual environments, making them also suitable for combination with VR technology. The work of Alahakone and Senanayake consisted of the development of a biofeedback system that incorporated a sensory device, a data processing aspect and feedback output. Here, (visual-)tactile feedback was used to not interfere with the subject's visual or acoustic dependence on their task. The biofeedback system was developed to provide feedback about improper movements in real-time during physical training.

Further developments have been made on developing adaptable haptic interfaces, such as the one by Tsetserukou et al. (2010) [157]. Their developed FlexTorque haptic interface by Tsetserukou et al. was partly designed to allow users with physical impairments to control torque from the interface during therapeutic exercises. The setup was, however, not tested with rehabilitants.

B.4.4.3 *Augmented Reality*

Augmented Reality, computer-generated virtual objects are laid over a real-world captured scene. This means that footage of the world is combined with virtual elements and places AR between the completely virtual VR world and the real world. This can either be in 2D (with a further distinction being between indirect 2D, which is, for example, when using a phone, or direct 2D when using an HMD such as a Google Glass) in which additional 2D information or visuals can be rendered when interacting with a real-world object; or in 3D (for example, when an HMD is used that can render 3D effects next to the real-world objects). As with VR, technology based on AR systems has been implemented in rehabilitation settings. This can, for example, be found in the work of Alamri et al. (2010) [158], who determined that AR can be used to encourage rehabilitation patients to repeat otherwise tedious reaching tasks. In the study by Burke et al. (2010) [153], a review of various AR studies is given from which issues are identified. According to Burke et al., issues such as the camera position, depth perception and lighting can affect the usability of AR within rehabilitation, leading to difficulties for motor learning. AR has been previously applied in combination with sensor technology to determine kinematic changes in jump tasks, see [159].

B.4.5 *Additional notes on perceptual-cognitive pressure*

The coordination of movements can be improved in rehabilitation by manipulating the movement constraints. For instance, for a sports-related task (such as dribbling or sprinting) that may have a movement goal to score points, the task dynamics can be manipulated by object or body manipulation. Object manipulation could be to add a ball to the executed movement (e.g. dribbling with and without a ball), while body manipulation may require the athlete to be stationary or move to different places (e.g. stationary dribbling or dribbling towards the basket). The nature of the task may help to understand which of the different features within the individual and the environment are especially important to the task. Based on these features, a setup can be made that embodies the nature of the task while still allowing a somewhat isolated measurement of biomechanical parameters. In addition, the relevant features can be used to gradually increase the functional task complexity and, therefore, help bridge the gap to the high perceptual-cognitive demand of the return to sport.

Aside from using task-relevant features, the goal-directed attention of an athlete [104] can be used as a perceptual-cognitive factor in performance. With this form of directed attention, the athlete is actively seeking out relevant information from their environment that can be used to shape their coordination and control. This can be both in the form of internal and external attention (i.e. focus on body movement and the execution of the task, respectively). Contrary to goal-directed attention is self-directed attention. This entails that the athlete directs their attention only to their bodies rather than the functional task execution. The attention in this form is directed at how the movements feel rather than how they can perform the movement task. Using goal-directed attention, the athlete can explore the functional task environment as it slowly increases in complexity (both in terms of physical and perceptual-cognitive performance load). By incorporating a gradual increase of physical and perceptual-cognitive load within training, the athlete can reduce the uncertainty of their strategic and tactical control, such that they can avoid the panic-driven reaction control in favour of strategic and tactical control.

B.5 PSYCHOLOGICAL EFFECTS RELATED TO VIRTUAL REALITY

Aside from all diagnostic purposes that Virtual Reality can hold, it is also important to consider what psychological effects may underlie its usage for any user. With VR, especially with immersive goggles such as the Oculus Quest 2 which allows for providing visuals as well as audio to its user, the most dominant senses are closed off from the real world, which allows the user to completely lose themselves into the presented virtual environment. Because our brain cannot be at two places at once, VR users often lose themselves within the virtual environment. This is also seen in online videos of VR users who forget about the physical world around them and trip over break real-life objects around them. The more someone loses themselves within the virtual world, the bigger the sense of 'presence' [160], the subjective feeling that you are completely in the virtual environment, which leads to an increased likelihood of the user showing behaviour and emotions similar to those they would show in the real world. This effect also allows, for example, the use of Virtual Reality exposure therapy [161], in which someone who suffers from a specific phobia uses Virtual Reality to be exposed to their fears again and again in a safe way. The user is, in that case, transported to a situation where they can confront and learn how to deal with their fears. In the study by Donker et al. (2018) [161], Virtual Reality exposure therapy showed very promising effects to treat anxiety disorders and specific phobias. The addition of serious gaming elements in their study, as integrated with the exposure therapy, helped to reduce distress while the continuous confrontation with the phobic stimuli can be played repeatedly. Virtual Reality can also be applied to help people adapt their behaviour based on the avatar that they are interacting with or interacting as. Experiencing the body ownership of a virtual avatar increases the feeling of presence [160], which can be used to improve self-confidence or reduce self-defeating behaviour. In the study by Banakou et al. (2018) [162], participants saw themselves in a VR environment as famed physicist Albert Einstein looking back in a mirror. Compared to participants who saw a 'normal' avatar body, this embodiment of a 'super genius' improved the participants' performances on cognitive tasks. This phenomenon is also described by the so-called 'proteus' effect (coined by Yee et al., 2007 [163]), which states that an individual adapts their behaviour to conform with the characteristics of their virtual avatar. In the study by Banakou and colleagues, this effect meant that seeing themselves as an intelligent person (with Einstein being a recognisable embodiment of genius), thus giving them more self-confidence in the cognitive puzzles. The study of Van Gender (2022) [160] showed a similar principle, where the use of VR allowed participants, all convicted offenders, to see a future avatar of themselves. Here, the more life-like the avatar, the less likely the participants were to portray self-defeating behaviour due to their connection to their own future.

C

OVERVIEW OF OBSERVATIONS AT SPORTS REHABILITATION CLINIC OCON HENGELO

Within this appendix, a complete overview of the observations at the OCON Orthopaedic Centre in Hengelo, the Netherlands, is given. In addition, evaluations that were done with the specialists at OCON for the interaction setup are described. This overview is re-used in parts of the thesis work where appropriate.

C.1 SHADOWING SESSIONS OF OCON SPECIALISTS

During two separate moments, the physiotherapists and sports doctors at OCON Hengelo were shadowed. At the OCON clinic, around 450 ACLR operations are done per year. Before the operation (around 6 months beforehand), as well as 6, 12 and 24 months after the operation, evaluations are held. Throughout the rehabilitation procedure, the sports physiotherapists at OCON keep in touch with the patients' sports trainers and daily physiotherapists.

During these sessions, several consultations were attended, from which the structure of a typical ACL evaluation was determined. This evaluation consists of the following steps. First, as a patient arrives at the clinic, they perform an isokinetic force measurement using an IsoForce device. During this exercise, the patient sits (and is strapped into) a chair, with a bar in front of one of the patient's legs. While keeping the speed of movement consistent, the patient tries to push as hard against the bar as possible, thus stretching their leg to their maximum, within three sets of five, fifteen and five repetitions respectively. The first two sets of stretches are at maximum force, the third set is as fast as possible. The force at which the bar pushes back during the second and third sets is determined based on the performance in the first set. In addition, a calibrating movement is made at the start of the exercises to establish the ROM of the knee to avoid overstretching. After completing the sets for the affected leg, the procedure is repeated for the healthy leg to be compared. While performing the isokinetic force exercises, the physiotherapist is very encouraging towards the patient, providing them with verbal motivation to keep on going and push themselves harder. Once the test is complete, the system creates an overview of the force per leg and graphs the performance of the two legs. Based on the comparison between the two legs, the difference in peak torque should be less than 20% to allow for an ACLR operation. In addition, the total peak torque of the knees is evaluated.

After the isokinetic evaluation, patients perform a series of jumping exercises. First, the patient performs three single-leg jumps with each leg. At the landing of the jump, the patient should stand stable on their single leg, otherwise, the trial is not counted. The maximum distance jumped is noted down for both legs. Second, the patient performs three triple single-leg jumps with each leg. Again, at the landing, the patient should stand stable and the furthest distance is noted down. Finally, the patient jumps sideways with one leg over two pieces of tape, spaced at a distance of 30 cm as often as possible for 30 seconds.

Once these trials are completed, the physiotherapist performs a physical evaluation that can consist of the laxity and bending tests described in subsection 2.2.1. These tests are intended to get a feel of the movement performance and overall stability of the knee. Often, the knees are also visually compared in stance or sitting position. In addition to this, the physiotherapists ask the patient about their experiences in the rehabilitation procedure and issues that they may have encountered.

According to the physiotherapists at the clinic, patients that arrive with ACL injuries are often caused through sports with feints and diversions, such as football or basketball. Sports that are explosive without sudden changes within the movement plans, such as squash, do not have a high prevalence of ACL ruptures. In current practice, the ability to correctly respond to sudden (and unexpected) changes in the required movement pattern is trained by light cords, in which the patient has to respond to one in a series of lights being suddenly turned on. Another option is to provide three possible ways for a player to shoot a ball or move past a target and suddenly block one of the options, thus forcing the patient to correct their movements as they are already occurring. A similar method could be implemented in the VR, according to the physiotherapists, by having objects appear that suddenly alter the movement path of the patient. However, this can lead to unsafe environments, as the objects may appear outside of the user's direct view, thus scaring them when they suddenly see them.

Based on the patient interviews that were shadowed, there were some patients in which pain and fear of movement interfered with their physiotherapy progress. Some patients were 'stuck' in the same phase of their physiotherapy progress, which gave them a lot of frustration. In the case of this patient, she was rehabilitated to achieve the required 20% maximum difference in peak torque between her knees. However, as she continued not to meet this requirement, she felt demotivated and her progress decreased further. This patient also indicated that seeing her progress, even in a VR evaluation (as she was briefly introduced to the thesis topic) might improve her motivation to keep on improving herself. In addition, wrong diagnoses and being sent from expert to expert seemed to weigh heavily on individual patients. By providing objective progress within the VR environment, patients might develop more trust in their rehabilitation procedure and personal progress. In addition, showing progress may help with feeling more motivated, as one patient, briefly informed of the study, indicated. Another patient indicated to have a lot of fear of movement, which made it difficult for her to trust her knees again and return to her previous level of activity. When the physiotherapist noticed the patient's fear of movement, he indicated that she could be referred to a mental coach for this. Later, the physiotherapist indicated that they usually do not have the time to provide a lot of mental support for patients, which sometimes results in decreases in performance. A suggestion made for the VR was to include a method for them to also indicate their fear of movement throughout or after the interaction.

Additional suggestions made by the physiotherapists were to look at what distance (between the used 20, 40, 60 and 80% of the single-leg jumping distance) patients start to rely more on compensating techniques, such as arm swings and torso movements, to increase their distance and keep their stability. Especially during the speed decrease in the landing are such compensation techniques used to reduce load on the quadriceps. According to the physiotherapists, adapting the landing strategy in such a way is not good or bad per se, but the difference between the strategies used for the two legs is something that they take note of during single-leg jumps and might be interesting to further analyse. It is also possible that patients may not use such torso-moving compensation strategies when wearing VR goggles, as bending forward may risk the goggles sliding off.

C.2 Evaluation sessions of the interaction

Aside from the shadowing sessions of the physiotherapists at OCON Orthopaedic Centre, the initial VR and interaction concepts (described in subsection 4.2.2) were presented to three physiotherapists and one orthopaedic knee surgeon at OCON. During this session, the three concepts were presented, after which the attendees gave their feedback on aspects that they would find beneficial in the interaction or not. In addition, the physiotherapists were asked for comments on specific aspects. Their insights are gathered in this section, with additional comments made on how the insights led to additional ideas for the development.

Based on their comments, concept two, which consisted of the sporting game, would be the least desirable, as there are many different types of athletes who come to OCON, and most would, therefore, not recognise their own sporting environment in the interaction. The physiotherapists did indicate that this concept did hold the most promise for future expansions if multiple sports environments could be rendered (such that each patient could experience the interaction within their own preferred sporting environment), but for now, a more generic environment would be suitable. The physiotherapists found the first or third concept the most interesting, with the first being the most immersive and the third one having an interesting game element to it.

Another point that was discussed during this session was the option to adapt the visual texture of the ground. This way, if patients would have the visual experience that their jumping landing is on a soft ground but it is actually the (real-life) hard ground, they will have to quickly adapt themselves. However, there would then be a sensory disconnection between what the user sees in the virtual environment and what they feel as they walk around. As humans are very adapting to their environment, this might not have a significant effect. In addition to this, the physiotherapists thought it was beneficial to use a point-based reward system (as was initially described for concept 1) and to introduce a competitive element. They described that their patients are often athletes, who are always eager to have a competition. With regards to an initial base measurement of the maximum single-leg jump, it was determined that it helps people to have a goal. In the current situation, patients often take note of lines on the floor to see if they are improving themselves over the trials they have for the single-leg jumps. Therefore, it might be good to first have an "open" maximum single-leg jumping trial, which allows the system to evaluate how far users are able (and feel comfortable) to jump within the VR system. The system could then provide them with a jumping goal which is set further than their initial trial, to see if the user can be motivated to jump further. Based on these insights from the physiotherapists, it would be interesting to first determine the "real-world" single-leg jumping distance in the same way as is currently being measured in practice. After this, the user can make a maximum single-leg jump in the VR environment to see if the unusual environment, as well as the VR goggles on their head and controllers in their hands, affect their jumping distance. Finally, it was suggested to evaluate how accurate the single-leg jump would have to be. Within the initial concepts, it was determined that the user would have a starting point and a target to jump towards (with the distance between the two being adapted based on the maximum single-leg jump distance for either leg. The physiotherapists indicated that it might be interesting to consider, possibly in a future iteration, to also evaluate how well the person performed the jump by having the target be similar to a bulls-eye target, where the closer someone lands to the centre of the target, the better the jump (and, possibly, the higher the points gained for it). Based on this insight, it might also be good to consider whether a user has a stable landing on their single-leg, or whether they have to correct their position by making an additional jump or putting their other foot down. A similar evaluation is done in the current practice (see also the description in subsection C.1), where a single-leg jump is not considered when the patient does not land correctly. Here, this evaluation is done by inspection of the physiotherapists, this could also be done in the interaction environment, where the physiotherapist can remove data from jumps they did not consider to be correct.

One of the issues that were raised for the implementation of the design within practice is the required space for the interaction. To have an engaging interaction, patients would need to walk around to explore the world around them and be triggered to make jumps where appropriate. This requires a larger space than what is currently available at the OCON Orthopaedic Centre in Hengelo (or, to the knowledge of the OCON physiotherapists, most other physiotherapy clinics). While the evaluation of the system would be held within a large space at the University of Twente (such as in the sporting facilities on campus), the implementation in practice would, therefore, be an issue. This point was, for the current stage of development, considered to be a future issue, as the extensive evaluation of the system and its possibilities would take precedence over the required space. The physiotherapists were more interested in gaining an understanding of what was possible with the system and how users would react to it, with limitations in the available space being possible to adapt later on once the evaluation was complete.

D
PATIENT INTERVIEWS

To understand the journey of patients throughout the rehabilitation trajectory (see 2.4), two patient interviews were held. Within this appendix, an edited, summative transcription of these interviews is provided.

D.1 INTERVIEW WITH PARTICIPANT P01

Participant P01 is a 24-year-old woman, who was in the 5th month of her ACLR rehabilitation during the interview. The participant plays basketball, which involves a lot of turning, jumping and having short sprints. Having started in 2011, the participant used to train once a week and had, during the season, additional competitions at the weekend. In addition to this, she used to do fitness, which would result in around 5 times sporting per week. The participant suffered an ACL injury when she was playing a basketball game with friends. The injury occurred without being tired from the game and having warmed up beforehand. She was in the air after a jump during an attack on the basket, while she came into contact with an opponent. This unbalanced her during her landing on her right leg while rotating, which as a result shot out from under her. After the injury happened, the participant took time to stretch her leg but was eventually able to continue playing. The day after, she had trouble with walking the stairs and visited a physiotherapist. Here, she underwent a set of standardised tests that determined she had an ACL rupture. She was then referred to her general practitioner, who ordered an MRI. Based on the results, she received consultations from her general practitioner, and later also the surgeon, that determined that an ACLR was the best option for her. In the meantime, she continued going to her physiotherapist to train the muscles in her upper leg (specifically her hamstrings) to increase the probability of a better outcome after the surgery. In addition, she did stretching exercises at the physiotherapist to allow for easier placement of the autograft. She waited two months between her fall and her surgery. During the operation, a part of the tendon of her hamstring was removed to replace the ACL as an autograft.

After the operation, the participant was told she should start rehabilitating with the physiotherapist as soon as possible. Specifically, she was told to do stretching exercises to prevent stiffness of the knee. The day after her surgery, the participant started her rehabilitation with three sessions at her physiotherapist per week. In addition, she did the following exercises three times at home in three sets of 10:

- Stretching her toes towards herself while sitting down.
- Pushing her affected knee into the ground to excite the hamstrings, while keeping the leg stretched.
- Bending her foot with a washing cloth on it towards her.

Two days after the operation the bandage around her knee was removed. She then wore a compression stocking for two weeks while continuing the exercises above and adding one.

- Sitting on a chair and slowly lifting her affected knee off the ground.

Aside from these, she also continued stretching exercises. In addition, she made sure to walk every hour to prevent thrombosis onset. During her physiotherapist sessions, she would do cycling exercises on a higher saddle that would keep her knee angle large. She slowly progressed from walking with two crutches to walking with one crutch to walking completely without. During this time, she focused on doing strength training with deadlifts, squats and leg presses.

As she could slowly start with running again, she also performed ladder training. The running itself started on a treadmill at a very slow speed and under short time intervals. In the beginning, she found this to be quite painful due to the continued impact of her knee on the ground, but this improved over her training.

The next step was for her to relearn how to make vertical jumps again. She started with two-legged jumps and progressed to single-leg jumps. At the moment of writing, she is currently still progressing through the jumping exercises. She now visits her physiotherapist twice a week, once for strength training and once for jumping. During the jumping training, she works on jumping with one leg on and off a step. During the jump down she automatically locks her knee, as she subconsciously aims to avoid a new injury. For her, this is a part of the fear of movement she is experiencing in her rehabilitation. She is now learning how to bounce on impact rather than keeping her knee stiff. She also still does running in straight lines (without turns and rotational movements) on a treadmill.

During one physiotherapist's session, she noticed that she has less proprioception in her affected knee compared to her unaffected knee. This is because the sensors of the ACL were removed, so she now needs to relearn how the various movements of her knee feel to her when doing the movement exercises. She noticed this while doing squats in front of a mirror and kept checking to make sure the knee movements were symmetrical. Based on her physiotherapist's advice, she started doing the exercises with her back to the mirror, which required much more focus and led to an asymmetrical result because she could not feel the movement as well as before.

At the beginning of her rehabilitation process, the participant knew that there was a chance that she would not be able to fully stretch her leg after the surgery, which motivated her to work hard with the physiotherapist during the preoperative phase. Additionally, the participant was motivated in doing her exercises by not feeling pain but rather feeling better in movement during her recovering period. However, the participant's main motivation comes from the fact that she wants to play basketball again with her team and return to competitions.

The participant has made big strides in her rehabilitation. Currently, the main limitation she notices is that she cannot sit on her knees. She is now able to bend them fully, but sitting on her knees stretches the autograft, which hurts her and worries her of rupturing the tendon again. Her current goal is to rehabilitate to be able to do this again, as she is focused on rehabilitating herself back to her pre-ACLR state again. Her additional goal is to train her muscles to better protect her from a re-injury. This helps motivate her through her strengthening exercises. From her physiotherapist, she receives general encouragement

through the exercises, but her progress is based on her internal motivation. Knowing that she is doing well compared in her rehabilitation to others in the same phase is also motivating to her, although she acknowledges that if she would be on the negative side of the comparison she would be demotivated by it.
The exercises she performs during her rehabilitation are not aimed at basketball in particular, which is what she aims to return to. A large component of her current rehabilitation consist of strength training and jumping, which are often needed for basketball, but the exercises are not particularly tailored to the sport that the participant will return to. During the final phase of rehabilitation, the participant is allowed to train along with her team, which does introduce sport-specific elements into the rehabilitation. At the start of the rehabilitation, both the physiotherapist and the surgeon of the ACLR inform about the sport that the participant wanted to return to, such that they can give a more tailored recommendation about the procedure.

Based on the protocol made for the participant, her physiotherapist decides whether she is ready for the next phase of the rehabilitation based on their experience and the comparison to other patients. The exercises in the protocol are based on the rehabilitation phase and the available equipment and space. For the participant, this means that there are no options for specific basketball elements to be incorporated in her rehabilitation, while at other physiotherapists there are opportunities to, for instance, allow football players to incorporate short sprints on a football field. Aside from the sport-specific component, the physiotherapist does check the progress of the participant during each session and adapts the training to it, for instance by switching from running to cycling when the participant is tired.

When thinking about returning to basketball, the participant feels very saddened that she is unable to join sooner. She still joins the training sessions to remain part of the team but has abandoned her aim to do her rehabilitation exercises while the team trains, as this pushed her to work beyond her limits. Because she loves her sport so much, sitting on the bench is very hard for her, but she does like that she can still cheer on her team. She does feel uncertain about whether something else might happen again when she returns to play. The participant knows that there is a probability that the other ACL might be ruptured because she would be (subconsciously) compensating for her affected leg. Because of this, she thinks that in the future would avoid competitor contact in the games. She also thinks that when she returns to play she might slowly feel more secure in playing, but that she will always keep the fear that she might re-injure her knee. When it comes to the stages in which the participant would like to return, she envisions them as the following:

1. Starting with training but not joining competitions. During training, she would also avoid the practice games but rather do more individual training.

2. Once she can do the individual training well, she would join the training exercises with her team members, as they know of her injury and will likely be sure to play calmly with her.

3. Moving towards practice games with her team during training and joining the warming up of competitive matches but not playing in the actual game.

4. Slowly starting to play the competitions again, while avoiding intensive competitor contact.

Currently, the participant already completed 4.5 months of rehabilitation and she thinks that there has been a lot of progress now that she can do running and jumping again. The estimation for the entire rehabilitation is 9-12 months, so she thinks that her rehabilitation is going much faster than expected. At the same time, the rehabilitation does seem like it has been going on for a very long time for her.

D.2 INTERVIEW WITH PARTICIPANT P02

Participant P02 is a 23-year-old woman, who does competitive skating. She has skating training 3 times per week. In addition, she does running, power training and cycling, which gives a total of 4-6 times per week (depending on whether she is in the competition season or not). She started at 7 years old with skating when her father signed her up for it. Before her ACL injury, she also exercised 4-6 times per week, which had increased during her student time. Three years prior to the interview, she had an ACL partial rupture.

The partial rupture occurred when she was playing a game of ribbon rugby, where the objective is to take someone else's ribbon rather than tackling them, making the game supposed to be safer than actual rugby. She was sprinting forward but slipped while decreasing speed and her leg shot out in front of her. She fell while her knee was bent 90 degrees and heard three snaps in her knee. The knee immediately became very thick. After checking with a local physiotherapist that she could not be checked upon as an emergency case, participant P02 was finally able to visit a physiotherapist days later and, days after that, with a general practitioner. In the meantime, she walked on crutches. After her second physiotherapist appointment, she was referred to an orthopaedic surgeon and got a second opinion.

Before her operation, she had an MRI, before she only had a Rontgen scan. She had to wait 6 weeks for the MRI and another five weeks for the results. She had to do the MRI because it was not certain (based on the Rontgen) whether her ligament was ruptured or not. From the MRI it also appeared as if cartilage was floating around the knee. Therefore, she also had to do a looking operation. From this, it was determined that the cartilage was still intact, but the ACL was a partial rupture in length. The ends of the ligament became cyclops (small props), which were removed. During the removal, the surgeon pulled on the knee to determine whether there was enough resistance to give a stable knee. Five days after the operation she started with the physiotherapist twice a week for rehabilitation and three months after the fall she had her surgery.

At the physiotherapist, the participant had to do specific exercises. The physiotherapist knew that the participant wanted to skate again and adapted the procedure to that goal. This meant that she had to do, among others, a lot of jumping exercises. Other exercises were to do stepping-up a block exercises with one and two legs; jumping off, balancing, and continuing; one-legged hopping – during which she noticed that the knee control had become different after her surgery (thinking on how to do the jump and continue); training hamstrings with bridge exercise; jumping off objects; and squats. At the beginning of her rehabilitation, she started with squats and one-legged deadlifts for stability, while later she did more jumps and the exercises became more targeted to skating.

At home, she mainly did leg stretching exercises, as she was unable to fully stretch her leg (last degrees were difficult). She also put elastics attached to the coach around her leg to stretch to add more resistance and train her quadriceps. Furthermore, she pushed herself up from lying on her back to train the hamstrings. Aside from the exercises, she started building up her running and cycling condition. For her, the focus was less on power training and more on being able to run and cycle again. This mainly entailed running with a low heart rate, to keep the impact on her knee low.

Her motivation through the exercises was that she wanted to be able to skate again. She was at a very high level in the season before her injury, and she wanted to reach and surpass that level again. She thoroughly enjoys exercising and wanted to be able to compete again. The physiotherapist was thinking along with her wanting to skate again and adapted the exercises to this. At times, she was fearful of moving and putting pressure on her knee again, but her physiotherapist motivated her to try. Generally, however, her physiotherapist was the one slowing her down when she wanted to push herself too far.

Regarding the fear of movement, she was afraid that the knee would be hurt again. She especially had this fear when jumping backwards. The fear was amplified by not being able to do anything with the knee for over 3 months.

The physiotherapist evaluated her progress during training by asking her to rate her pain. Based on that, the therapist determined which exercise would be done during that session. At the end of her rehabilitation, the therapist did a few standard tests to determine the strength in her knee compared to her unaffected leg. This consisted of jumping left and right over two lines for 30 seconds and the single-leg hop test. The tests were performance indicators but not real predictors for skating (only for knee stability).

She had the surgery in September and in January the year after she was able to skate again. The return to play was very exciting for the participant. At first, she did not want to overexert herself and felt nervous to skate again. She also experienced some pain in the corners when exerting force sideways. She would then take a break in training. While returning to play, she had a "no pain = no harm" mentality, meaning that she felt confident as long as she was not experiencing pain. After completing her rehabilitation, she still visited the physiotherapist a few times because her knee would be thick and painful due to fluid in it, which was related to her injury and hurt.

The most important aspect of the interview for the participant was that her physiotherapist adapted the therapy to her wish to return to skating. Her therapist also told her that, because she would return to skating and not to a ball playing sport, there would, for instance, be no purpose in doing ball-related exercises and that they both rather focus on skate-specific exercises. She would find it, therefore, interesting to develop something which makes the therapy more targeted to the sport of the patient, as this was very helpful for her.

The rehabilitation was very easy for her, but this is also partly because she does a lot of sports already. For people who do not exercise a lot, the rehabilitation might be harder, as they might miss motivation. The knee will not become healed by itself. In addition, having a good therapist is very important for rehabilitation.

E
OVERVIEW OF PHYSIOTHERAPIST EXERCISES

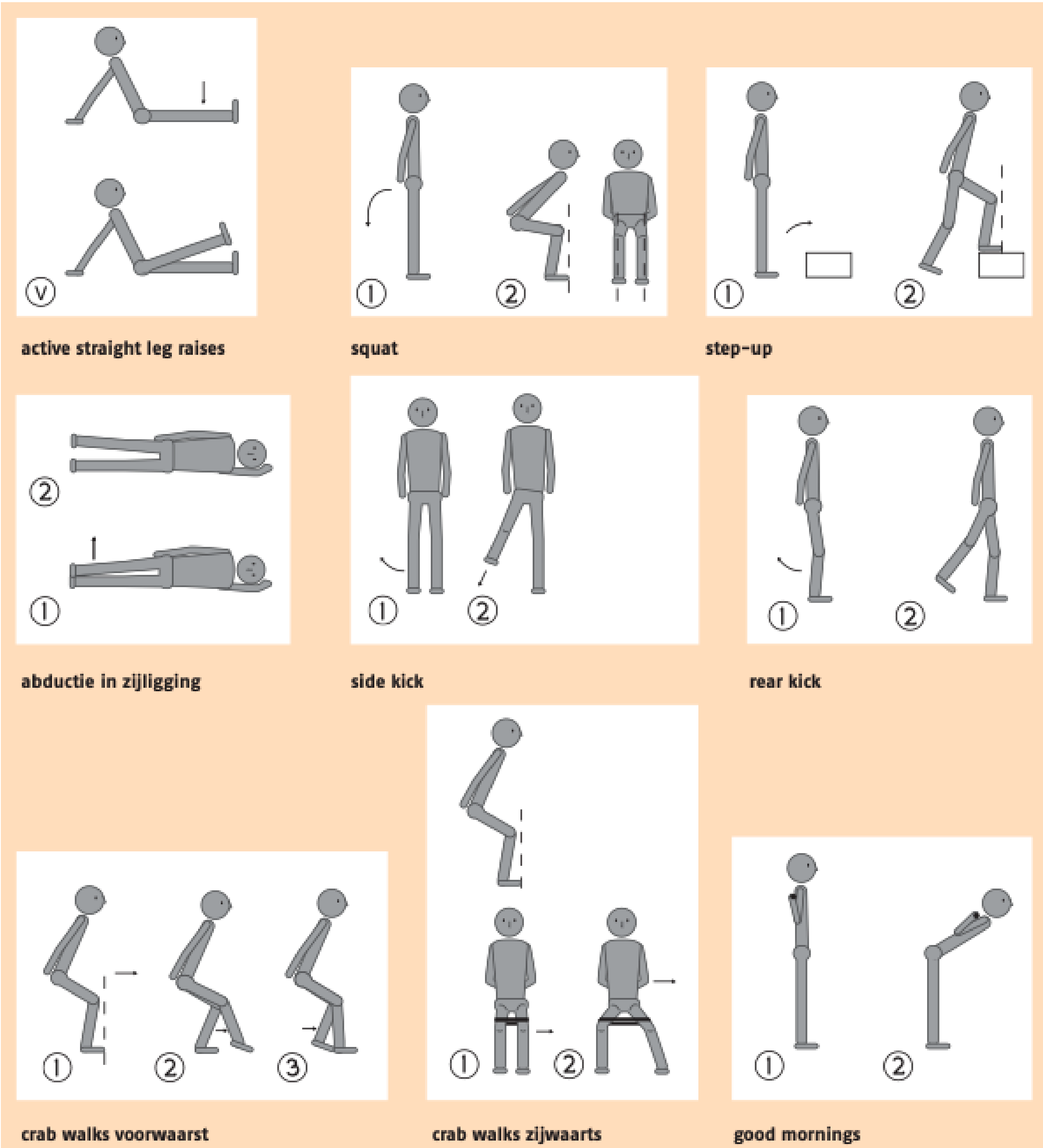


Figure 33: Rehabilitation exercises for increasing strength in the early postoperative phase (up until 6-8 weeks postoperatively), from [2].

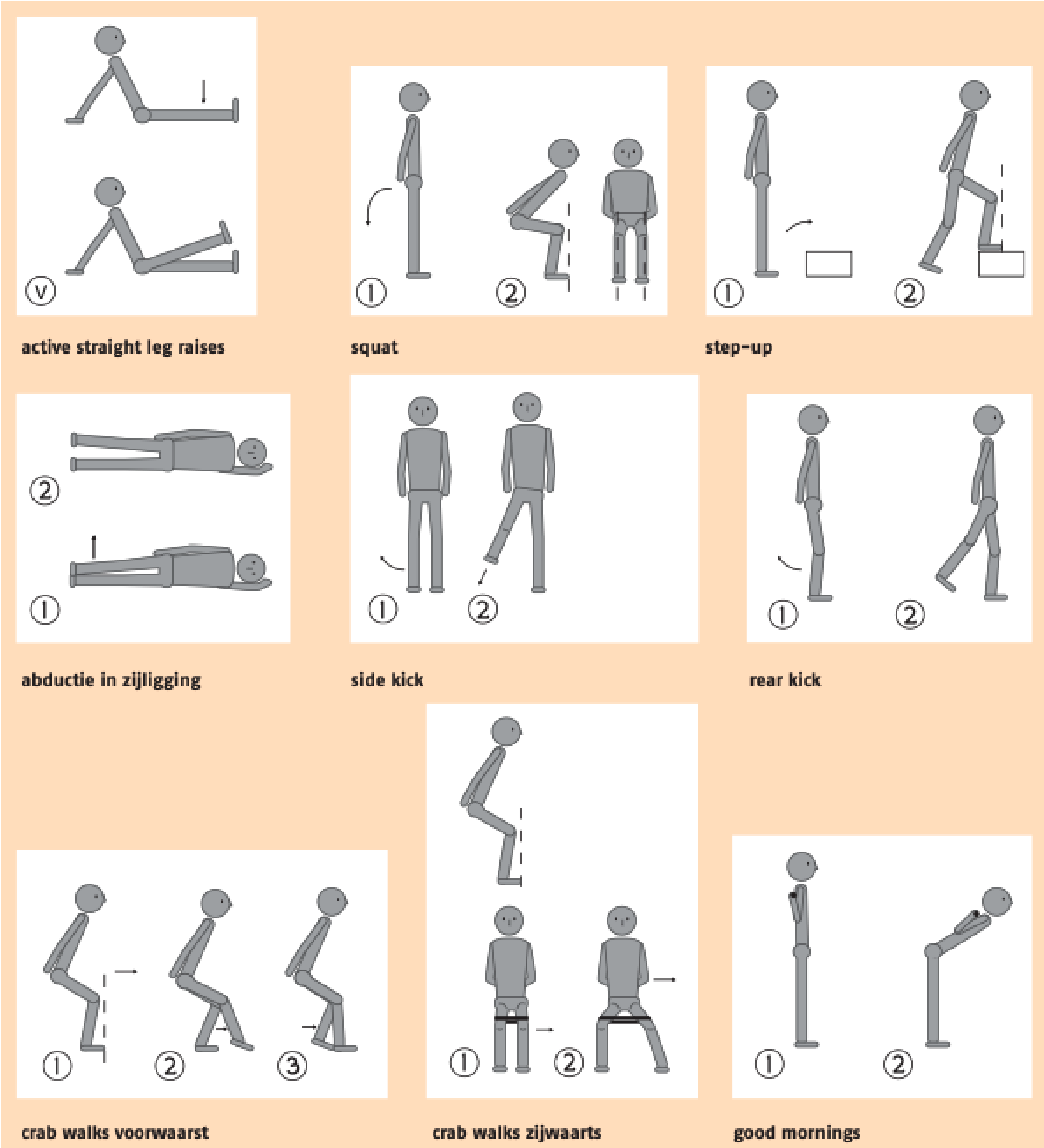


Figure 34: Rehabilitation exercises for the strengthening phase/return to activity phase, from [2].

F

ADDITIONAL NOTES ON DESIGN

From a holistic perspective of the design, the aim of the system is to complement the existing RTS diagnostic evaluation currently used in practice. The system builds on the existing practice to create a meaningful and objective evaluation. This integration of the developed system within the current practice is shown in Figure 35. As was discussed in subsection 1.1, there are two main objections to the current practice, which can be summarised by the lack of objective measurements on the one hand and the use of a non-sport-specific diagnostic context on the other hand. The aim of the VR and sensor integration is to create a system that effectively addresses both issues. Connecting this system to the current practice means that the physiotherapist remains the sole interpreter of the provided sensor data. The algorithms within the system are descriptive and do not take over the expert role of the physiotherapist. This makes the system complementary rather than an oracle module that takes the gathered data to immediately provide a diagnosis. This interaction between the system and the physiotherapist can be seen in Figure 35, where the system essentially works as a "sixth sense" layer to provide the physiotherapist with information about the patient's movement behaviour that would not be visible without the intervention of the technology. Rather than only having direct observation, the technology makes the invisible seen to the physiotherapist by enriching their perceptions of the movements through data. It is important to note here that the physiotherapists in practice do not have specific measures that qualify a jumping movement as 'good', which was also discussed in subsection 2.3. Therefore, the technology at this point can only be used as a supportive measure rather than fully assuming the interpretation of data as well. The sixth sense layer helps the physiotherapist by making the unseen visible, providing objective data on certain key parameters regarding knee stability, and by visualising that data, such that the therapist can see more and arrive at a better and more grounded diagnosis. Adding the sixth sense layer may also adapt the internal model of the physiotherapist to the movement pattern, which can lead to a better understanding of what metrics form a good jumping performance.

The holistic overview of how the system and the physiotherapist must work together is presented in Figure 35. Here, the system is represented as the sixth sense layer (visualised as a mirror) through which the physiotherapist is able to monitor the performance of the patient. On the side of the physiotherapist, data comes in that compares knee stability parameters between the healthy and the unaffected leg. Based on the presented data, the physiotherapist is able to gain a deeper understanding of the patient's movements based on metrics that are unseen in the current practice. For the patient, the system adds three specific aspects. First, the system includes gamification aspects, which specifically here entails a platforming game with rounds and levels, as well as a leaderboard construction in which the patient can compare their performance to that of previous rounds. Secondly, the system is hosted through an interaction for which the projection gamification and a VR setup were compared. The final step includes data processing through machine learning. This specific component

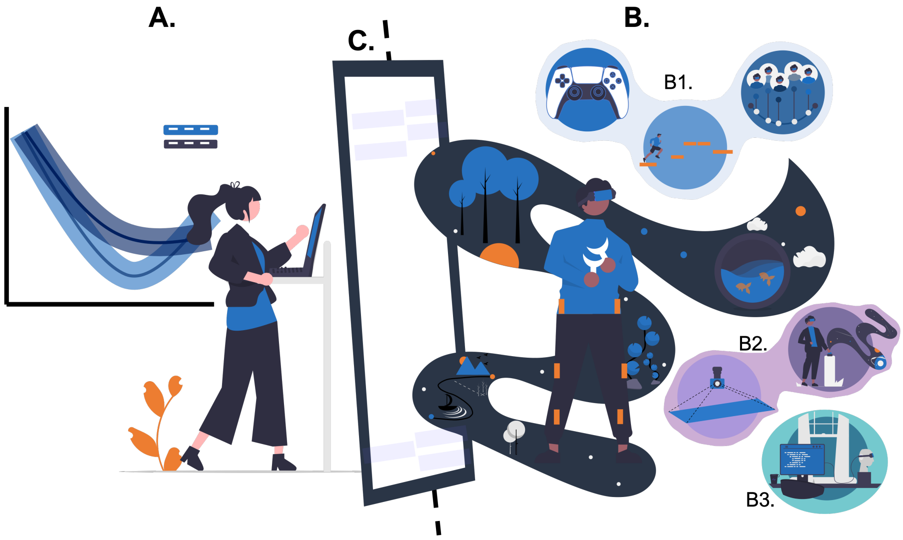


Figure 35: Overview of the three system components, with the physiotherapist (A) looking at their patient (B) through a "sixth sense" layer (C) to evaluate the movement performance. This performance is affected by gaming, platform interactions and leaderboard dynamics (B1); projection gamification or Virtual Reality design choices (B2) and underlying algorithms and machine learning (B3).

transcends the system within its original setup by further increasing the role of the sixth sense layer, also further described below. On the patient's side, the system is engaged in triggering movement behaviours and measuring related parameters that are potentially discriminating for a diagnostic-relevant evaluation. Here, the data of the affected knee is compared to reference data (e.g. data from the healthy leg; by comparing earlier movement performance to the current behaviour or by comparing to other patients in a similar rehabilitation phase). The final step to this is to implement movement detection and diagnostic interpretation of the data to serve as an oracle module to the physiotherapist.

On each of the three parts of the system (the data interpretation of the physiotherapist; the sixth sense layer and the interaction and sensor measurement occurring at the patient) adaptations can be made to further improve the setup. An example for the physiotherapist would be to generate an augmented environment that strips the sixth sense mirror away in favour of a more immersive setup that shows the patient's movement alongside relevant graphs or to include extensive evaluations with the physiotherapists to create even richer data for an optimal interpretation. For the sixth sense layer, additions could be made by utilising machine learning to create an oracle module that classifies patient movements and automatically interprets the data to generate diagnoses. For the patient, iterations could be made that create a more immersive gaming experience or to tweak the sensor placement and algorithms to increase the depth of the data. However, for the initial setup of this system, a proof-of-concept will be generated that considers a simple sensor setup with a single interaction task, gathering data that is presented to the physiotherapist using straightforward statistics and designs. Based on this initial proof-of-concept, recommendations may lead to continued improvements on any of the three components in future work (this is described within Chapter 8).

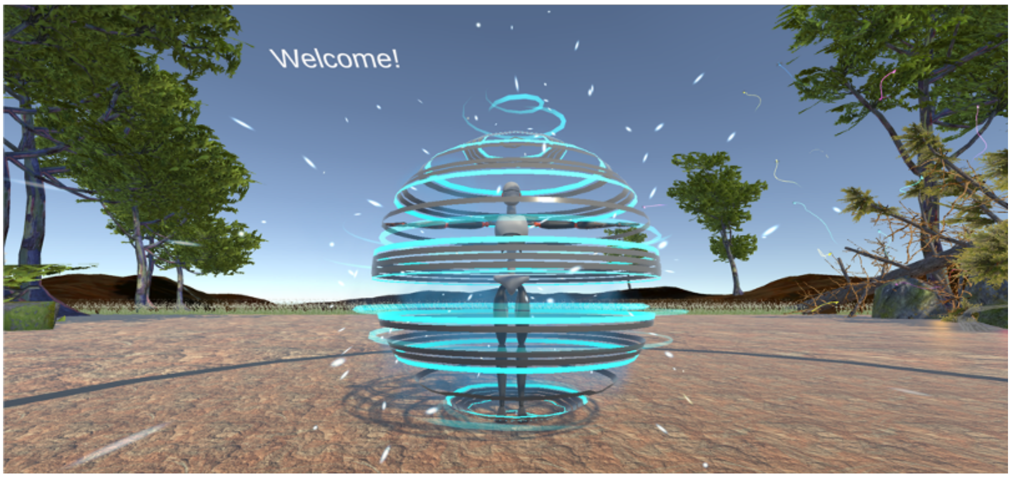
(a) MVN sensors within their protective case.

(b) Oculus Quest 2 HMD alongside its two controllers.

Figure 36: MVN sensors and Oculus.

(a) Yogaball approaching lavaball.

(b) Lavaball explosion (with an outward pressure wave causing a mirroring distortion) after being hit with a yogaball.



(c) Respawning animation.

Figure 37: Overview of the lavaball and respawning animations. Shown is the Movella MVN avatar in place of the user with the information text displayed in the sky.

G

EVALUATION OF THE INTERACTION CONCEPTS SURVEY

To evaluate the perception of the three concepts described in subsection 4.2.2, a survey was held. In this survey, participants were asked about their experiences with (ACL) rehabilitation and to evaluate the presented concepts based on their overall ability to be applied for ACL rehabilitation, the embedded motivational aspects and their ability to distract users from the movement task. In total, $n = 35$ participants completed the survey (response rate of 85%). Of this group, 25 participants were female, with the majority (91.2%) of the participants belonging to the 21-25 age category, and a majority (79.4%) having a Dutch nationality. A full overview of the demographic data from the survey is presented in Table 8.

Table 8: Demographic data from the concept evaluation survey.

Participant demographic	Number of participants (percentage of total)
Gender	Female: 25 (71.4%) Male: 10 (28.6%)
Age	18-20: 2 (5.7%) 21-25: 31 (88.6%) 26-30: 2 (5.7%)
Nationality	Dutch: 28 (80.0%) German: 2 (5.7%) Indonesian: 2 (5.7%) Indian: 2 (5.7%) Romanian: 1 (2.9%)
Participating in physiotherapy	Yes, participated in ACL rupture physiotherapy: 1 (2.9%) Yes, participated in other forms of physiotherapy: 13 (37.1%) Never participated in physiotherapy: 21 (60.0%)

The 14 participants who have participated in physiotherapy completed additional questions about their experience during their rehabilitation. Of this group, 7 (50.0%) completed their rehabilitation longer than a year ago. Two individuals (14.3%) completed it 1-3 months prior to filling in the survey; one person completed it 4-6 months and another two 7-12 months prior. One person was still doing physiotherapy and had started less than 6 months ago, one person was still in physiotherapy and had started more than 6 months ago. Within this group, 8 individuals (57.1%) indicated that they were not rehabilitating to return to playing recreational or professional sports again; 5 respondents (35.7%) indicated were rehabilitating for sports and one person (7.1%) was unsure. Participants were asked to rate statements about their rehabilitation on a scale from 1 ('never') to 10 ('a lot'). Using this Likert scale, the participants provided a mean score of 5.4 (standard deviation of 2.1) to the question "Do/-did you experience any fear in making movements with your affected limb?". A mean score of 4.9 (standard deviation of 3.0) was given to the question "Do/did you experience a lack of motivation to do your daily physiotherapy exercises?". Finally, participants gave a mean score of 3.0 (standard deviation of 2.4) to the question "Do/did you experience a lack of motivation to visit your physiotherapist?". When openly asked participants indicated that more enjoyable exercises and better insights into the underlying issues they were rehabilitation for and their progress could have improved their motivation during the entire rehabilitation overall. For the general rehabilitation, participants indicated that a clearer schedule of their exercise progression would have created a smoother process. In addition, participants put a lot of emphasis on the effect that the physiotherapist has on their rehabilitation, with the availability, encouragement and support from the physiotherapist being a key point for their own motivation. For the question "Did you feel secure in the evaluation of your rehabilitation progress by your physiotherapist", six participants indicated 'yes, very much'; five indicated 'yes, a reasonable amount', one participant was neutral and two indicated 'no, not really'. Regarding their RTS moment, of the nine participants who had reached this phase, one felt very self-assured in their own movement abilities in this phase; three felt reasonably self-assured; one participant was neutral and five did not feel self-assured at all. Of the participants who did the RTS phase, five noted that they would have liked a better transition in their rehabilitation to go from generic to sport-specific exercises.

After receiving basic information on ACL rehabilitation, all participants continued to fill in questions regarding their perception of the application of VR and interactive elements in a (hypothetical) ACL rehabilitation process. Participants rated statements on a Likert scale ranging between 1 (absolutely do not agree with this statement) and 10 (absolutely agree with this statement). An overview of the mean values and standard deviation per statement is provided in Table 9. Based on these results, it seems that this group of participants would be very willing to participate in a study that applies VR within rehabilitation (mean score of 8.0 to try out such a system). However, the willingness to do ACL rehabilitation evaluations in the VR system (systematically) is lower than for the current, physical world evaluations (mean score of 5.3). Interesting is the difference in the willingness to walk and move versus the willingness to jump in the VR environment. This result might indicate that patients would need some time to adjust to the VR setting and get comfortable moving in it. Another important observation is that the participants' scores did indicate the importance of including an evaluation of mental well-being in the rehabilitation, participants were less willing to indicate such aspects in the interaction (mean of 6.7) as compared to discussing it with their physiotherapist (mean of 7.1).

The final part of the survey focused on evaluating the three interaction concepts described in subsection 4.2.2. After reading all three descriptions, participants were asked to indicate their preferred concept overall, as well as based on the provided motivational elements and distractions. The results of this evaluation are presented in Table 10. Note here that for the motivational elements, one person indicated not to have a preference (2.9% of the total). For Concept 1, participants often indicated a passion for a space-related subject, as well as the immersive ability of this idea, especially because of flying distractions which cannot be perceived outside the VR. Participants found the idea of using coins as rewards to be mo-

Table 9: Results from the concept evaluation survey.

Survey statement	**Mean score (standard deviation)**
I would be excited to try out a rehabilitation evaluation in a virtual reality environment.	8.0 (1.8)
I would be unafraid to walk and move around in a virtual reality environment.	7.2 (2.0)
I would be unafraid to make forward jumps on one or both legs in a virtual reality environment.	5.6 (1.9)
I would enjoy being able to interact with the virtual world around me (e.g. grabbing virtual objects) while I move around during an evaluation.	8.0 (1.6)
I think it is important to include mental wellbeing (i.e. experience of pain/fear during movement) with a standard/VR rehabilitation evaluation.	8.2 (1.3)
I would want the VR system to allow me to indicate my mental well-being (i.e. experience of pain/fear during movement) during the rehabilitation evaluation.	6.7 (2.0)
I would only want to discuss my mental wellbeing (i.e. experience of pain/fear during movement) with my physiotherapist rather than through a VR system.	7.1 (2.1)
I would prefer doing my ACL rehabilitation evaluations in a virtual world over the physical world (i.e. real-world lab setting).	5.3 (2.1)

Table 10: Response to interaction concepts.

Aspect	**Percentage of participants preferring concept**		
	Concept 1	**Concept 2**	**Concept 3**
General preference	14.3%	25.7%	60.0%
Motivational element	25.7%	28.6%	42.9%
Distractions	25.7%	8.6%	65.7%

tivational because it creates a 'safe' competition with themselves (although one participant did indicate that they would also enjoy being able to 'spend' their rewards somehow in the game). Multiple participants also indicated that they would enjoy this concept, alongside Concept 2 because it does not have a time constraint and was perceived as less 'stressful' than Concept 3. For Concept 2, participants specifically enjoyed a sportive environment that would be targeted to their individual sport. Interestingly, some participants stated that having a cheering sound as positive feedback would be motivational (with one person stating that they would prefer this concept as there are only positive forms of feedback), whereas others found this stressful and would not want this. Participants also indicated that the realistic setting of the concept was motivational. Several participants also indicated that having a 'gym-like' floor would make it feel safer to make a jump in VR as opposed to a less realistic surface. Concept 3 was considered to be the most game-like of the three, with the game elements naturally coaxing players into making the correct movements without overthinking them. For this concept, some participants indicated the time factor to be (continuously) motivating rather than stressful as was indicated by others. Some participants also indicated that by using time there is a competitive element, similar to the coin-based motivation used for Concept 1. In addition, the idea of adding 'dangerous' elements that the player should be on the lookout for was considered to be positive distractions that add to the immersion in the VR environment.

After evaluating each concept separately, participants were asked whether they would want to combine elements from different concepts, whether there were things they would absolutely not want to have in the interactions and whether there were still elements that they would like to add. Several participants indicated that they would enjoy the addition of the coins-element from Concept 1 embedded within Concept 3, or add the positive feedback with cheering from Concept 1 into Concept 3. In addition, the setting and storyline of Concept 1 were highlighted by several participants, while others indicated that the use of a motivational coach from Concept 2 could be implemented in the other concepts as well. With regard to elements that should be removed from the interaction, different suggestions were given. The most common element to be removed was the time pressure, as well as the use of auditory noise in the interaction. For additions, participants indicated that insights into their progression over time (e.g. between different rounds) would be very interesting. Furthermore, participants highlighted the motivational use of competitive elements, as well as storyline elements and additional characters that could follow the player in the interaction to provide motivation. One participant also stated that incorporating different types of jumps would be very beneficial to the interaction.

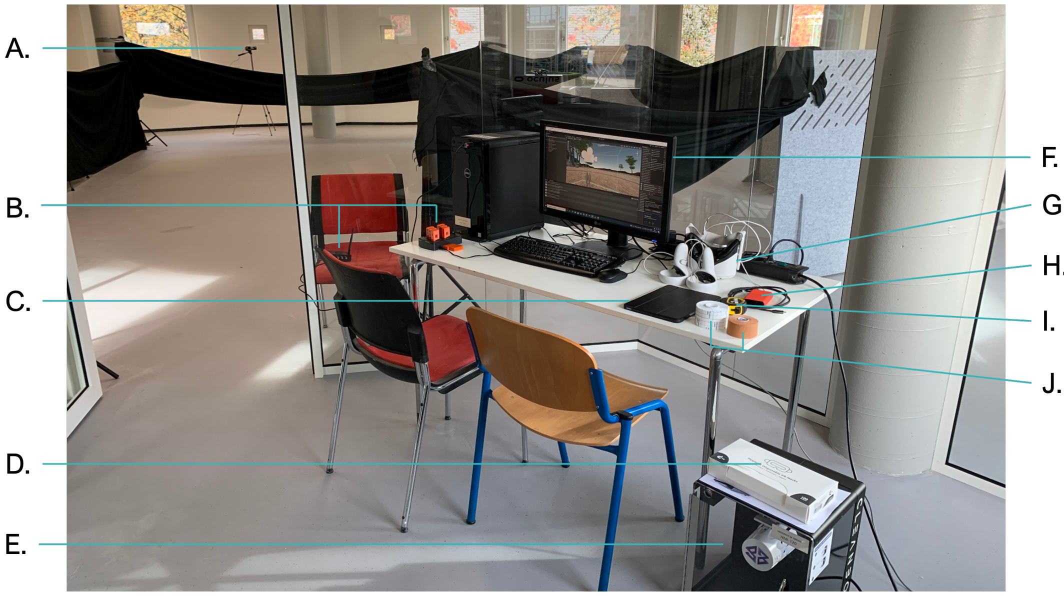
H
ADDITIONAL NOTES ON METHODOLOGY

H.1 OVERVIEW OF STUDY SETUP AND MATERIALS

Table 11: Materials needed for VR ACL evaluation study.

Material	**Amount**	**Purpose**
Study information brochure and informed consent; pen	N/A	Information for and signature of the participant.
Study sequence of operations; study case report form	N/A	Keeping track of study process.
Computer setup with webcams	1	Running VR experiences.
Router ROG Rapture GR-AX11000 with charger and network cable	1	Stabilising Oculus Air-Link connection.
Oculus Quest 2 (HMD and two controllers)	1	HDM for VR.
Oculus Quest 2 disposable coverings	1	Hygienic covering for inside the Oculus Quest.
VR HDM cleaning box	1	Cleaning of Oculus Quest after usage.
Measurement tape	1	Measuring real-life and VR maximum single-leg jumps.
Audio recorder	1	Recording interview sessions.
MVN sensors with straps, dongle and Awinda station	1	Biomechanical measurement.
Fixomull stretch and Leukotape P sports tapes	5	Providing perturbation to the leg.

(a) Testing environment setup showing the participants' real-world playing space. Participants' interaction with real-world pillars was prevented through soft boundaries hung up to cordone part of the environment.



(b) Setup of materials needed for the evaluation, including the video camera (A.), the MVN sensors charging and the MVN Awinda (B.), an iPad for note taking and audio recordings (C.), disposable HMD coverings (D.), VR cleaning box (E.); computer streaming Unity scene and SteamVR (F.), Oculus Quest 2 HMD and two controllers (G.), external charger for HMD (H.), measurement tape (I.), Fixomull stretch and Leukotape P sports tapes (J.).

Figure 38: Evaluation session setup showing the soft boundary and the technical setup.

Table 12: Overview of tested perturbations to simulate ACL-rehabilitation jumping behaviours in participant P21. For each jump, both the participant's dominant (right) and non-dominant (left) leg were tested with the perturbation unless indicated otherwise, and both as the jumping and swinging leg.

Trial number	**Description of perturbation**	**Observations of testing**
1.	One stroke of sports tape (brand Leukotape P) attached centrally on the leg, taped in extension.	Participant P21 considers the jump landing to become more stable. There is still a good knee flexion angle (approximately 85 degrees), so perturbation seems ineffective.
2.	Three strokes of sports tape, attached centrally, laterally and medially. Duct tape was added to keep the underlying sports tape from letting go.	Physically very restrictive, making it harder for the participant to walk and jump. During jump landing, the participant overshoots and has difficulties slowing down and correcting his movement. A visible wobble on impact and sideward correction is needed; the participant almost touches the ground with his hand to stabilise himself. After one jump, the tape on the knee was stretched out.
3.	Four strokes of sports tape, similar to jump 2 but with an added lateral stroke to keep the tape from stretching.	Knee seems to be searching for stability in landing and moves in all directions. Very strong wobble on impact.
4.	Use of a knee brace.	The brace gives a stable jump. Landing with the dominant leg seems less deep than with the non-dominant leg. The brace seems to be most limiting (and 'sitting in the way') on the swinging leg rather than the jumping leg.
5.	Use of a knee brace with added weights attached. Small sandbags with a total weight of 500 grams were tied directly onto the knee brace.	The weights do not seem to create a significant change in the landing strategy compared to jump 4.

Continued on next page

Table 12 – *Continued from previous page*

Trial number	Description of perturbation	Observations of testing
6.	Use of a knee brace with an added weight of 700 grams on the dominant leg.	When attached to the jumping leg, the participant can still generate a stable landing. When attached to the swinging leg, the participant becomes unbalanced during landing.
7.	Use of a knee brace with an added weight of 700 grams on the non-dominant leg.	The flexion angles on landing are similar to jump 6, but the participant does have an additional compensatory hop. The addition of weights to the knee seems to affect the balance of the landing.
8.	Holding a 1 kg weight in the hand on the jumping leg side.	No strong effect on the jumping behaviour was found.
9.	Holding two 2 kg weights in the hand on the jumping leg side.	No effect was found for the dominant side, but when jumping with the non-dominant leg a sideways unbalancing effect was found both when the weights were in the dominant and non-dominant hand.
10.	Two coin tokens taped together were placed inside the participants' shoe underneath the heel of the non-dominant leg to mentally affect the participants' landing strategy.	No strong effect on the jumping behaviour was found.
11.	A sponge was placed underneath the ball of the foot in the shoe.	No strong effect on the jumping behaviour was found.
12.	Added weights attached to the ankle. Small sandbags with a total weight of 700 grams were tied directly onto the ankle.	When the weight is added to the swinging leg, it limits the ability to swing and follow through.

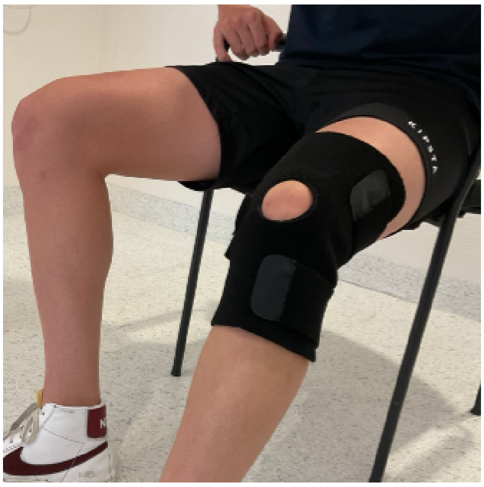
Continued on next page

Trial number	Description of perturbation	Observations of testing
13.	Use of sports tape combined with two weights (2 kg) in the hand opposite of the leg perturbation.	When the perturbed leg is swinging, it fully limits the movement. When the perturbed leg is jumping, the knee flexion is restricted. Additional correcting behaviours can be seen in added arm movement.
14.	Use of sports tape combined with two weights (2 kg) in the hand of the leg perturbation.	Light flexion is found in the landing and additional stabilisation is needed.

By applying the sports tape, flexion is the most restricted due to the physical barrier. The knee brace was also considered to give additional stiffness in moving, but as it was designed to provide stiffness in flexion it did not give any strong effects on the landing strategy. Adding either the coins or the sponge into the shoes also did not seem to affect the landing behaviour or the participant's mental anticipation of the landing. Possibly an effect could be found when putting something underneath the foot (or changing the floor characteristics for landing) to adept the proprioceptive experience of the landing but this was not considered feasible to achieve safely with the VR setting. The weights around the ankle did affect the balance during landing behaviour but were considered too dangerous for making participants jump in VR. The use of weights also created an imbalance, which does influence jumping behaviour but not necessarily as is the case for ACL-rehabilitating legs. When added with the sports tape, this gave a combined effect of limiting knee flexion with disturbing sideways balance. However, since mostly the knee flexion was of interest and the participant would also have to hold controllers during the interaction, it was decided to use sports tape to restrict knee flexion.

(a) One stroke of sports tape (trial 1).

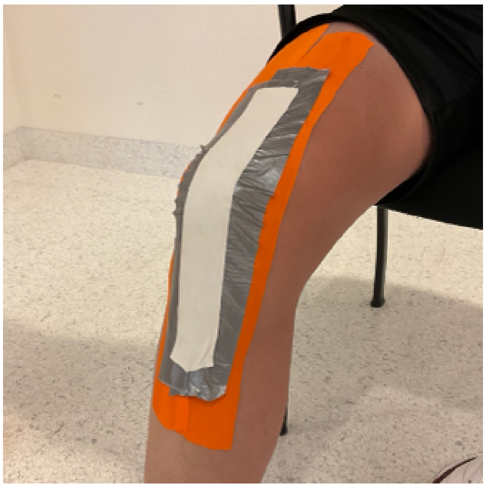
(b) Three strokes of sports tape held together by duct tape (trial 2).



(c) Use of a knee brace (trial 4).

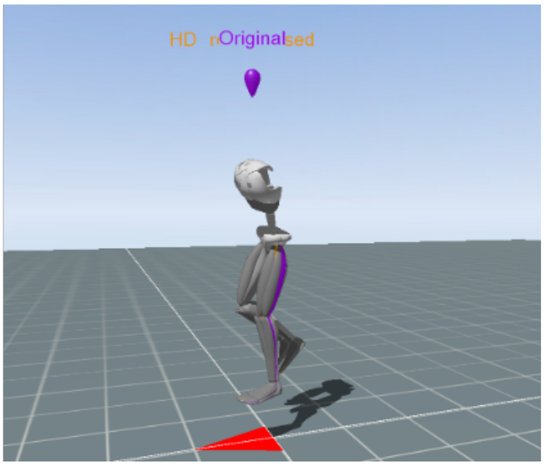
(d) Use of a knee brace with added weights (trials 5-6).

(e) Weights added to the ankle (trial 12).

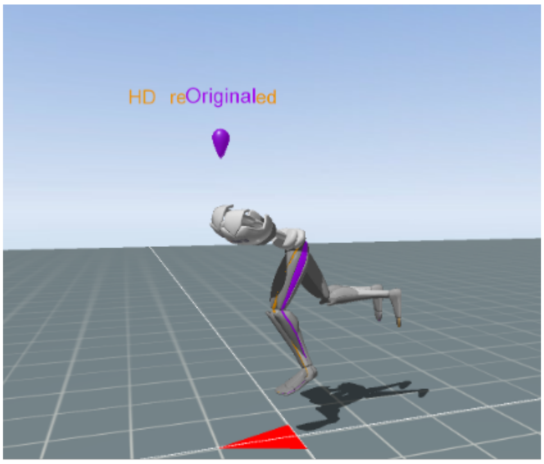


(f) Use of sports tape strokes being held together with duct tape and additional sports tapeP (trials 13-14).

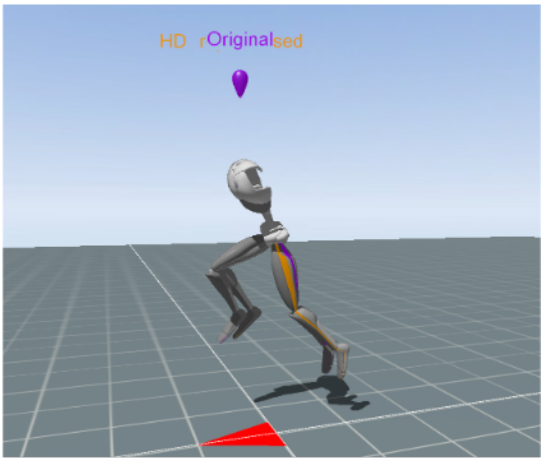
Figure 39: Overview of knee perturbations applied to participant P21.



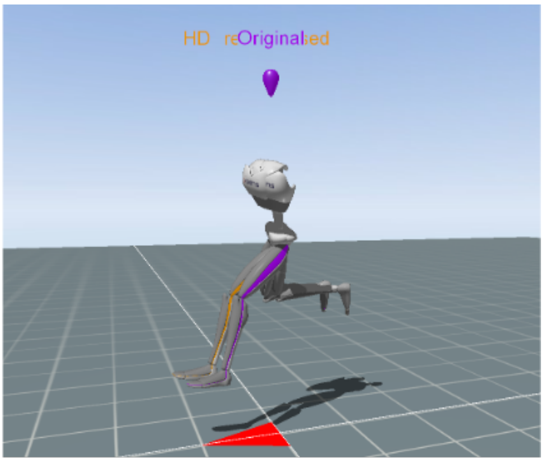
(a) Moving from neutral to start of the jump.



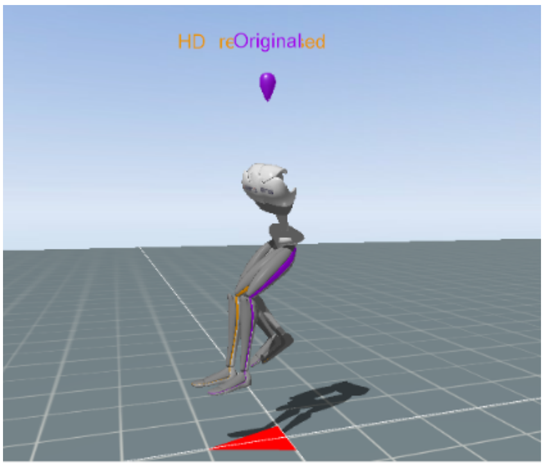
(b) Start of the jump.



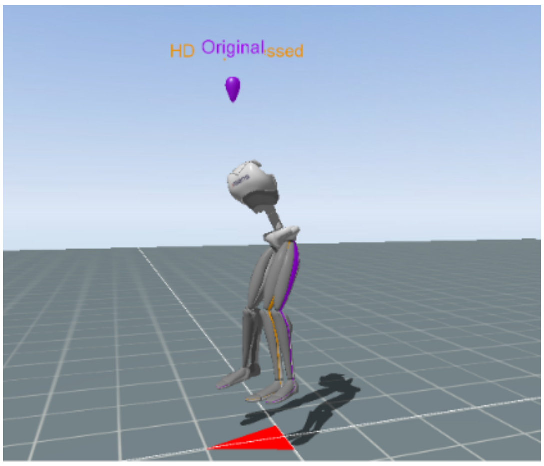
(c) Toe-off moment.



(d) Initial contact.



(e) Maximum flexion of landing.



(f) Touchdown of swing leg.

Figure 40: Effect of HD reprocessing, comparing the movement of the MVN avatar of the original file (shown with purple accents) with the HD reprocessed file (shown with orange accents) for the different phases of the perturbed non-dominant single-leg jump of participant P06.

Within the main Unity script, the variables described in Table 13 can be adapted to change the interaction gameplay.

Table 13: Overview of main adaptable variables in Unity master script

Variable name	Purpose
StartNewRound	Bool; if true, we start the new round.
WriteTheCVS	Bool; if true, we copy all timing and distance values to an Excel. Used at the end of the interaction.
AreWeDoingTheIntro	Bool; if true, we start with introduction instructions on the VR maximum jump and shooting lava balls.
NextInstruction	Bool; if true, we move to the next instruction.
PersonHasLanded	Bool; if true, we save the jumped distance from start to landing. Automatically switched to true upon the landing of the single-leg jump.
MaxJumpDistanceReal-Life (left/right)	Float; indicates the highest distance in meters that the user jumped in the real-life maximum single-leg jumps for the right or left leg. Insert after real-life maximum single-leg jumps.
MaxJumpDistanceVR (left/right)	Float; indicates the highest distance in meters that the user jumped in the VR maximum single-leg jumps. Check and adapt after VR maximum single-leg jumps.
CalibratePosition-Rotation	Bool; if true, we calibrate the rotation of the MVN suit with respect to the camera.
CalibrateMVNVertical	Bool; if true, we calibrate the vertical location of the MVN suit with respect to the camera.
JumpCompleteManual	Bool; if true, we manually complete a jump. Use when the participant does not correctly land on the landing target.
DualTaskLavaBall	Bool; if true, we use the dual task function.
FireARandomLavaBall	Bool; if true, we fire a random lava ball at the participant.

Continued on next page

Variable name	Purpose
TimeToLavaballFloat (min/max)	Float; indicates the minimum and maximum time in which a lava ball is fired at the user after standing on both jumping plane start circles.
LavaballDoesntCome-OneInXTimes	Int; adapts the odds that a lavaball is fired (the higher the int, the more likely the lavaball is fired).

I
POST-EVALUATION SURVEY AND INTERVIEW QUESTIONS

The survey and interview were held after the completion of the ACL-VR interaction. The full methods for this evaluation are provided in Section 5.3.

I.1 SURVEY QUESTIONS

The post-evaluation survey consisted of the following questions. For each closed question, the answer options are provided in *italics*. Before the start of the survey, participants

1. How old are you?
    a) *18-21*
    b) *22-26*
    c) *27-30*
    d) *31-35*
2. What is your gender?
    a) *Male*
    b) *Female*
    c) *Prefer not to say*
    d) *Other*
3. Please describe if you play videogames and your playing frequency (if any). [Open question]
4. Please describe any previous experience you have with physical rehabilitation (e.g. surgical, physiotherapy). If relevant, please indicate how long ago you had these experiences. [Open question]
5. Please describe any previous experience you have with knee injuries. If relevant, please indicate which leg and how long ago you had these experiences. [Open question]

Please rate the following statements on a scale from 1 (strongly disagree) to 5 (strongly agree).

6. I felt disoriented within the VR environment.
7. I would have liked the VR experience to continue.
8. I would recommend this VR experience to my friends.
9. I felt myself being 'drawn in' the VR environment.

10. I paid more attention to the VR environment than I did to my own thoughts (e.g. personal preoccupations, daydreams etc.).
11. I lost track of time during the interaction.
12. I enjoyed myself.
13. I felt mentally tired at the end of the interaction.
14. I felt physically tired at the end of the interaction.
15. I was actively trying to beat the time from my previous rounds.
16. I was very focused on performing a good jump with a stable landing.
17. I was more focused on the VR effects than on the jumping.

I.2 INTERVIEW QUESTIONS

The post-evaluation interview consisted of the following questions. Where relevant, (possible) follow-up questions are listed.

1. How did your perceived exertion change throughout the interaction?
2. How did the tape on your knee affect your movements?
   - Did the sports tape on your knee give you the idea that you should adapt your movements?
3. Did you think that you jumped further in the VR or outside the VR? Why?
4. How did it feel to make jumps in the VR?
   - Was jumping in the VR more challenging than in the real world?
   - Were you at any time afraid to hit something in the real world while in the VR?
   - How did the jumping compare to the walking around in the VR?
5. How did you experience the virtual guardian and real-world boundary around you?
6. Did the jumping experience change over time in the VR? What do you think changed over time?
7. How did your own performance in the game change over time? Did you get better at the game?
8. How did the chance of a lava ball affect your jumping technique?
9. Did the time bonuses and deductions motivate you throughout the interaction?
10. How did the entire interaction affect your focus on the jumping task compared to the first jumps outside the VR?
11. How did you experience the movement of the MVN avatar in the VR?
12. What was your overall experience of the VR environment (the setting) and the game?
13. Are there any issues that you experienced or recommendations you still have?

J SUPPORTING MATERIALS FOR MVN DATA ANALYSES

Within this Appendix, additional graphs and tables with analyses are presented as supplementary material to the results presented in Chapter 6.

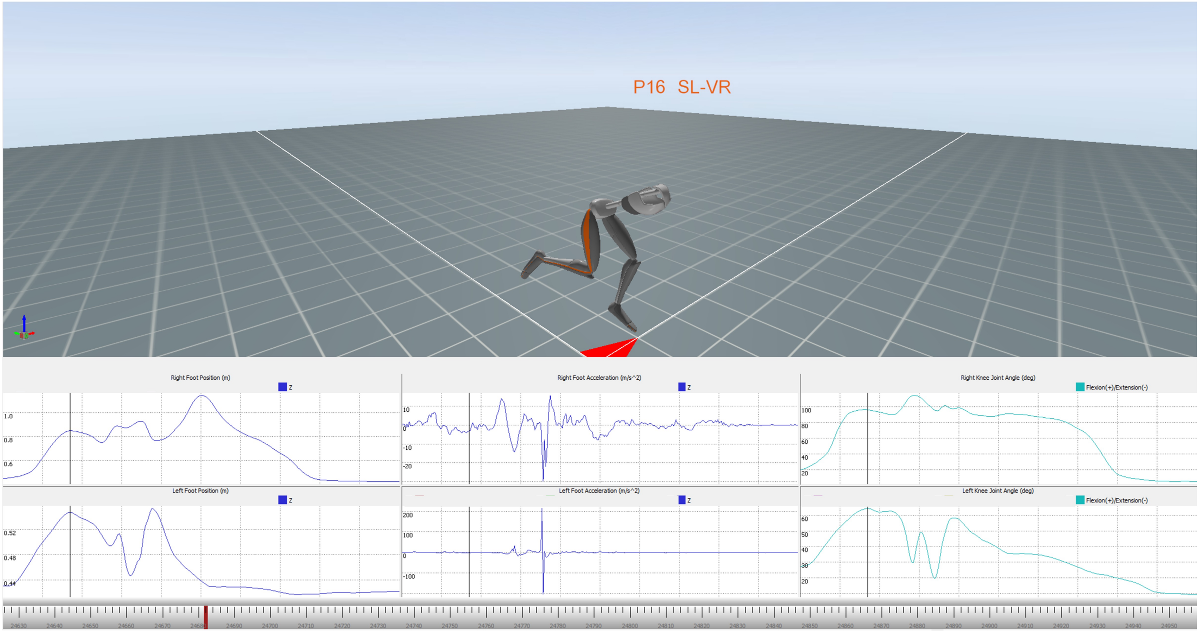
Table 14: Overview of the number of included (correct) jumps gathered per participant. Participants indicated with an asterisk (*) also include the additional measurement of interval jumps, participants indicated with two asterisks (**) also participated in the additional measurement of leg dominance interference. The number of jumps for these additional tests were not included in this overview.

		Non-perturbed dominant leg					Perturbed non-dominant leg				
Participant	**Nr. rounds played**	**SL jumps RW / VR**	**20% of max**	**40% of max**	**60% of max**	**80% of max**	**SL jumps RW / VR**	**20% of max**	**40% of max**	**60% of max**	**80% of max**
P03*	3	2 / 3	6	6	6	7	3 / 3	6	6	5	6
P04*	5	2 / 3	7	6	8	8	2 / 2	7	9	7	8
P05	3	2 / 2	4	5	6	6	2 / 2	6	6	6	6
P06*	6	8 / 4	18	18	15	17	9 / 5	15	18	18	15
P07	4	1 / 1	6	4	5	5	2 / 2	5	7	7	6
P08	3	2 / 1	4	4	5	5	2 / 2	4	3	5	4
P09	5	2 / 0	6	7	6	6	2 / 1	9	8	8	9
P10*	2	3 / 1	6	8	8	4	3 / 2	8	5	6	5
P11	5	2 / 1	7	8	8	6	2 / 2	10	8	8	7

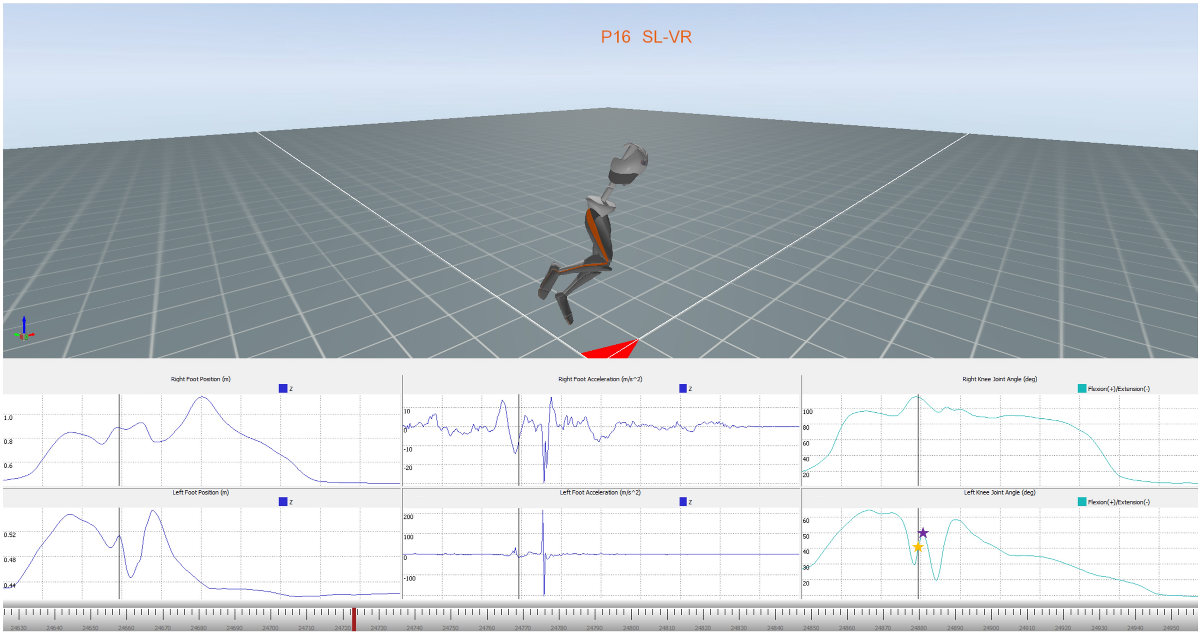
Continued on next page

Table 14 - Continued from previous page.

		Non-perturbed dominant leg					Perturbed non-dominant leg				
Participant	**Nr. rounds played**	**SL jumps RW / VR**	**20% of max**	**40% of max**	**60% of max**	**80% of max**	**SL jumps RW / VR**	**20% of max**	**40% of max**	**60% of max**	**80% of max**
P12*	3	2 / 2	7	8	7	6	2 / 2	8	6	7	5
P13	3	2 / 2	4	4	5	5	2 / 1	5	3	5	3
P14	4	2 / 1	5	5	6	4	2 / 1	5	5	4	3
P15	4	2 / 2	5	6	5	4	2 / 1	4	5	7	2
P16	5	2 / 2	8	9	8	9	2 / 2	10	10	8	10
P17	6	2 / 3	7	8	8	9	2 / 1	9	9	7	7
P18	4	1 / 1	6	7	7	5	2 / 0	8	8	7	6
P19	3	2 / 2	1	2	1	3	2 / 2	3	2	3	4
P20*	2	3 / 3	7	8	6	7	2 / 3	8	6	6	4
Total	70	42 / 34	114	123	120	116	45 / 34	130	124	124	110

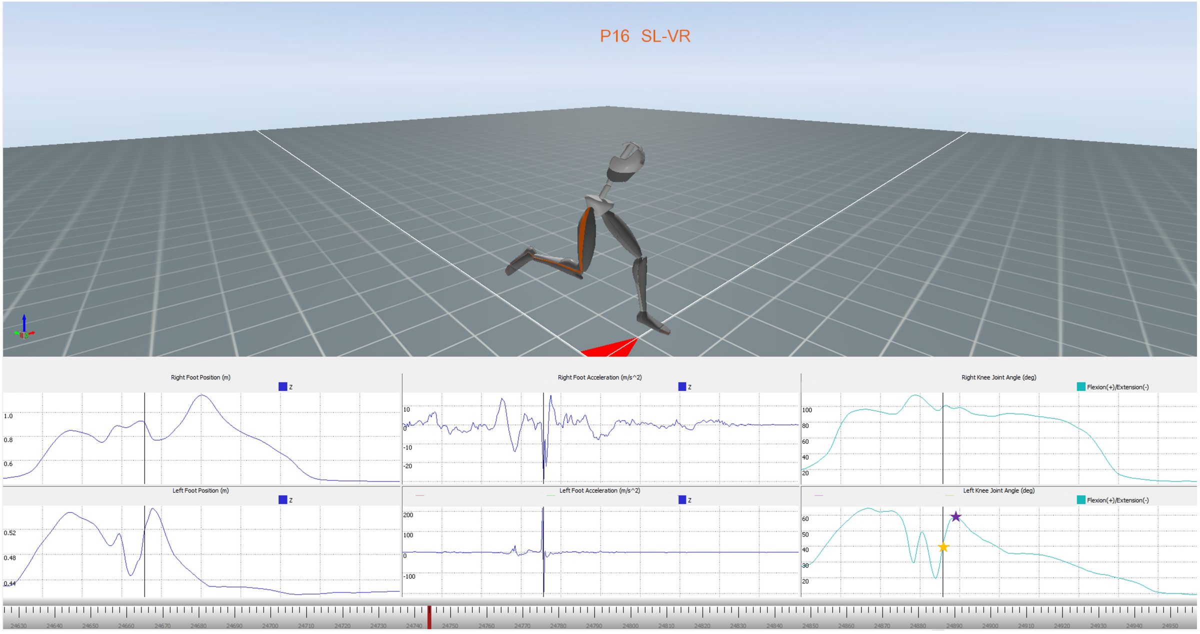


(a) Starting phase, starting at the first strong positive peak of the jumping leg's foot position.

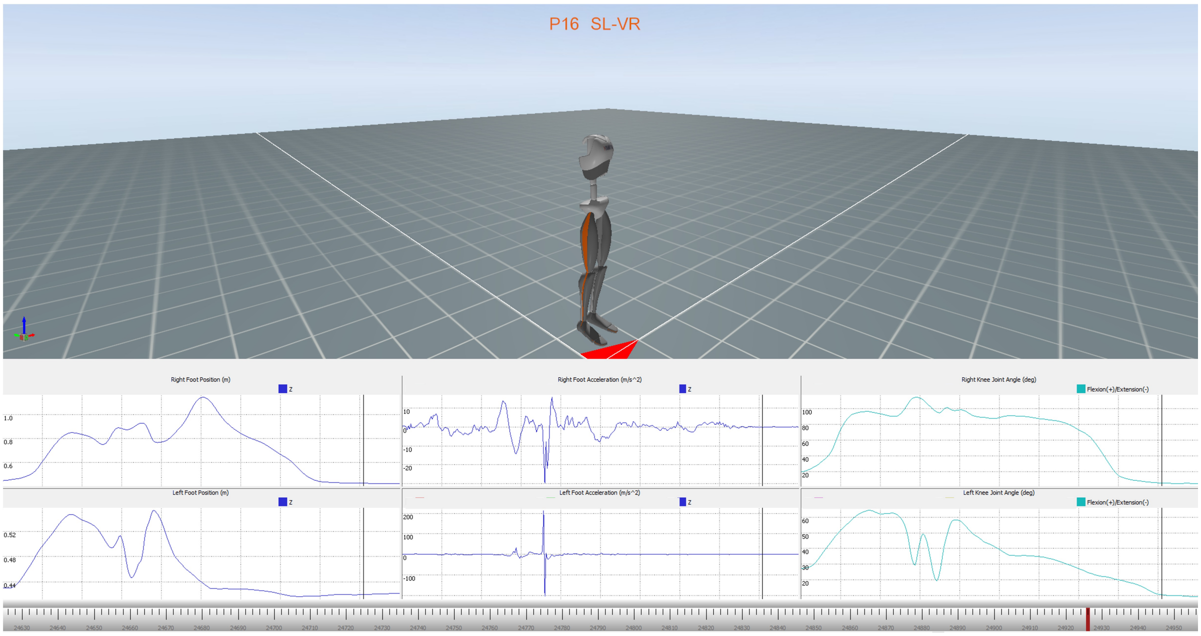


(b) Flight phase, starting at the negative acceleration peak of the jumping leg foot as it corresponds with the MVN avatar's toe-off movement. The RoF surrounding the toe-off is determined between the moment of toe-off (indicated with a yellow star) and the maximum flexion during the flight phase (indicated with a purple star).

Figure 41: Example of the indicators segmenting the three different jump phases of a perturbed non-dominant (left leg) VR single-leg jump of participant P16: toe-off, flight and landing phase. Shown is the MVN avatar as it moves through the jump, with below graphs for the foot position (left), foot acceleration (middle) and knee angle (right) of the right swing leg (top row) and the left jumping leg (bottom row) leg. For the RoF at the toe-off and landing phases, the two moments between which the flexion is considered are indicated with stars in the left knee flexion (bottom right) graph.



(c) Initial contact phase (subphase of landing phase), starting at the negative acceleration peak of the jumping leg as it corresponds with the MVN avatar's contact to the ground after the flight phase. The RoF surrounding the landing is determined between the moment of initial contact (indicated with a yellow star) and the maximum flexion during the landing phase (indicated with a purple star).



(d) Continued landing phase, ending at a stable torso and return to standing knee flexion.

Figure 41 - *Continued from previous page.*

J.1 Additional information for statistical analysis - landing phase

The linear mixed effects model based on significant fixed effects as determined by the bottom-up approach described in Section 6.2 can be seen per segment in the box below. Note, the ϵ in this model represents the probabilistic part of the model due to random effects that we cannot control for. This is a standard error term incorporated to represent all deviations from the model-based predictions.

Linear mixed effects model overview of VR-ACL evaluation study data - landing phase analysis

Knee RoF ~ Perturbance + Jump type + Perceived fatigueness + (1 + Perturbance | Participant) + (1 | Trial ID) + ϵ

Hip RoF (log transform) ~ Jump type + Interaction condition + (1 + Perturbance | Participant) + ϵ

Torso RoF (log transform) ~ Jump type + Participant length + (1 + Perturbance | Participant) + ϵ

The interaction of perturbance and jump type is presented for each segment in Figure 42.

J.2 Additional information for statistical analysis - toe-off phase

Linear mixed effects model overview of VR-ACL evaluation study data - toe-off phase analysis

Knee toe-off RoF (log transform) ~ Perturbance + Jump Type + Trial Number + Participant length + (1 | Trial ID) + (1 + Perturbance | Participant) + ϵ

Hip toe-off RoF (log transform) ~ Jump type + Interaction condition + (1 | Trial ID) + (1 + Perturbance | Participant) + ϵ

Torso toe-off RoF (log transform) ~ Perturbance + Interaction condition + Perceived fatigueness + Participant length + (1 | Trial ID) + (1 + Perturbance | Participant) + ϵ

For the random effect structures in Tables 15, the inclusion of random effects with a positive ΔAIC were used to negate categorisation effects of the assumptions of the model (see also Appendix K.1).

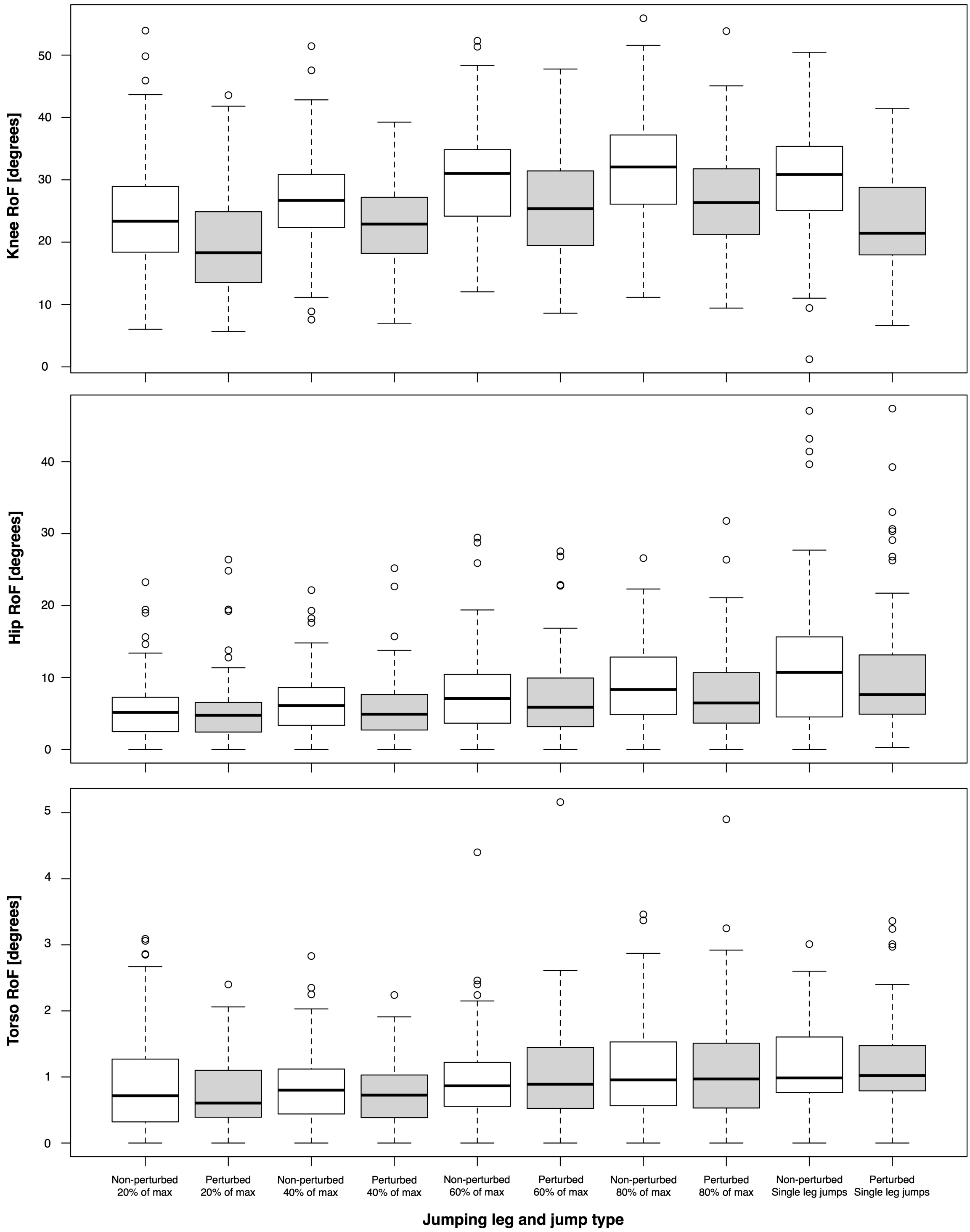


Figure 42: Boxplot of the knee (top), hip (middle) and torso (bottom) range of flexion of the landing phase as a function of the interaction of the perturbed non-dominant (P) or non-perturbed dominant (NP) legs with the jumping distances of 20%, 40%, 60%, 80% of maximum and the single-leg jumps (indicated as 100%). The interval distances of 20, 40, 60 and 80% of max were based on the single-leg jumps in the VR condition. Shown is the accumulated data for all participants. No data transforms were used for these boxplots.

Table 15: Fixed and random effects structure of linear mixed effects models for predicting knee, hip and torso range of flexion in the toe-off phase. Note, the estimate consists of log odds; standard errors are denoted by SE; confidence intervals are denoted by CI; standard deviation is denoted by std. dev.

Knee range of flexion (log transform)

Fixed effects	**Estimate**	**SE**	**T-value**	**P-value**	**Lower 95%-CI**	**Upper 95%-CI**
Intercept	-0,66	0,54	-1,21	0,24	-1,56	0,32
Perturbance	-0,11	0,04	-2,60	<0,05	-0,17	-0,04
Jump type	0,01	0,00	10,27	<0,001	0,01	0,01
Trial number	0,00	0,00	2,00	<0,05	0,00	0,00
Participant length	0,01	0,00	2,23	<0,05	0,00	0,01
Random effects	**Variance**	**Std. dev.**	**ΔAIC**			
1 | Trial ID	0,00	0,07	-7,06			
1 + Perturbance | Participant *Perturbance*	0,01	0,07	-7,43			
1 + Perturbance | Participant *Full slope*	0,01	0,10	-162,27			

Hip range of flexion (log transform)

Fixed effects	**Estimate**	**SE**	**T-value**	**P-value**	**Lower 95%-CI**	**Upper 95%-CI**
Intercept	1,22	0,05	23,48	<0,001	1,14	1,31
Jump type	0,00	0,00	9,67	<0,001	0,00	0,00
Interaction condition	-0,06	0,01	-5,20	<0,001	-0,08	-0,04

Hip range of flexion (log transform) - continued

Random effects	**Variance**	**Std. dev.**	**ΔAIC**
1 | Trial ID	0,00	0,03	-4,23
1 + Perturbance | Participant *Perturbance*	0,03	0,17	-166,64
1 + Perturbance | Participant *Full slope*	0,04	0,20	-729,47

Torso range of flexion (log transform)

Fixed effects	**Estimate**	**SE**	**T-value**	**P-value**	**Lower 95%-CI**	**Upper 95%-CI**
Intercept	0,39	0,25	1,55	0,14	-0,03	0,80
Perturbance	-0,04	0,02	-2,12	<0,05	-0,07	-0,01
Interaction condition	-0,01	0,00	-2,33	<0,05	-0,01	0,00
Perceived fatigueness	-0,01	0,00	-3,38	<0,001	-0,02	-0,01
Participant length	0,00	0,00	2,13	<0,05	0,00	0,01
Random effects	**Variance**	**Std. dev.**	**ΔAIC**			
1 | Trial ID	0,00	0,00	0,85			
1 + Perturbance | Participant *Perturbance*	0,01	0,08	-253,82			
1 + Perturbance | Participant *Full slope*	0,01	0,08	-624,47			

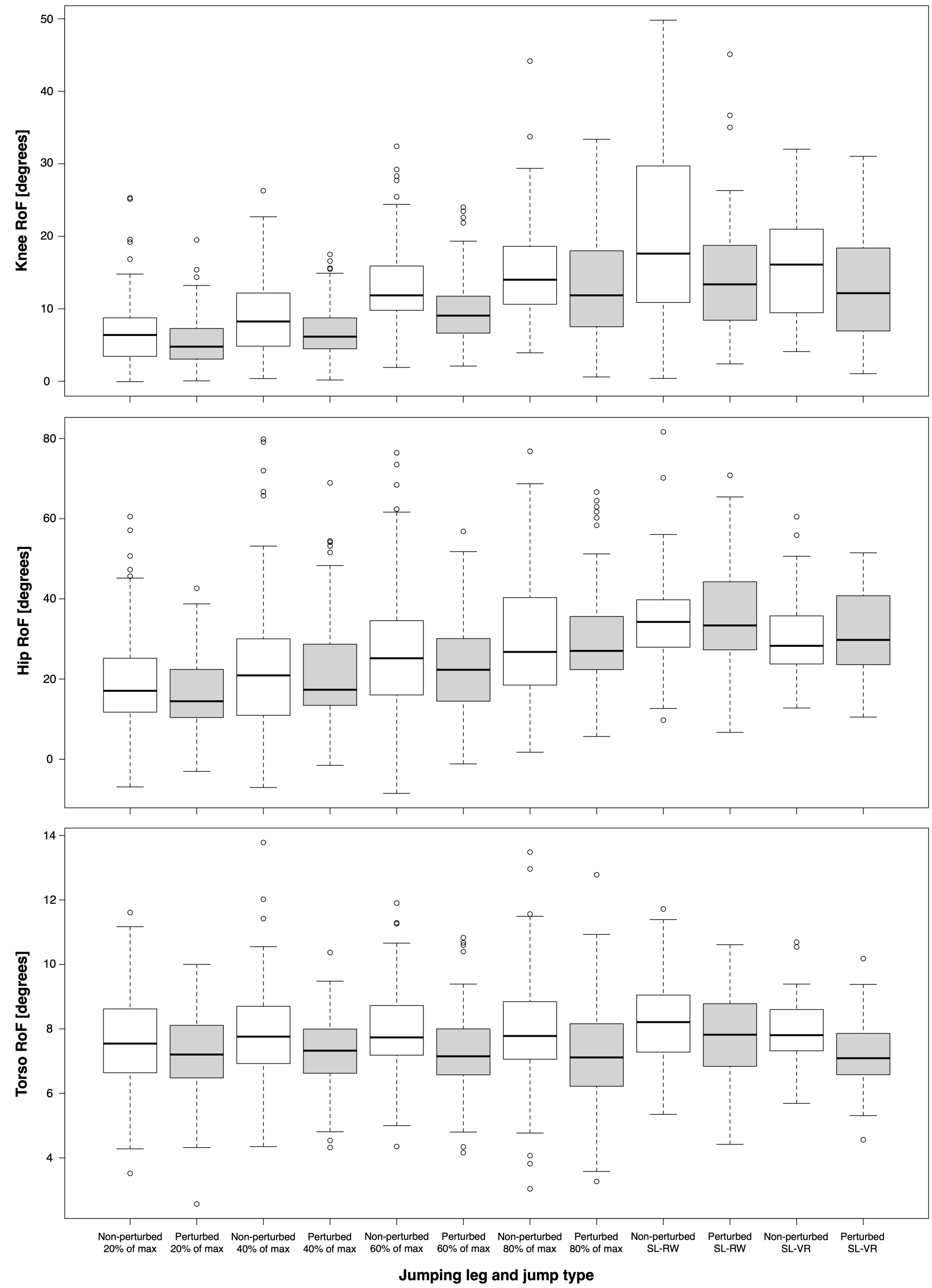


Figure 43: Boxplot of the knee (top), hip (middle) and torso (bottom) range of flexion of the toe-off phase as a function of the interaction of the perturbed non-dominant (P) or non-perturbed dominant (NP) legs with the jumping distances of 20%, 40%, 60%, 80% of maximum and the single-leg jumps (indicated as 100%). The interval distances of 20, 40, 60 and 80% of max were based on the single-leg jumps in the VR condition. Shown is the accumulated data for all participants. No data transforms were used for these boxplots.

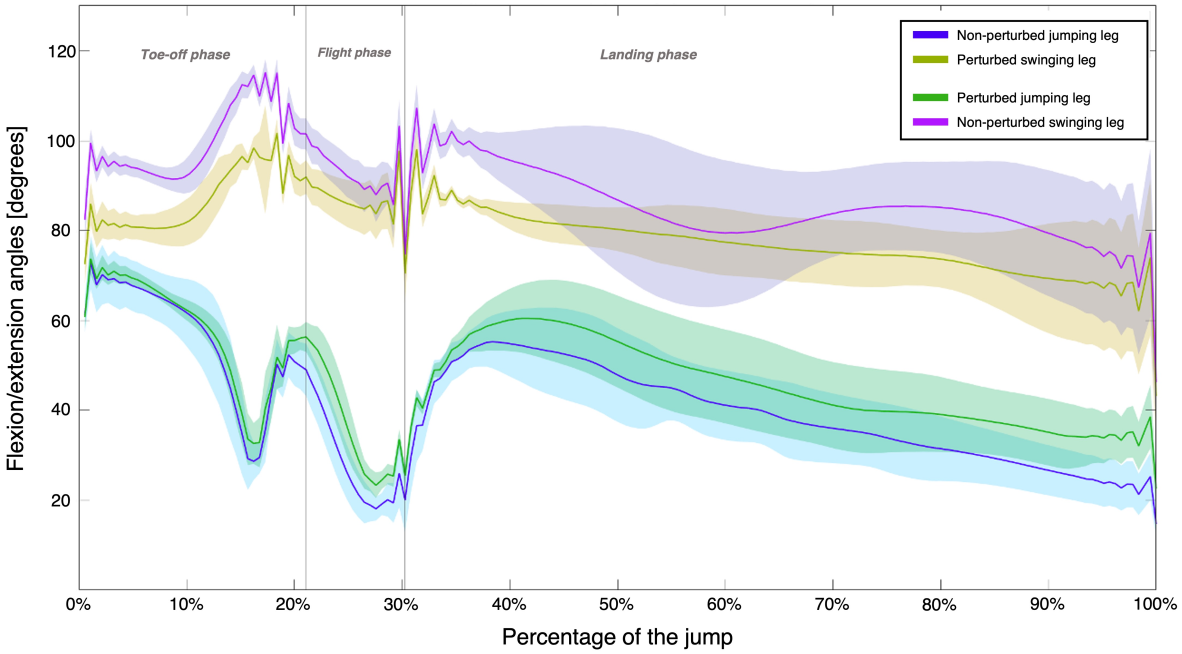
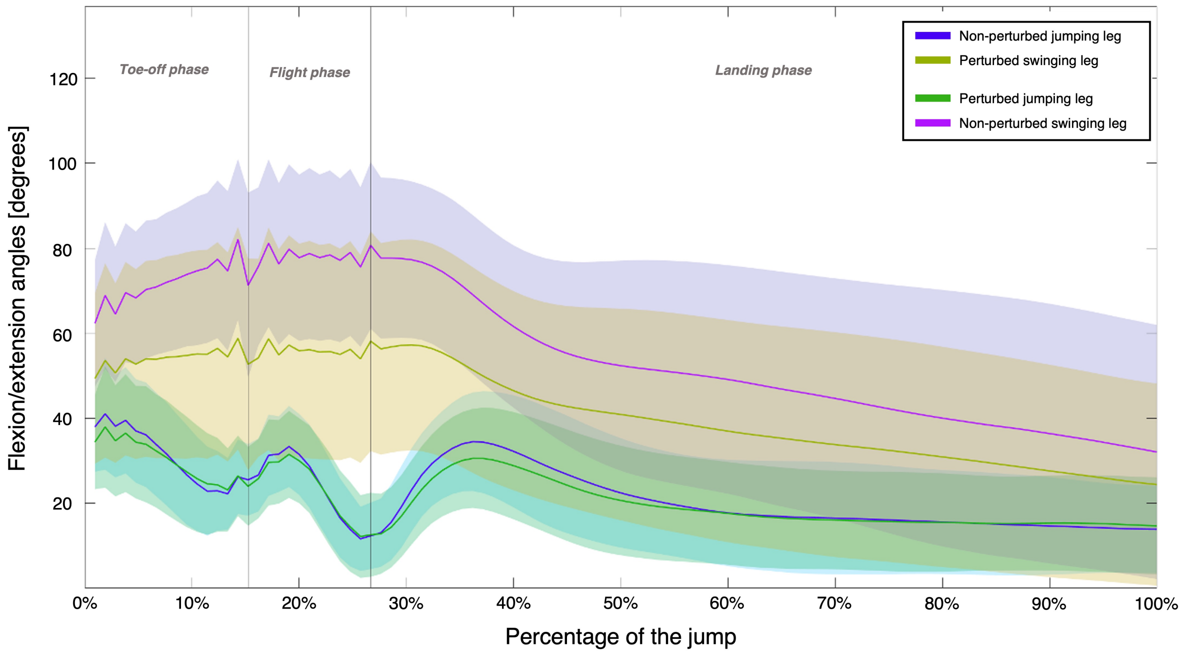
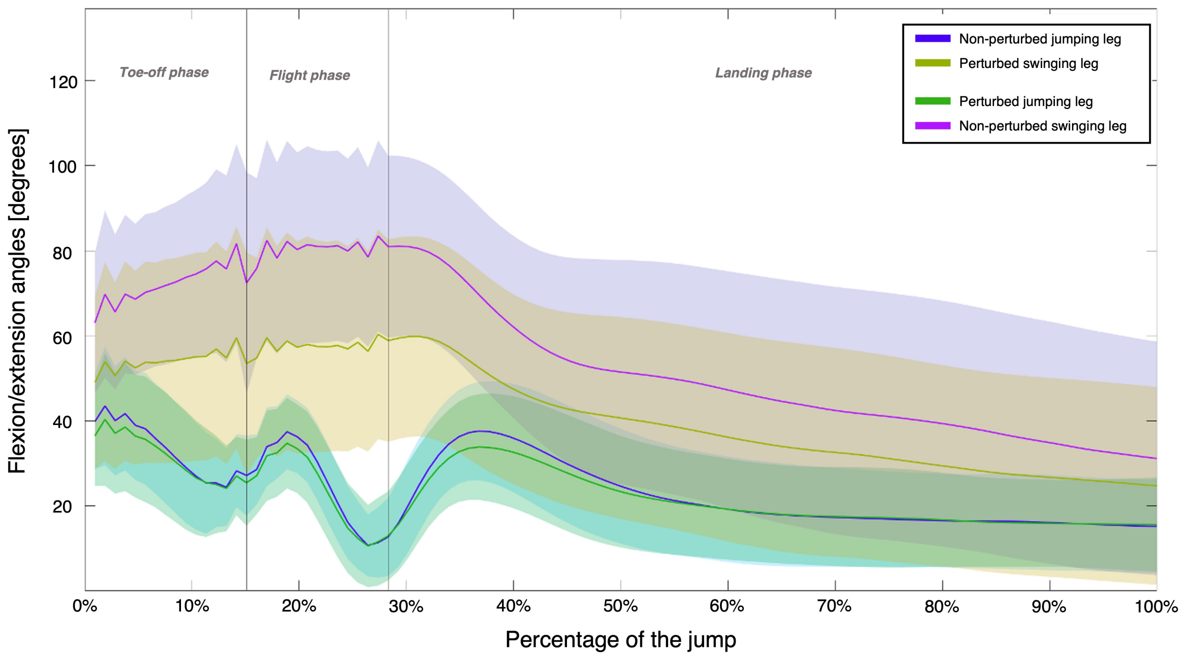


Figure 44: Example of summative outcomes for the mean knee angles with standard deviation of P16 at jump type 80%, showing the jumping of the non-perturbed dominant (blue) and perturbed non-dominant (green) leg, as well as their respective swinging legs with the perturbed non-dominant (yellow) and non-perturbed dominant (purple) leg for the three phases of the jump.

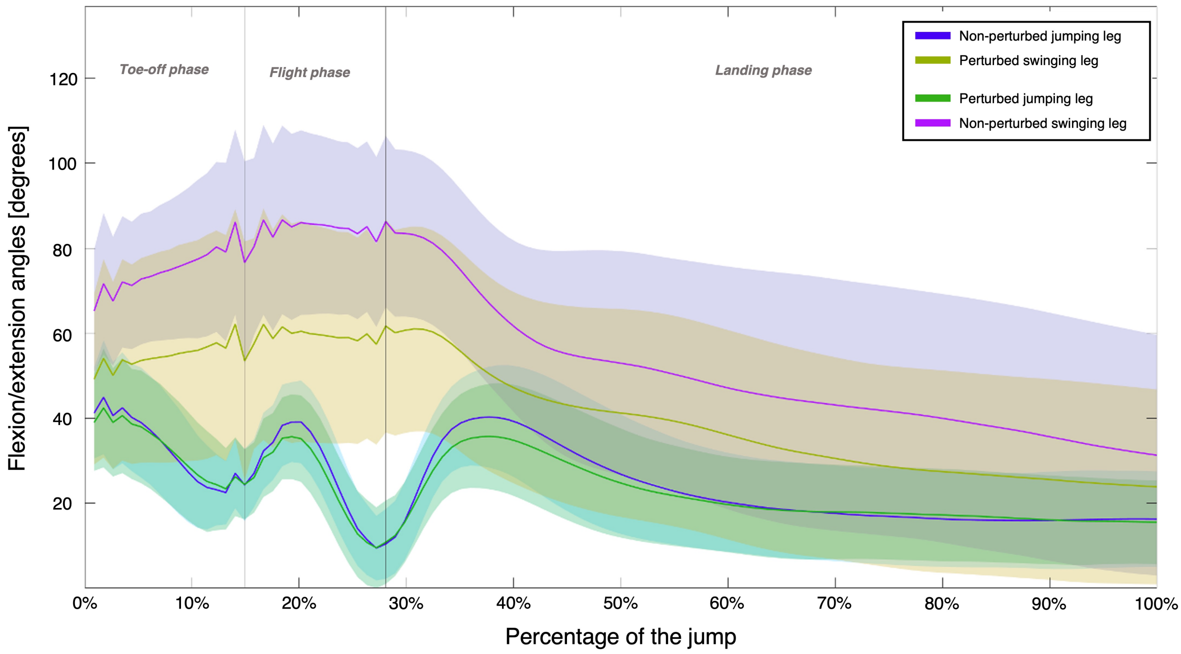


(a) Knee angles for jump type: 20% of maximum.

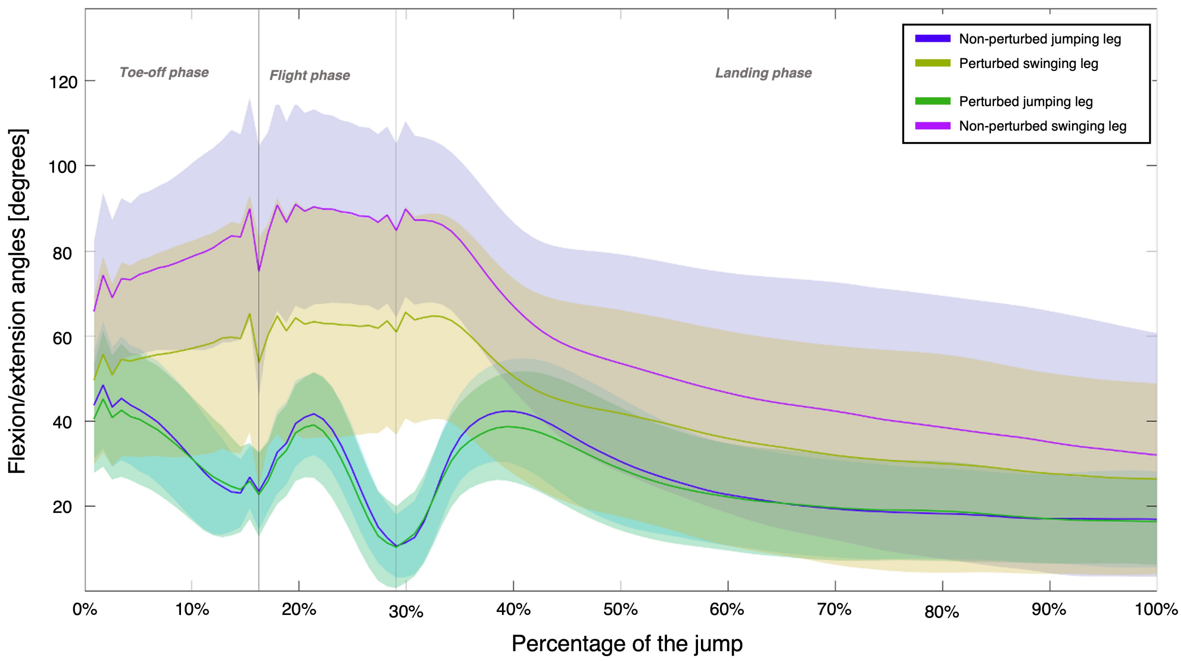


(b) Knee angles for jump type: 40% of maximum.

Figure 45: Summary visual plot of the knee flexion of non-perturbed (dominant) and perturbed (non-dominant) legs as jumping and swinging legs for the six jump types. Full participant dataset included.

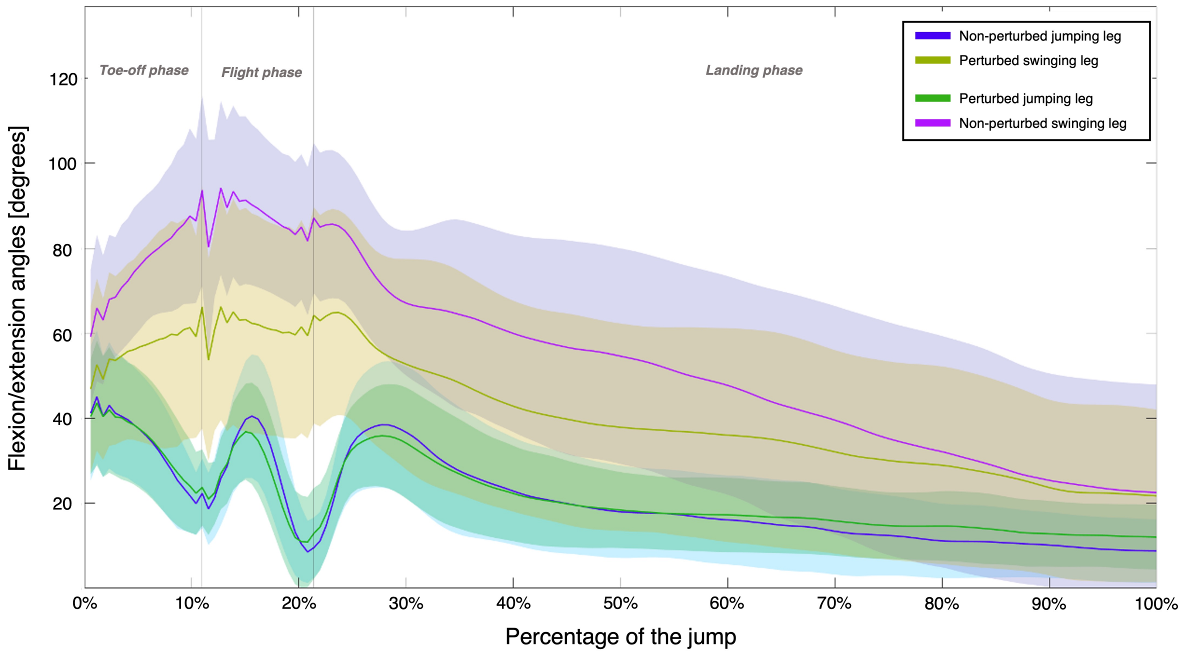


(c) Knee angles for jump type: 60% of maximum.

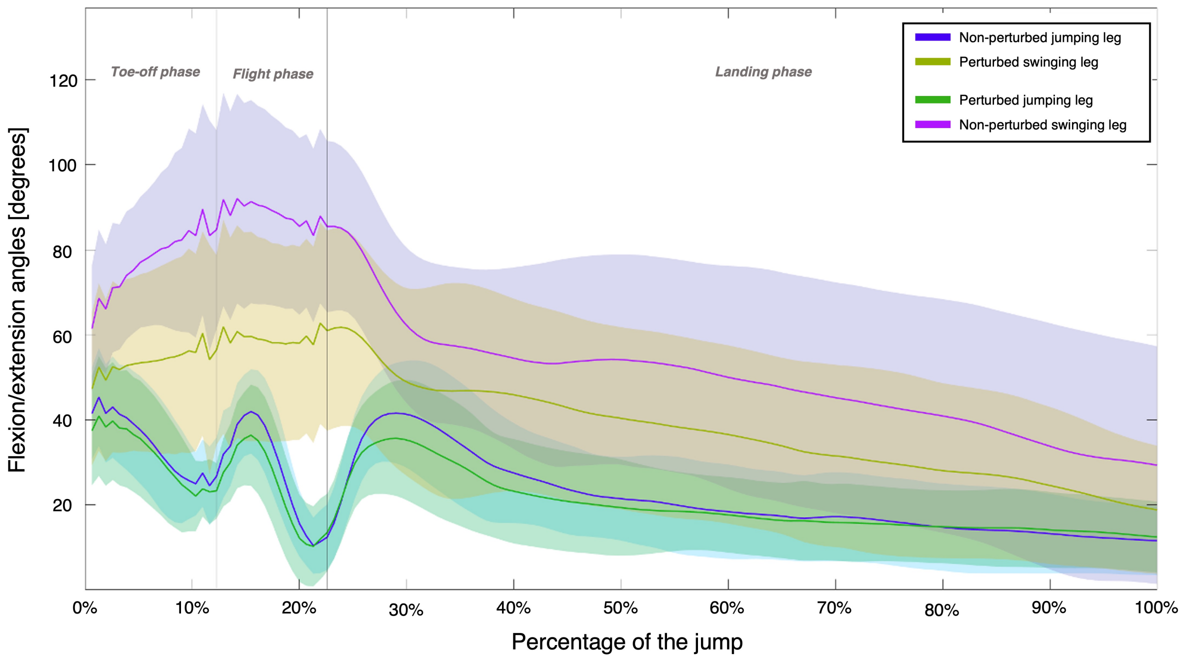


(d) Knee angles for jump type: 80% of maximum.

Figure 45 - *Continued from previous page.*

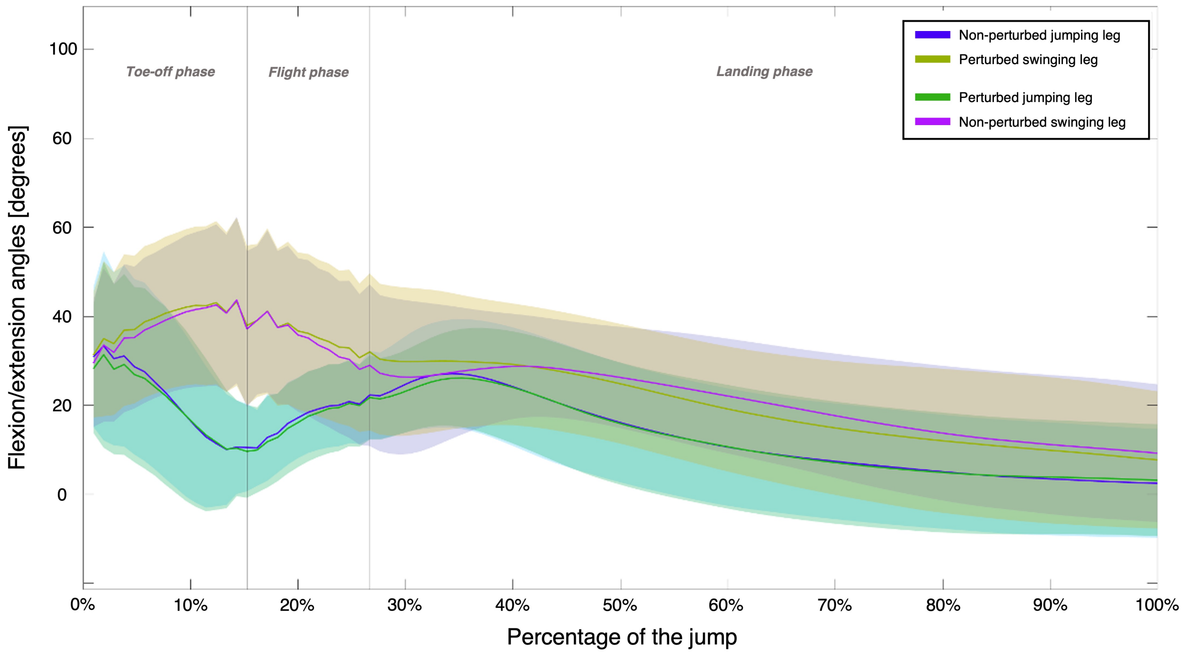


(e) Knee angles for jump type: single-leg VR.

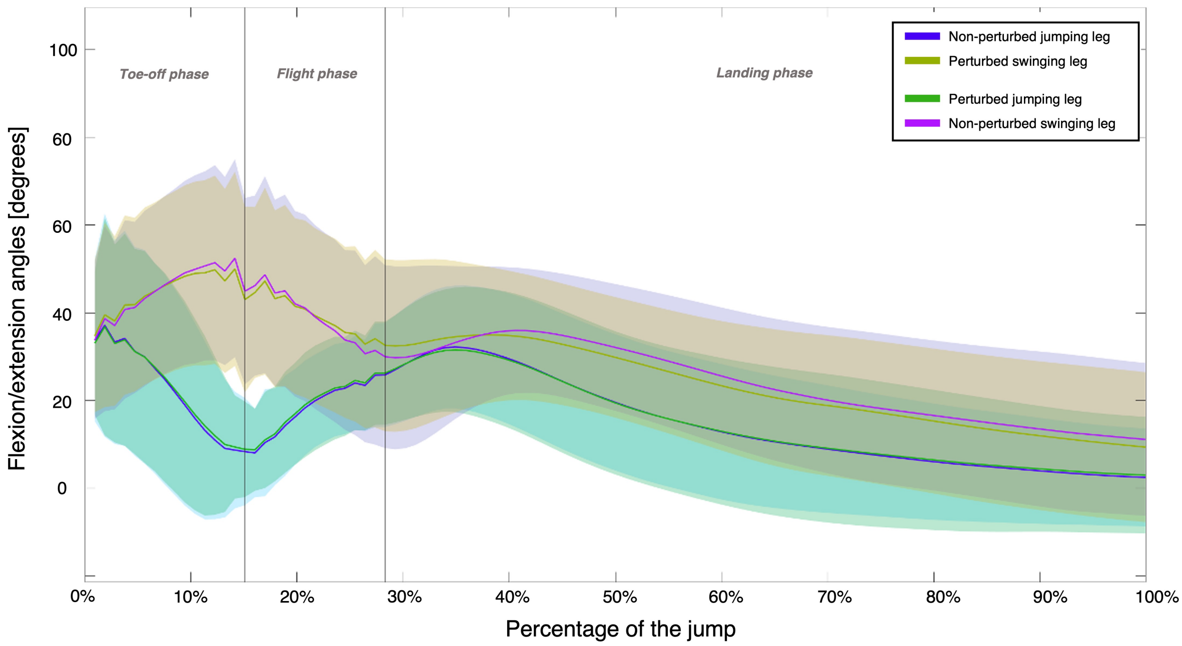


(f) Knee angles for jump type: single-leg real-world.

Figure 45 - *Continued from previous page.*

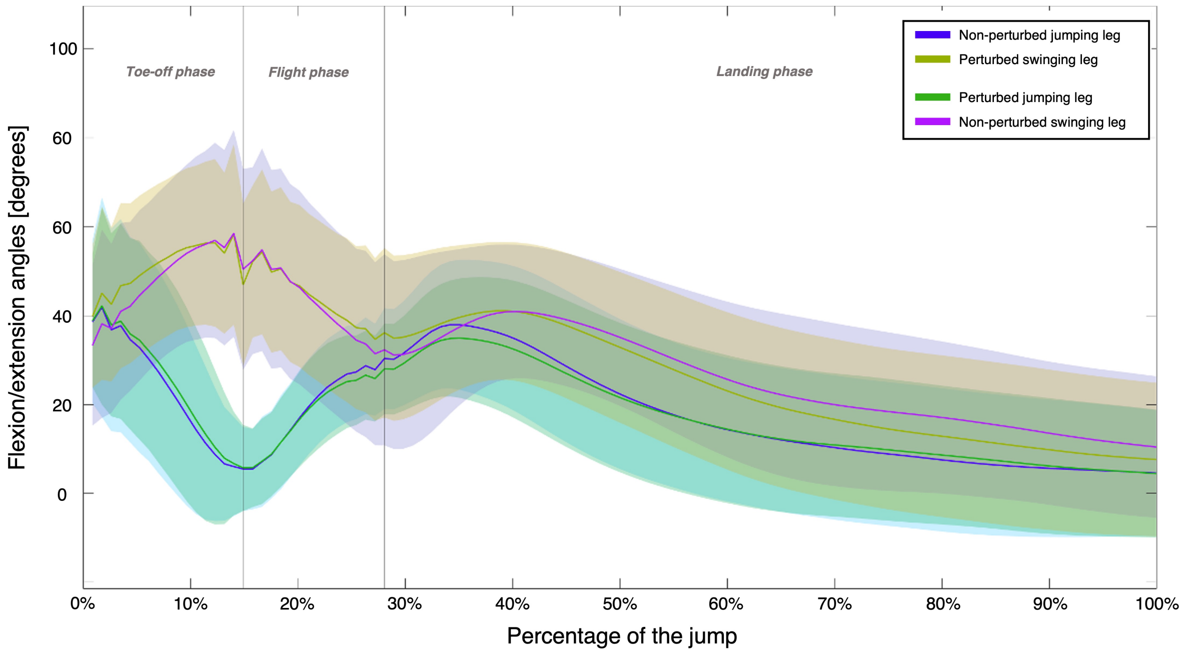


(a) Hip angles for jump type: 20% of maximum.

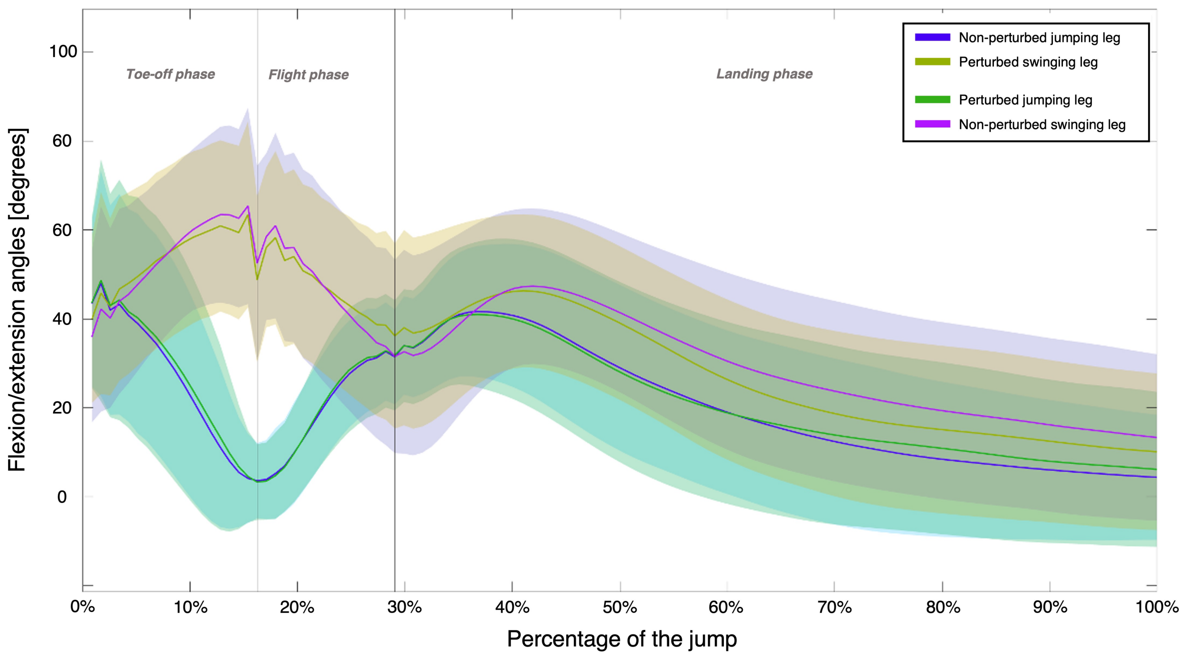


(b) Hip angles for jump type: 40% of maximum.

Figure 46: Summary visual plot of hip angles on the non-perturbed (dominant) and perturbed (non-dominant) side, considered for when either side was jumping or swinging for the six jump types. Full participant dataset included.

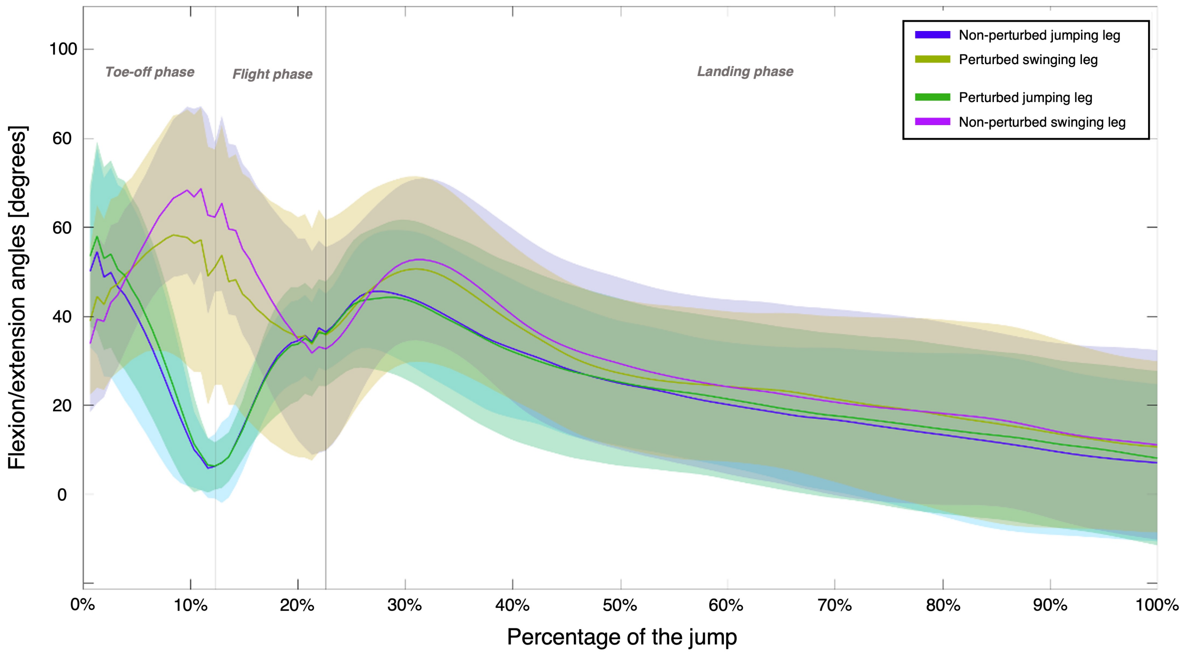


(c) Hip angles for jump type: 60% of maximum.

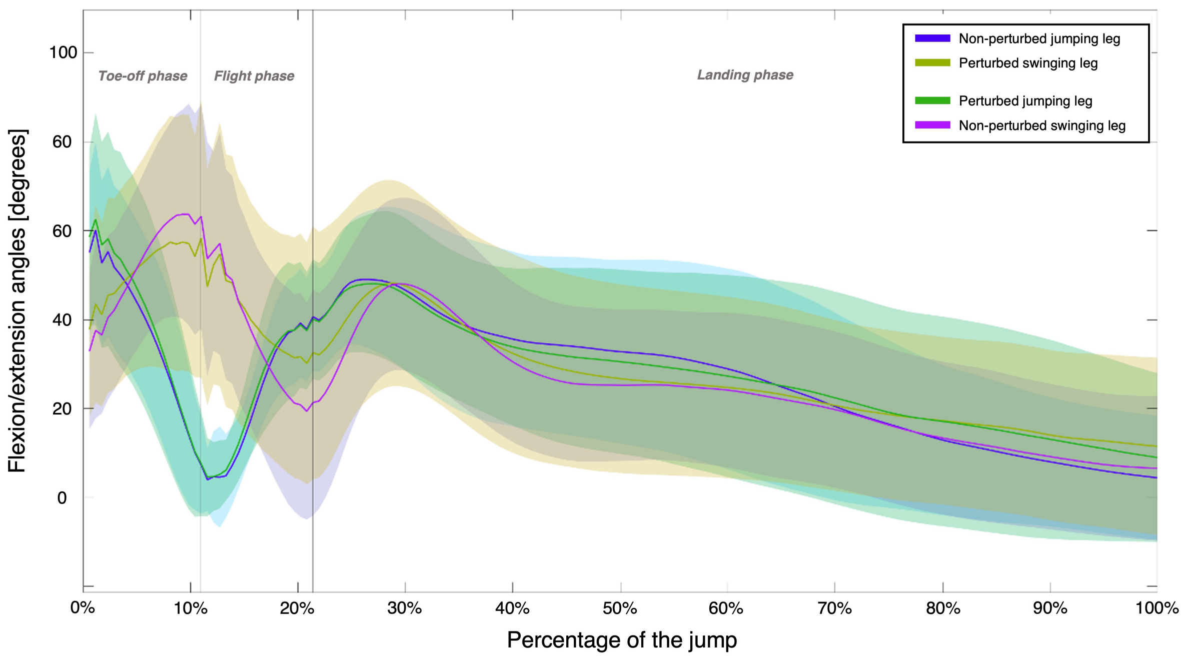


(d) Hip angles for jump type: 80% of maximum.

Figure 46 - *Continued from previous page.*

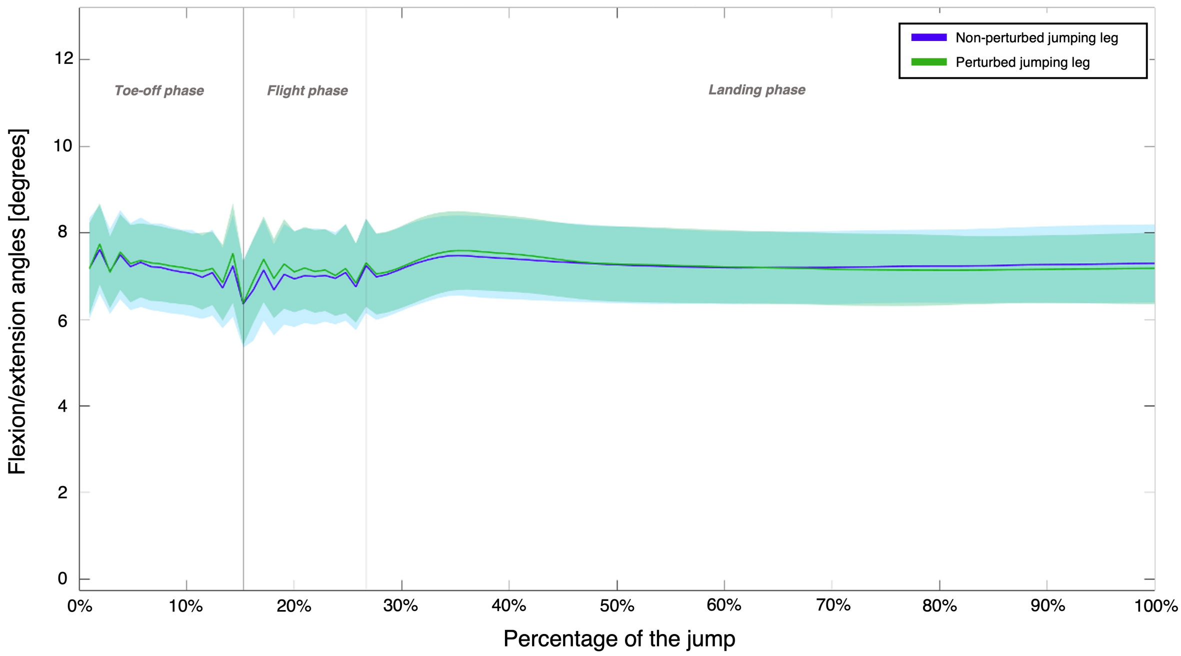


(e) Hip angles for jump type: single-leg VR.

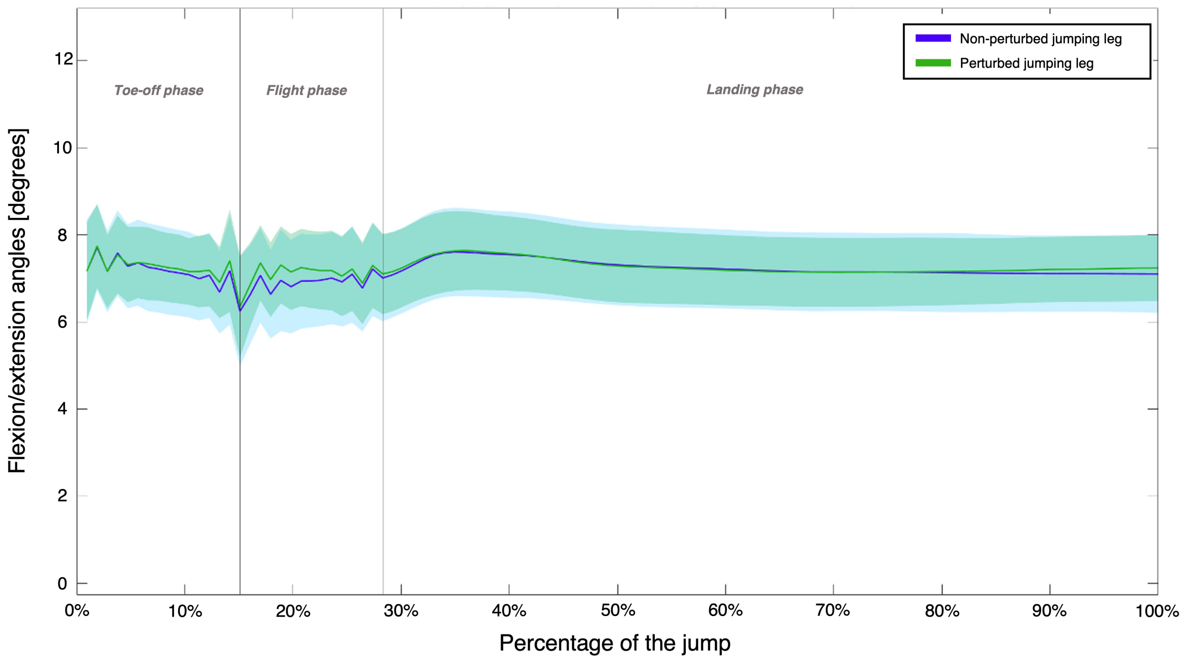


(f) Hip angles for jump type: single-leg real-world.

Figure 46 - *Continued from previous page.*

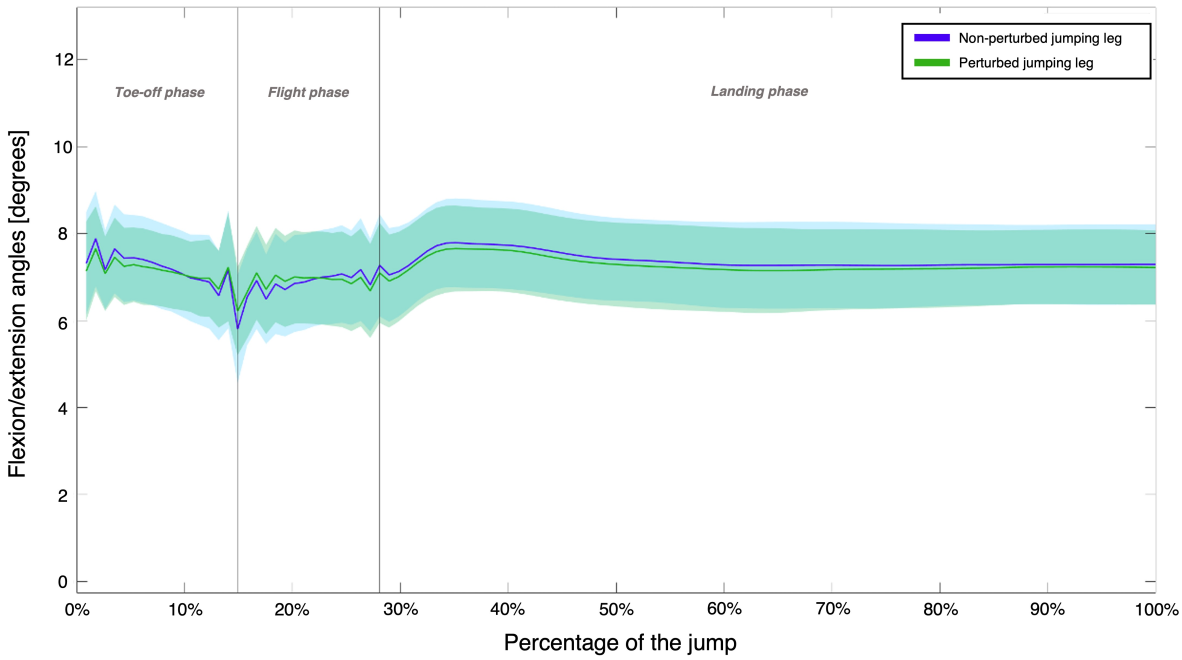


(a) Torso angles for jump type: 20% of maximum.

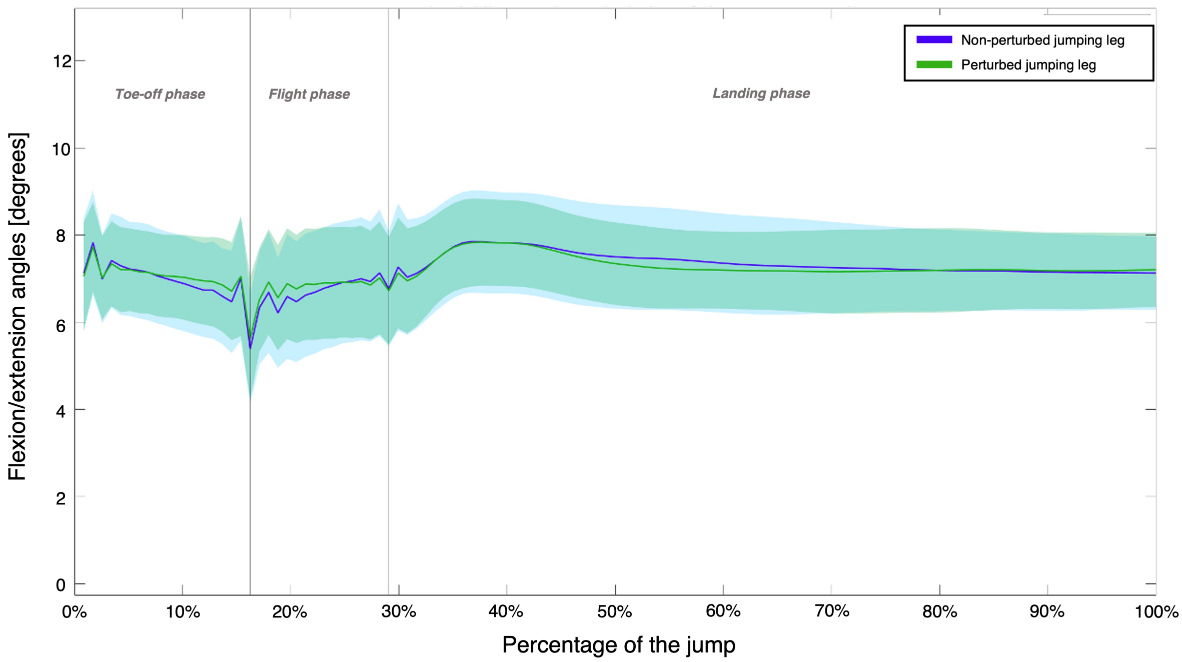


(b) Torso angles for jump type: 40% of maximum.

Figure 47: Summary visual plot of torso angles for non-perturbed (dominant) and perturbed (non-dominant) legs as jumping and swinging legs for the six jump types. Full participant dataset included.

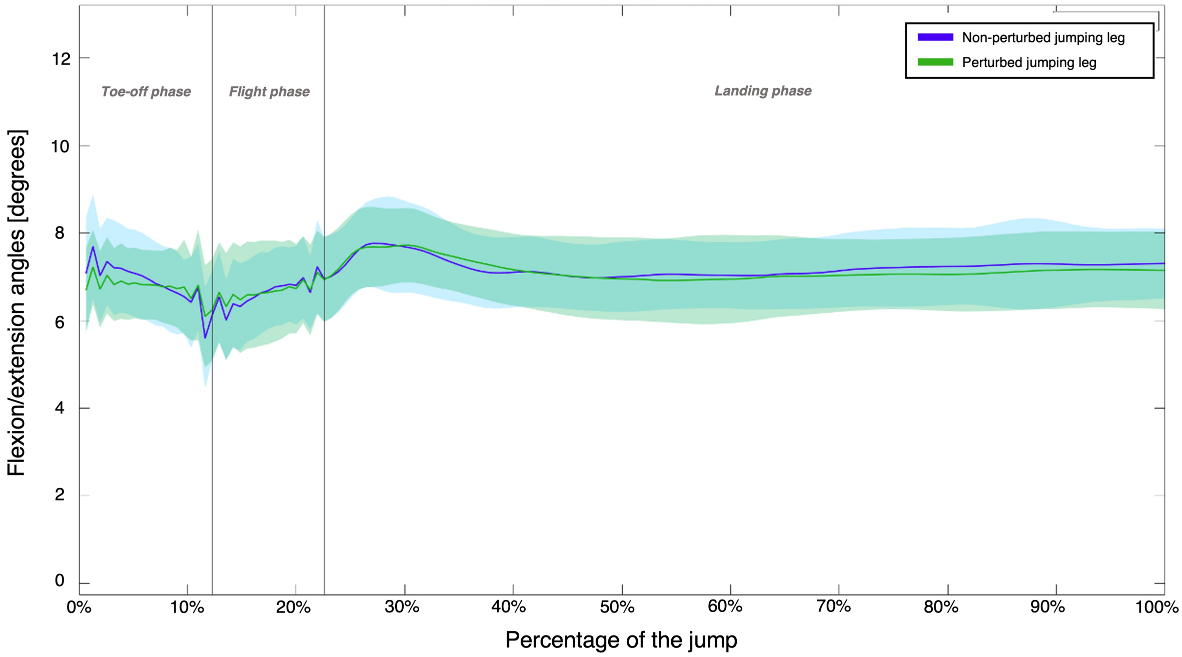


(c) Torso angles for jump type: 60% of maximum.

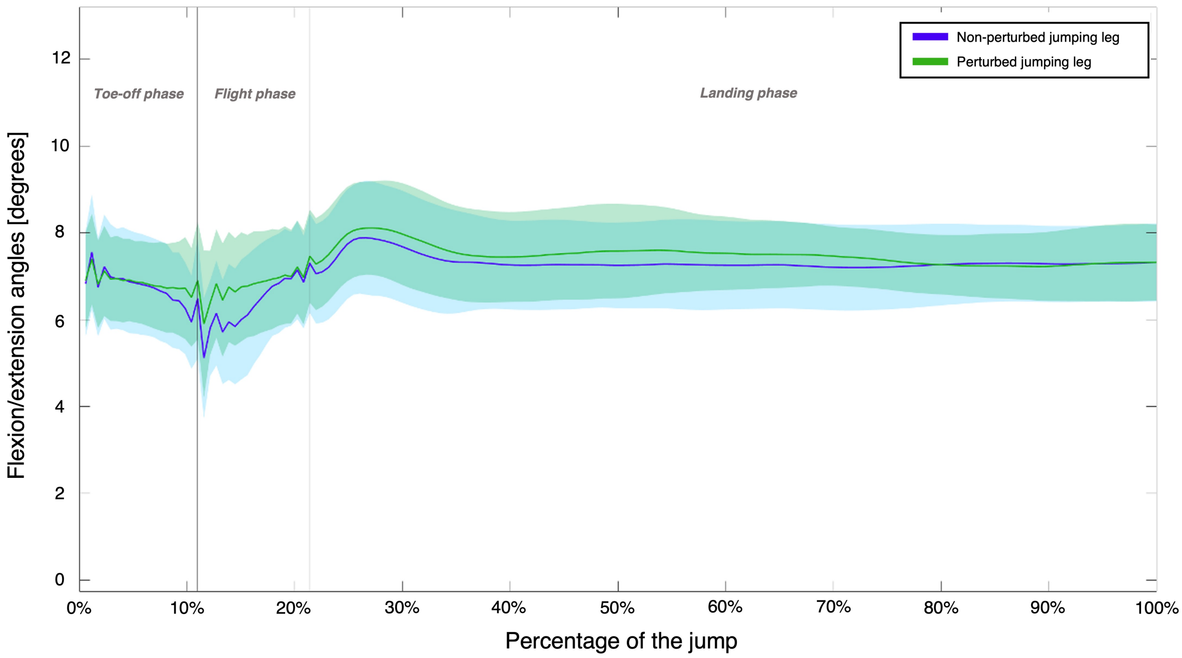


(d) Torso angles for jump type: 80% of maximum.

Figure 47 - *Continued from previous page.*



(e) Torso angles for jump type: single-leg VR.



(f) Torso angles for jump type: single-leg real-world.

Figure 47 - *Continued from previous page.*

Linear mixed effect models of dominance influence measurement for landing RoF

Knee RoF ~ Perturbance + Jumping leg dominance + (1 | Participant) + ϵ

Hip RoF ~ (1 + Jumping leg dominance | Participant) + ϵ

Torso RoF ~ Age group + (1 + Jumping leg dominance | Participant) + ϵ

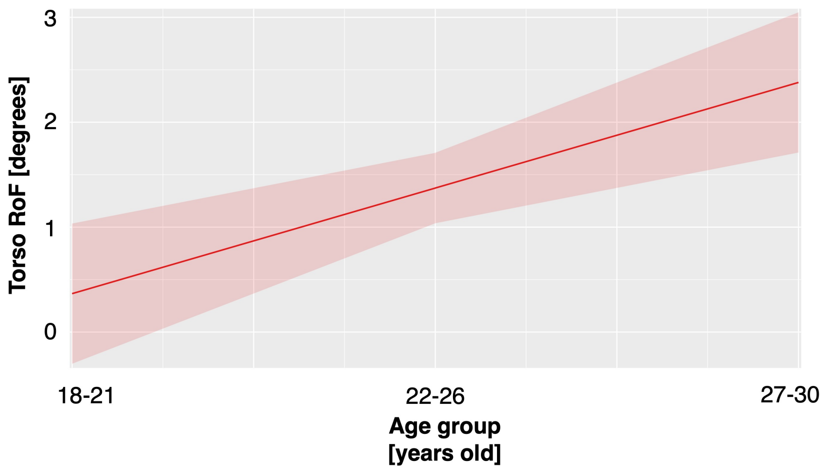


Figure 48: Predicted values of torso model plot landing RoF of dominance measurement as a function of age group.

Linear mixed effect models of dominance influence measurement for toe-off RoF

Knee RoF (log transform) ~ 1 + (1 + Perturbance | Participant)+ (1 + Jumping leg dominance | Participant) + ϵ

Hip RoF (log transform) ~ 1 + (1 + Perturbance | Participant)+ (1 + Jumping leg dominance | Participant) + ϵ

Torso RoF ~ Jumping leg dominance + (1 + Perturbance | Participant) + ϵ

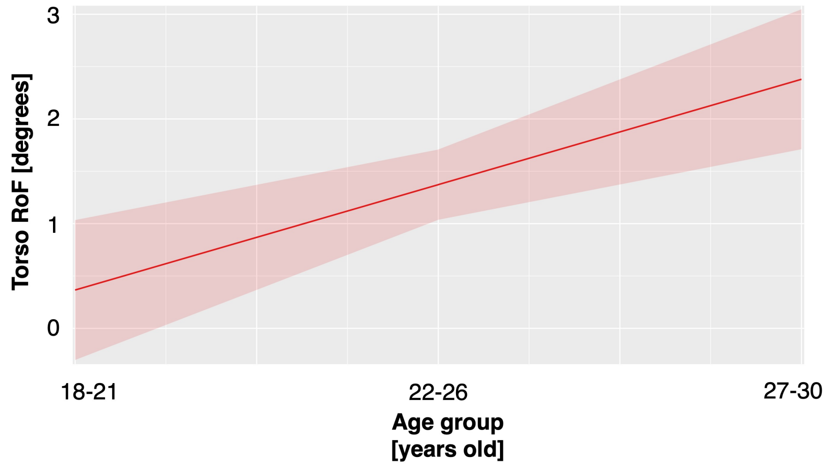


Figure 49: Predicted values of torso model plot toe-off RoF of dominance measurement as a function of jumping leg dominance group.

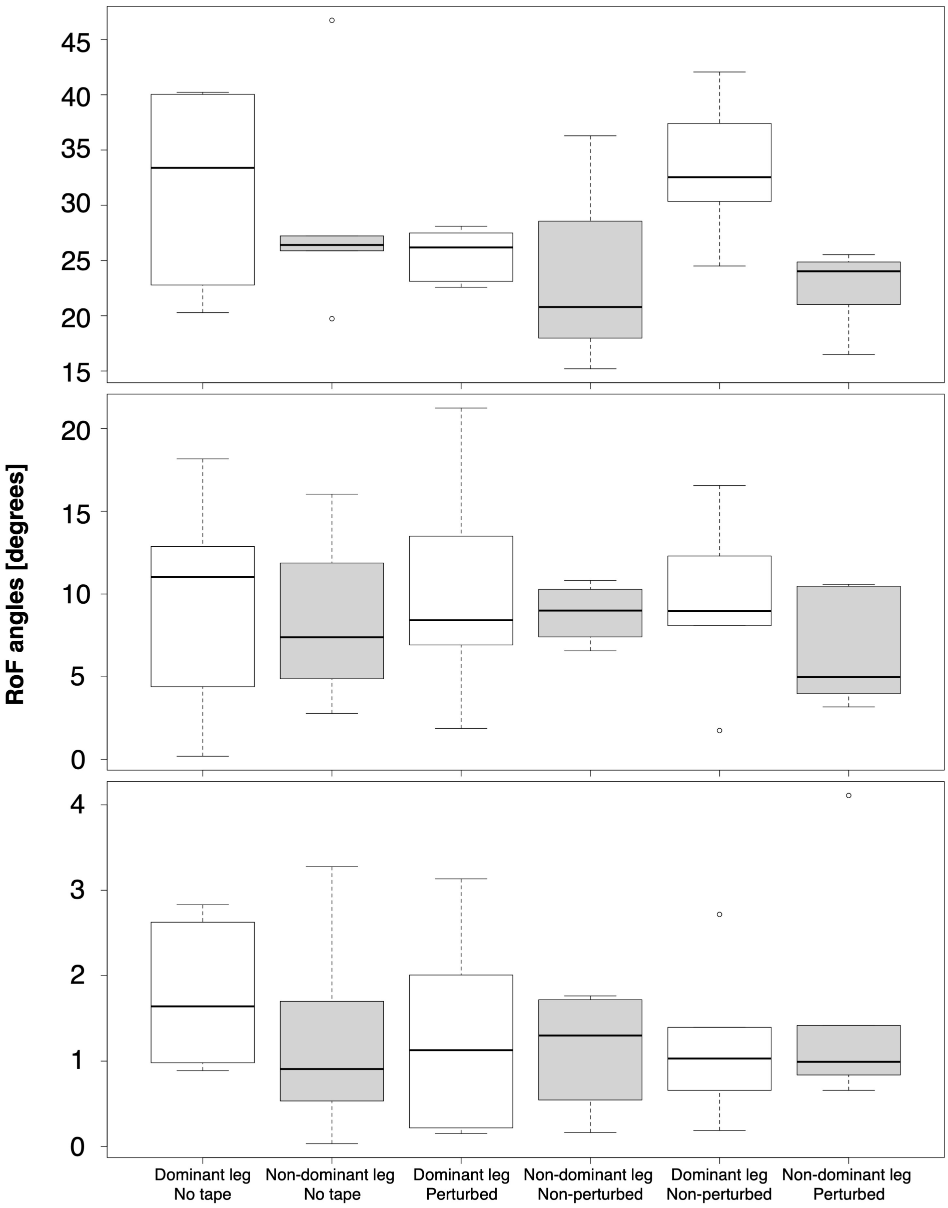


Figure 50: Boxplot of dominance measurement effects on knee (top plot), hip (middle plot) and torso (bottom plot) RoF during landing for the dominant and non-dominant leg. The graph is showing the boxplot of jumping distances made by all participants of the dominance measurement under the conditions of no tape on either the dominant and non-dominant leg (left two plots); perturbation attached to the dominant leg (middle plots); and perturbation attached to the non-dominant leg (right plots).

Table 16: Fixed and random effects structure of linear fixed effects and linear mixed effects models for predicting the knee, hip and torso range of flexion within the dominance measurement during the toe-off phase. Note, the estimate consists of log odds; standard errors are denoted by SE; confidence intervals are denoted by CI; standard deviation is denoted by std. dev.

Knee range of flexion (log transform)

Fixed effects	**Estimate**	**SE**	**T-value**	**P-value**	**Lower 95%-CI**	**Upper 95%-CI**
Intercept	1,31	0,06	20,18	<0,001	1,18	1,43
Random effects	**Variance**	**Std. dev.**	**ΔAIC**			
1 + Perturbance | Participant *Perturbance*	0,00	0,03	3,98			
1 + Perturbance | Participant *Full slope*	0,01	0,11	5,98			
1 + Jumping leg dominance | Participant *Jumping leg dominance*	0,01	0,11	1,31			
1 + Jumping leg dominance | Participant *Full slope*	0,04	0,19	3,31			

Hip range of flexion (log transform)

Fixed effects	**Estimate**	**SE**	**T-value**	**P-value**	**Lower 95%-CI**	**Upper 95%-CI**
Intercept	1,68	0,06	27,37	<0,001	1,57	1,79

Table 16 - Continued from previous page.

Hip range of flexion (log transform) - continued

Random effects	Variance	Std. dev.	ΔAIC
1 + Perturbance | Participant *Perturbance*	0,00	0,01	3,83
1 + Perturbance | Participant *Full slope*	0,02	0,14	5,83
1 + Jumping leg dominance | Participant *Jumping leg dominance*	0,00	0,04	2,85
1 + Jumping leg dominance | Participant *Full slope*	0,00	0,04	4,85

Torso range of flexion

Fixed effects	Estimate	SE	T-value	P-value	Lower 95%-CI	Upper 95%-CI
Intercept	5,21	0,42	12,33	<0,001	4,42	5,94
Jumping leg dominance	1,11	0,44	2,54	<0,05	0,35	1,86

Random effects	Variance	Std. dev.	ΔAIC
1 + Perturbance | Participant *Perturbance*	0,12	0,35	3,55
1 + Perturbance | Participant *Full slope*	0,72	0,85	2,98

For the random effect structures in Table 16, the inclusion of random effects with a positive ΔAIC were used to negate categorisation effects of the assumptions of the model (see also Appendix K.2).

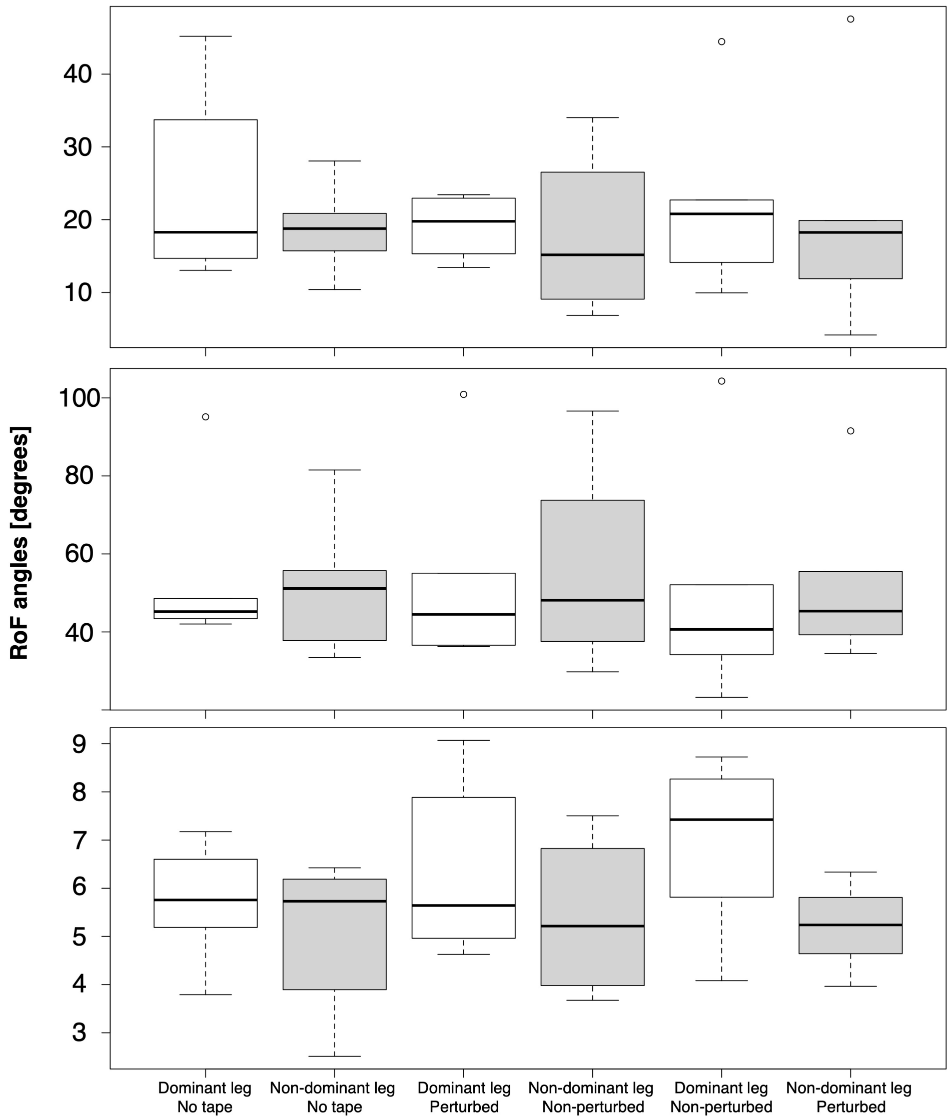
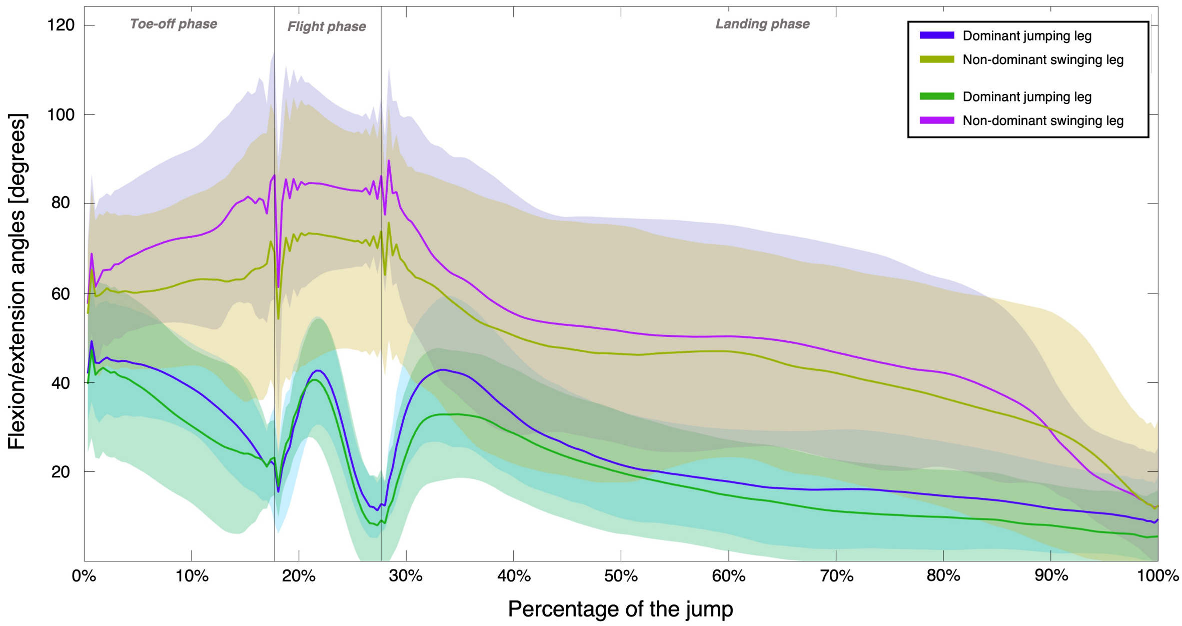
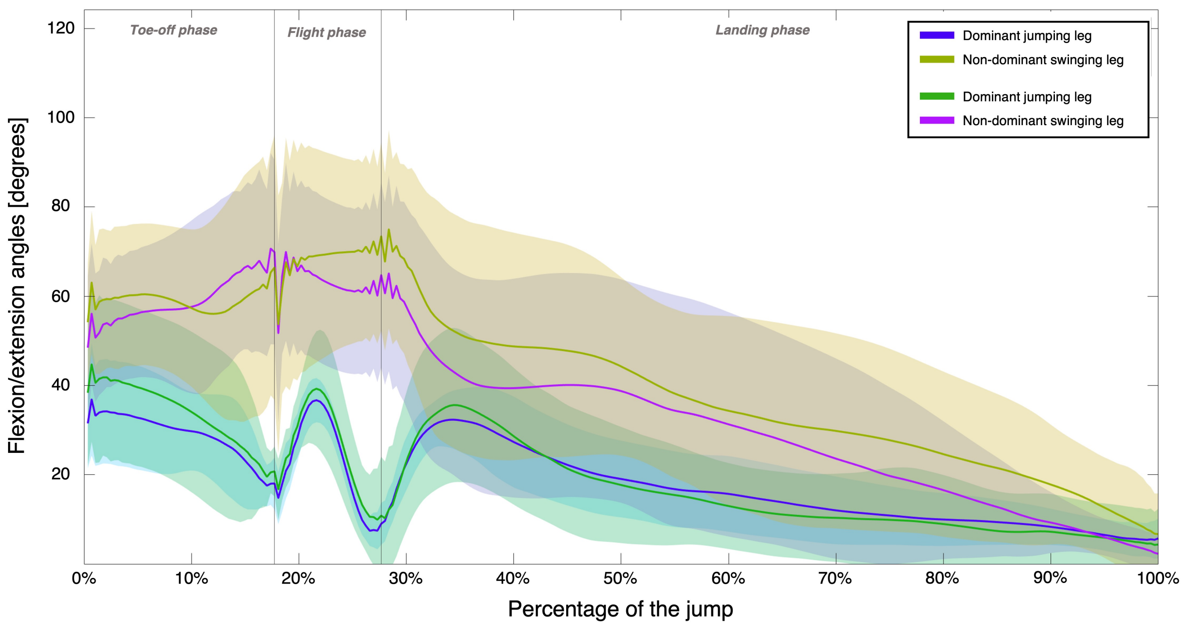


Figure 51: Boxplot of dominance measurement effects on knee (top plot), hip (middle plot) and torso (bottom plot) RoF during toe-off for the dominant and non-dominant leg. The graph is showing the boxplot of jumping distances made by all participants of the dominance measurement under the conditions of no tape on either the dominant and non-dominant leg (left two plots); perturbation attached to the dominant leg (middle plots); and perturbation attached to the non-dominant leg (right plots).

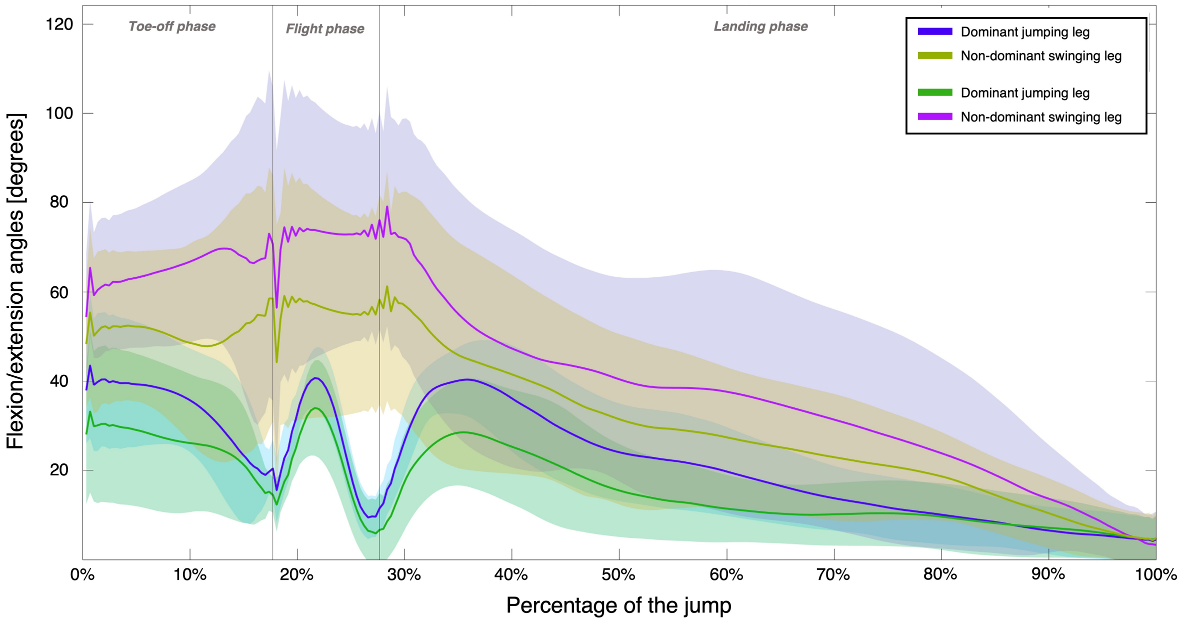


(a) Knee angles for no tape condition.

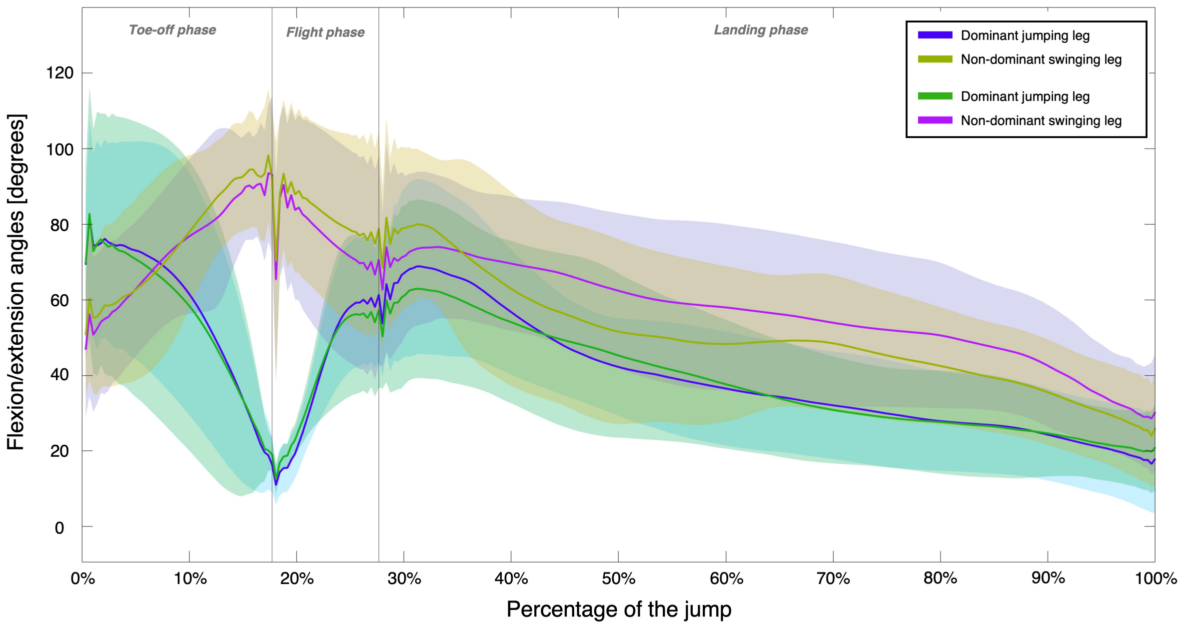


(b) Knee angles for dominant leg taped condition.

Figure 52: Summary visual plots of knee, hip and torso angles for the dominance influence measurement comparing the dominant and non-dominant legs as jumping or swinging legs for the three taping conditions.

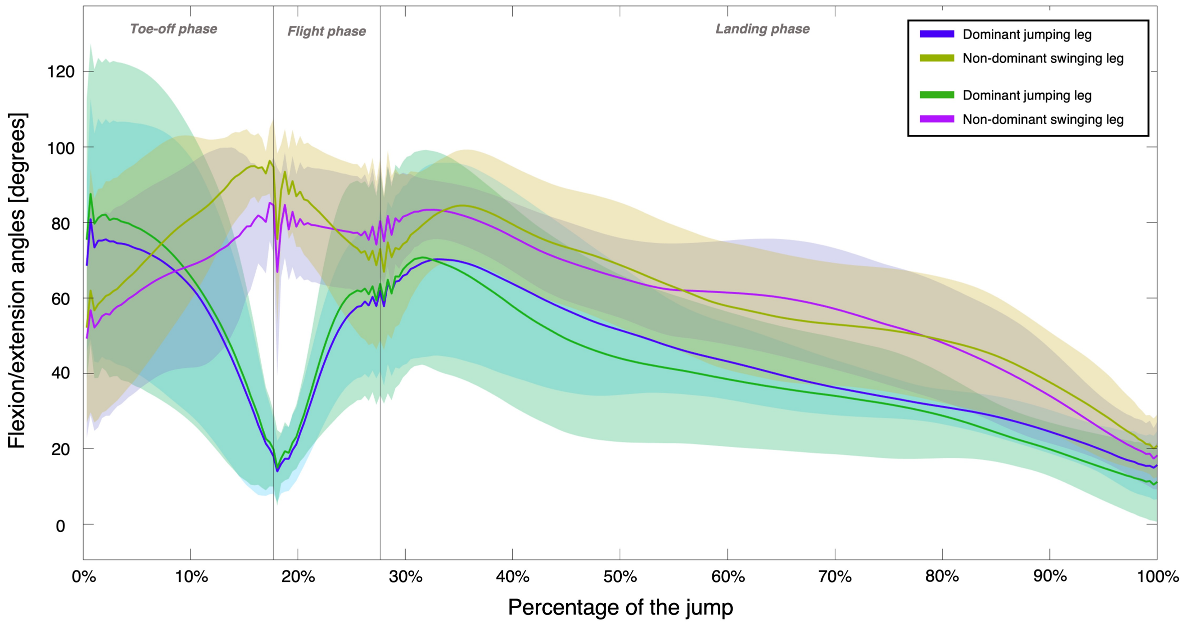


(a) Knee angles for non-dominant leg taped condition.

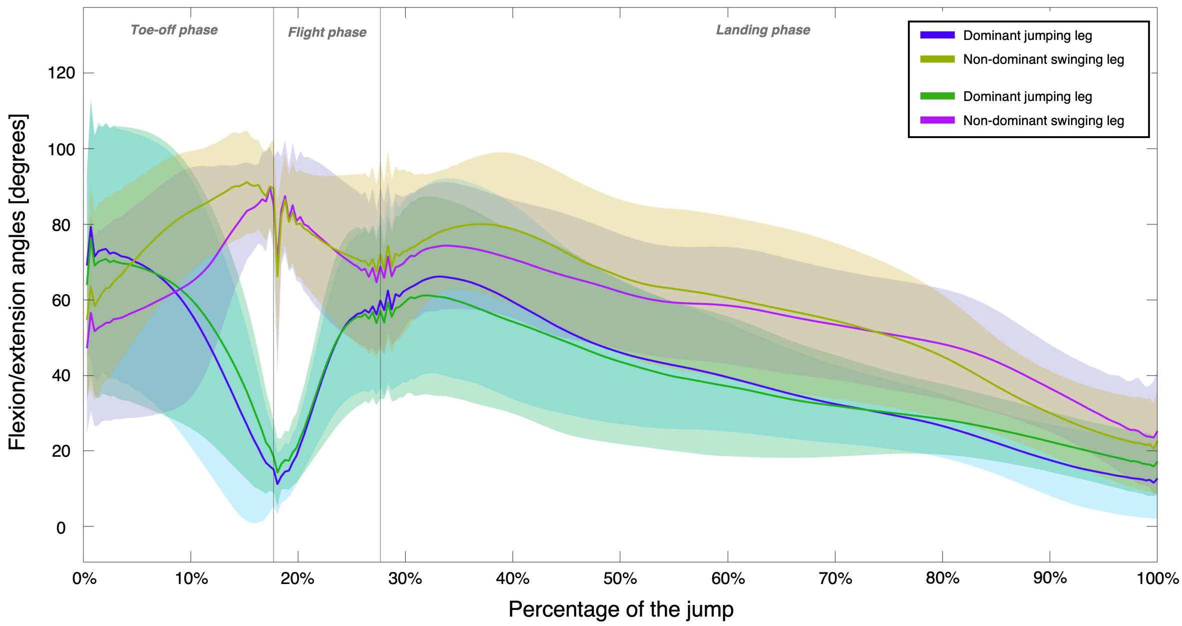


(b) Hip angles for no tape condition.

Figure 52 - *Continued from previous page.*

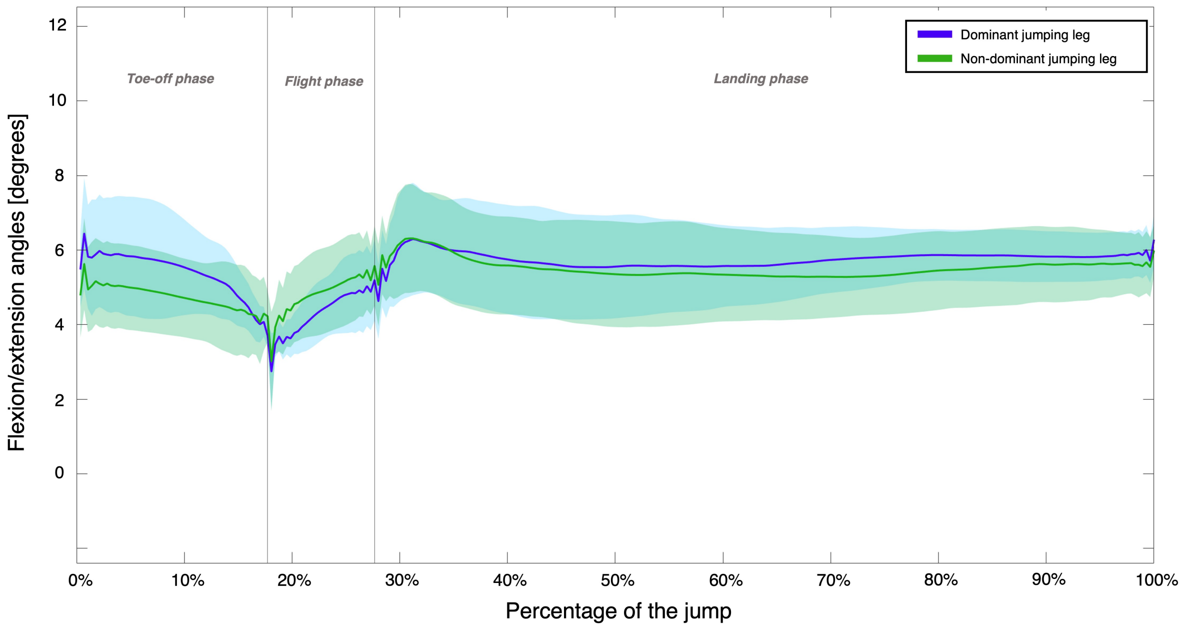


(c) Hip angles for dominant leg taped condition.

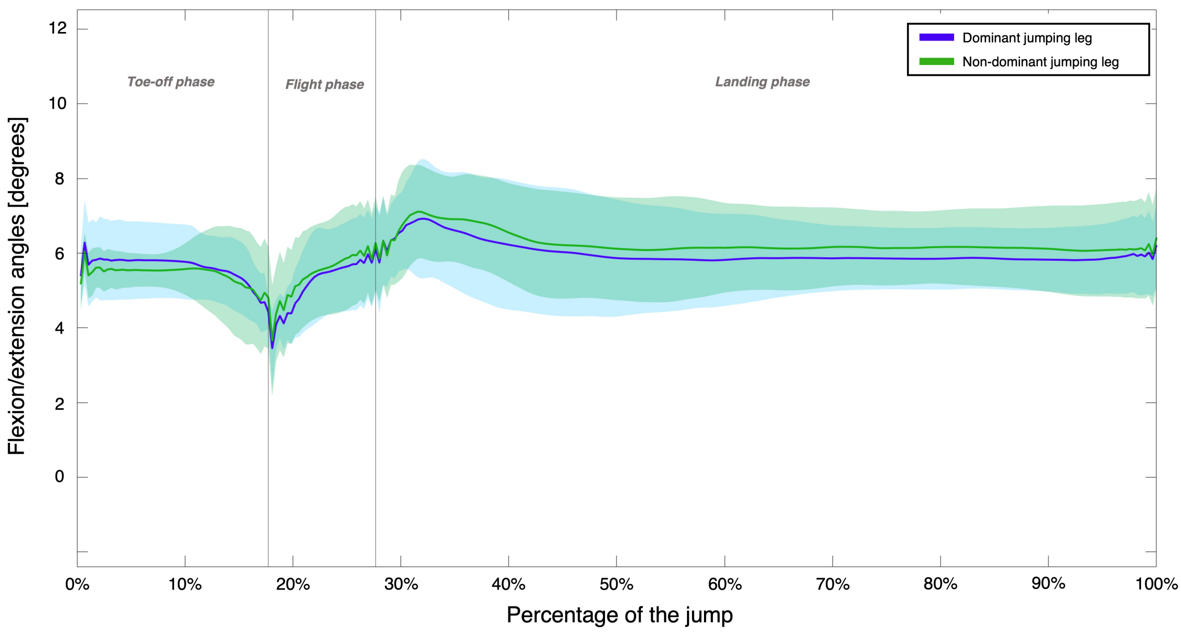


(d) Hip angles for non-dominant leg taped condition.

Figure 52 - *Continued from previous page.*

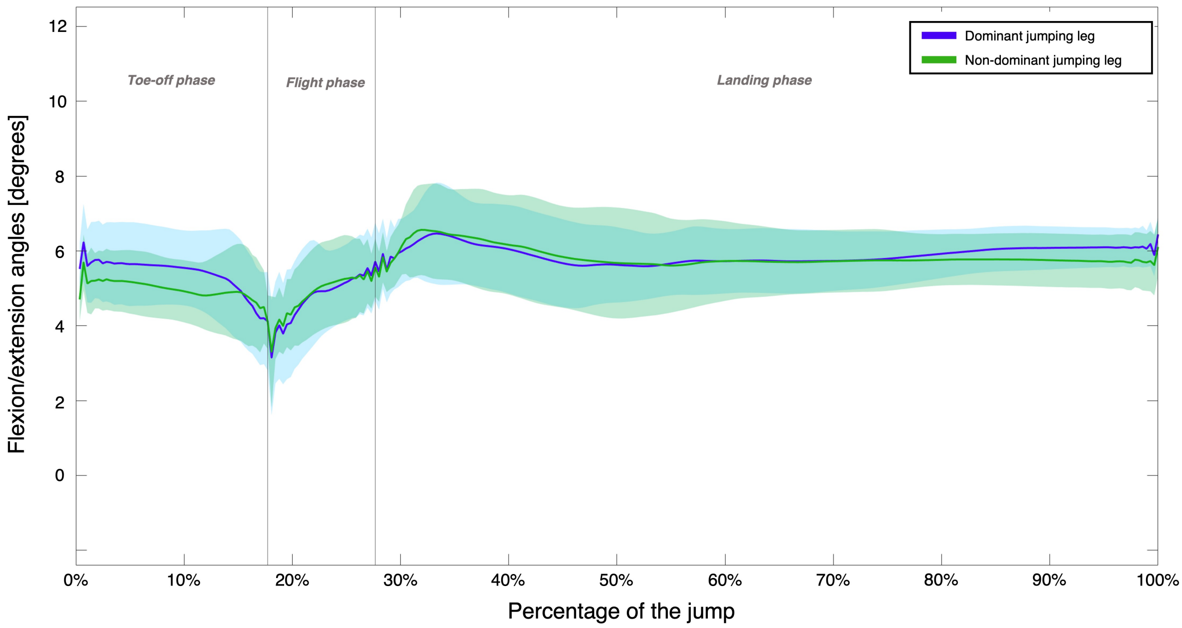


(e) Torso angles for no tape condition.



(f) Torso angles for dominant leg taped condition.

Figure 52 - *Continued from previous page.*



(g) Torso angles for non-dominant leg taped condition.

Figure 52 - *Continued from previous page.*

J.5 STATISTICAL OUTCOMES OF SINGLE-LEG JUMPS AND JUMPING ACCURACY AND TIMING ANALYSES

J.5.1 *Models of single leg jump distance analysis*

Linear mixed effect model of single-leg jump distance analysis of main dataset

Single-leg jump distance ~ Interaction condition + (1 | Participant) + ϵ

Linear mixed effect model of single-leg jump distance analysis of dominance effect dataset

Single-leg jump distance ~ Perturbance + Jump number + (1 + Interaction condition | Participant) + ϵ

Table 17: Fixed effects and random effects structure of linear mixed effects model for predicting single-leg distances of the single-leg jumps in the main evaluation dataset and the dominance effect measurement. Note, the estimate consists of log odds; standard errors are denoted by SE; confidence intervals are denoted by CI; standard deviation is denoted by std. dev.

Main evaluation

Fixed effects	**Estimate**	**SE**	**T-value**	**P-value**	**Lower 95%-CI**	**Upper 95%-CI**
Intercept	130,85	7,32	17,87	<0,001	118,56	142,95
Interaction condition	-6,19	2,03	-3,05	<0,01	-9,37	-2,73
Random effects	**Variance**	**Std. dev.**	**ΔAIC**			
1 | Participant	926,10	30,43	-274,87			

Dominance effect measurement

Fixed effects	**Estimate**	**SE**	**T-value**	**P-value**	**Lower 95%-CI**	**Upper 95%-CI**
Intercept	113,53	12,46	9,11	<0,001	88,73	140,16
Perturbance	4,99	1,25	3,99	<0,05	2,45	7,38
Trial number	2,48	0,67	3,71	<0,001	1,45	3,65

Table 17 - Continued from previous page.

Dominance effect measurement (continued)

Random effects	Variance	Std. dev.	ΔAIC
1 + Interaction condition | Participant *Dominant leg perturbed - non-dominant leg jumping*	95,99	9,80	-38,47
1 + Interaction condition | Participant *Non-dominant leg perturbed - dominant leg jumping*	44,55	6,68	-38,47
1 + Interaction condition | Participant *Non-dominant leg perturbed - non-dominant leg jumping*	136,49	11,68	-38,47
1 + Interaction condition | Participant *Full slope*	1225,71	35,01	-205,76

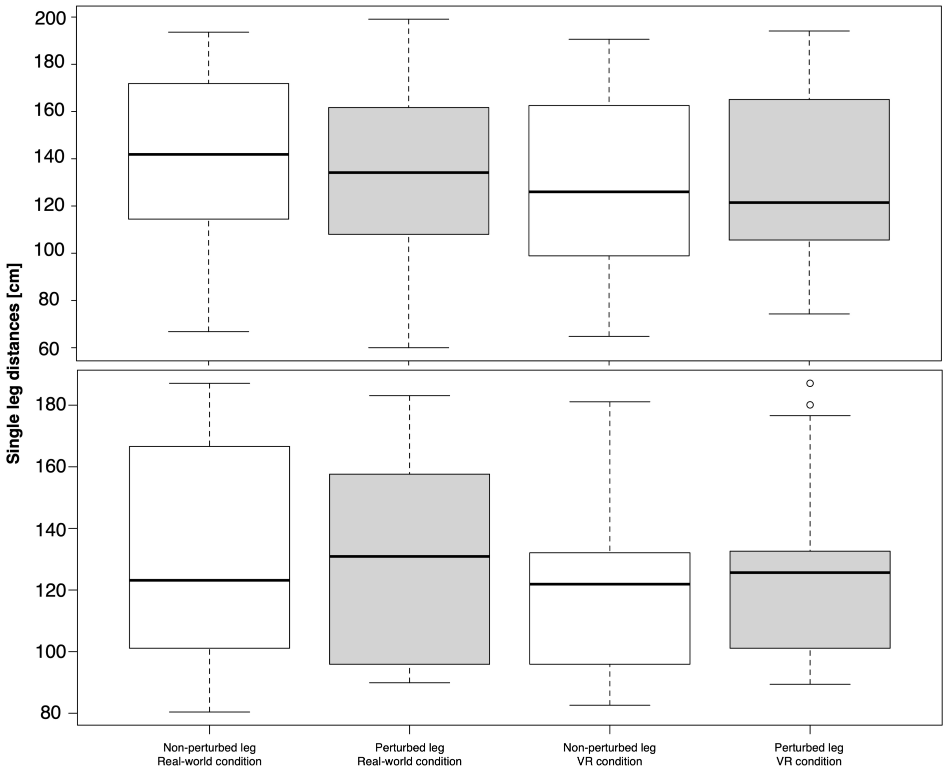


Figure 53: Boxplot of single-leg distances as a function of perturbance and interaction condition for the single legs of the main evaluation session (top) and the dominance effect measurement (bottom).

Table 18: Overview of LSI scores per participant per condition as determined by dividing the maximum jumping distance made with the perturbed non-dominant leg by the distance of the non-perturbed dominant leg. LSI values below 90% are indicated with an asterisk (*, indicating that the jumping distance was further for the non-perturbed dominant leg) and above 110% are indicated with a double asterisk (**, indicating that the jumping distance was further for the perturbed non-dominant leg).

Participant	**LSI for real-world condition**	**LSI for VR condition**
P03 (pilot trial)	81,73% *	92,06%
P04	110,00%	108,59%
P05	86,44% *	88,34% *
P06 (pilot trial)	111,95% **	101,54%
P06 (trial 2)	105,85%	99,46%
P06 (trial 3)	97,68%	101,84%
P07	85,51% *	107,99%
P08	116,51% **	95,95%
P09	105,24%	94,72%
P10	98,50%	96,64%
P11	109,51%	101,19%
P12	124,74% **	103,59%
P13	84,59% *	69,28% *
P14	93,61%	93,87%
P15	93,33%	107,96%
P16	102,02%	108,28%
P17	97,91%	78,87% *
P18	98,42%	105,52%
P19	91,04%	102,25%
P20	111,68% **	117,71% **

Table 19: Overview of LSI scores per participant per condition for the dominance influence measurement as determined by dividing the maximum jumping distance made with the non-dominant leg by the distance of the dominant leg for the different conditions. LSI values below 90% are indicated with an asterisk (*, indicating that the jumping distance was further for the non-perturbed dominant leg) and above 110% are indicated with a double asterisk (**, indicating that the jumping distance was further for the perturbed non-dominant leg).

Participant	**LSI for no tape condition**	**LSI for dominant leg perturbed condition**	**LSI for non-dominant leg perturbed condition**
P03	80,13% *	86,86% *	79,18% *
P05	83,23% *	82,95% *	93,64%
P10	113,44% **	96,92%	111,67% **
P12	110,96% **	91,89%	99,02%
P16	97,65%	98,91%	100,00%
P19	100,44%	107,30%	118,56% **

J.5.2 *Models of jump accuracy, lavaball hit accuracy and jump times*

Linear mixed effect model and linear model of jump accuracy and timing analysis

Jump accuracy (distance between landing point and target) ~ round number + (1 | Participant) + ϵ

Lavaball hit accuracy (percentage hits out of all lavaballs fired) ~ round number + (1 | Participant) ϵ

Round time (normalised) ~ round number + ϵ

For the random effect structures in Tables 20, 21 and 22, the inclusion of random effects with a positive ΔAIC were used to negate categorisation effects of the assumptions of the model (see also Appendix K.3).

Table 20: Fixed effects and random effects structure of linear mixed effects model for predicting round jumping accuracy (indicated as the distance between landing and the target location). Note, the estimate consists of log odds; standard errors are denoted by SE; confidence intervals are denoted by CI; standard deviation is denoted by std. dev.

Fixed effects	**Estimate**	**SE**	**T-value**	**P-value**	**Lower 95%-CI**	**Upper 95%-CI**
Intercept	0,28	0,01	45,06	<0,001	0,27	0,29
Round number	0,00	0,00	2,24	<0,05	0,00	0,01
Random effects	**Variance**	**Std. dev.**	**ΔAIC**			
1 + Perturbance |Participant *Perturbance*	0,00	0,01	0,13			
1 + Perturbance | Participant *Full slope*	0,00	0,02	-18,29			

Table 21: Fixed effects and random effects structure of linear mixed effects model for predicting lava-ball hit accuracy. Note, the estimate consists of log odds; standard errors are denoted by SE; confidence intervals are denoted by CI

Fixed effects	**Estimate**	**SE**	**T-value**	**P-value**	**Lower 95%-CI**	**Upper 95%-CI**
Intercept	0,64	0,04	15,22	<0,001	0,57	0,71
Round number	0,04	0,01	2,63	<0,05	0,01	0,06
Random effects	**Variance**	**Std. dev.**	**ΔAIC**			
1 | Participant	0,00	0,07	13,29			

Table 22: Fixed effects and random effects structure of linear mixed effects model for predicting jump times. Note, the estimate consists of log odds; standard errors are denoted by SE; confidence intervals are denoted by CI; standard deviation is denoted by std. dev.

Fixed effects	**Estimate**	**SE**	**T-value**	**P-value**	**Lower 95%-CI**	**Upper 95%-CI**
Intercept	2,10	0,20	10,52	<0,001	1,75	2,45
Jump type	0,01	0,00	9,47	<0,001	0,01	0,01
Round number	-0,05	0,02	-2,20	<0,05	-0,08	-0,01
Random effects	**Variance**	**Std. dev.**	**ΔAIC**			
1 + Perturbance |Participant *Perturbance*	0,01	0,10	0,10			
1 + Perturbance | Participant *Full slope*	0,59	0,77	-600,57			

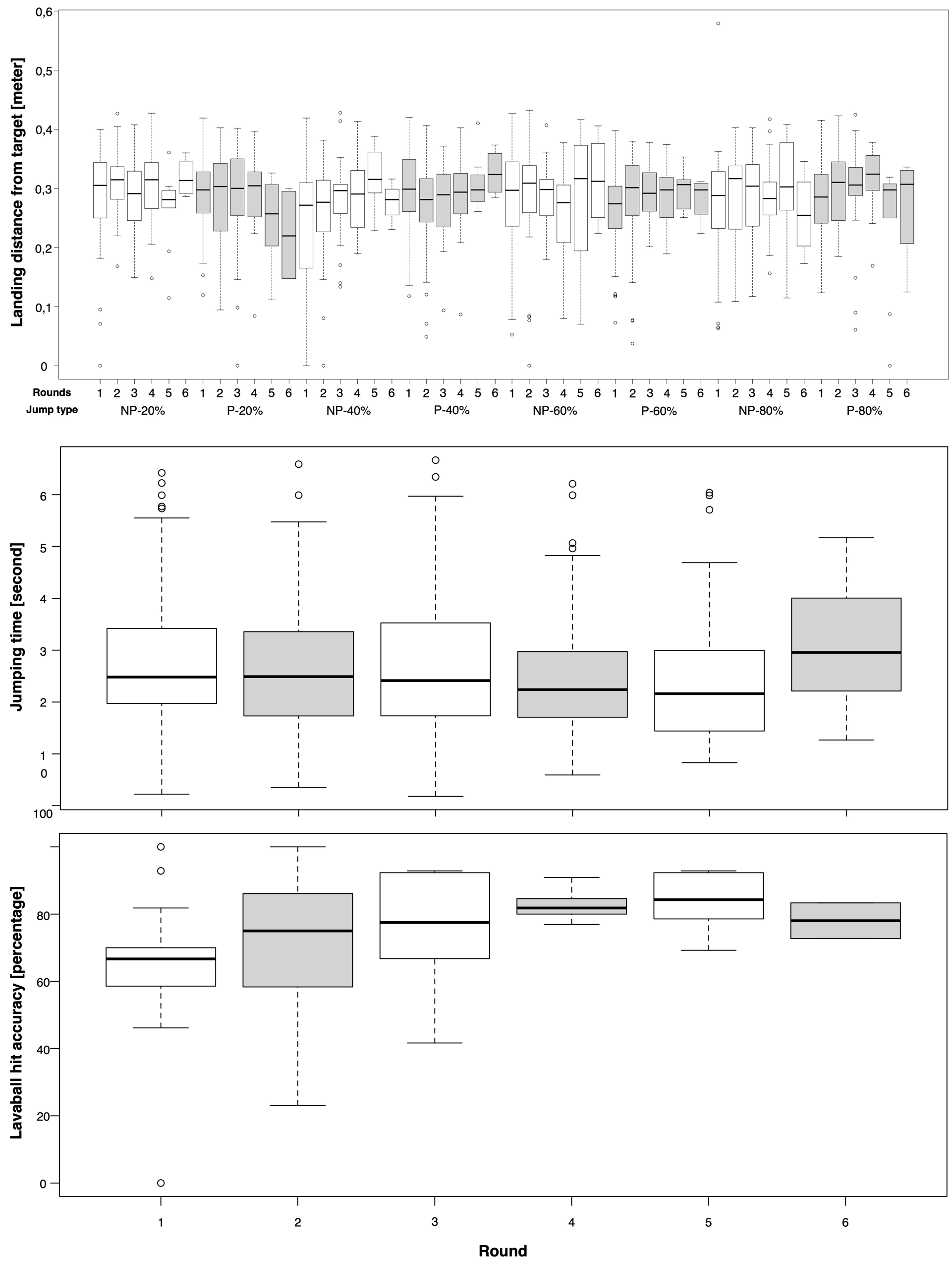


Figure 54: Boxplot of the jumping accuracy (determined by the landing distance from the target per round in meters) as a function of the round and the jump type based on the perturbance and the jumping distance (top plot) and the jump time (middle row) and lavaball hit accuracy (bottom row) as a function of the round. Shown is the accumulated data for all participants.

K

STATISTICAL MODEL ASSUMPTIONS

K.1 LME MODEL ASSUMPTIONS OF MAIN STATISTICAL ANALYSIS

The assumption plots of the LME models of Section 6.2 and subsection 6.2.3 and are presented in Figures 55 and 56 respectively.

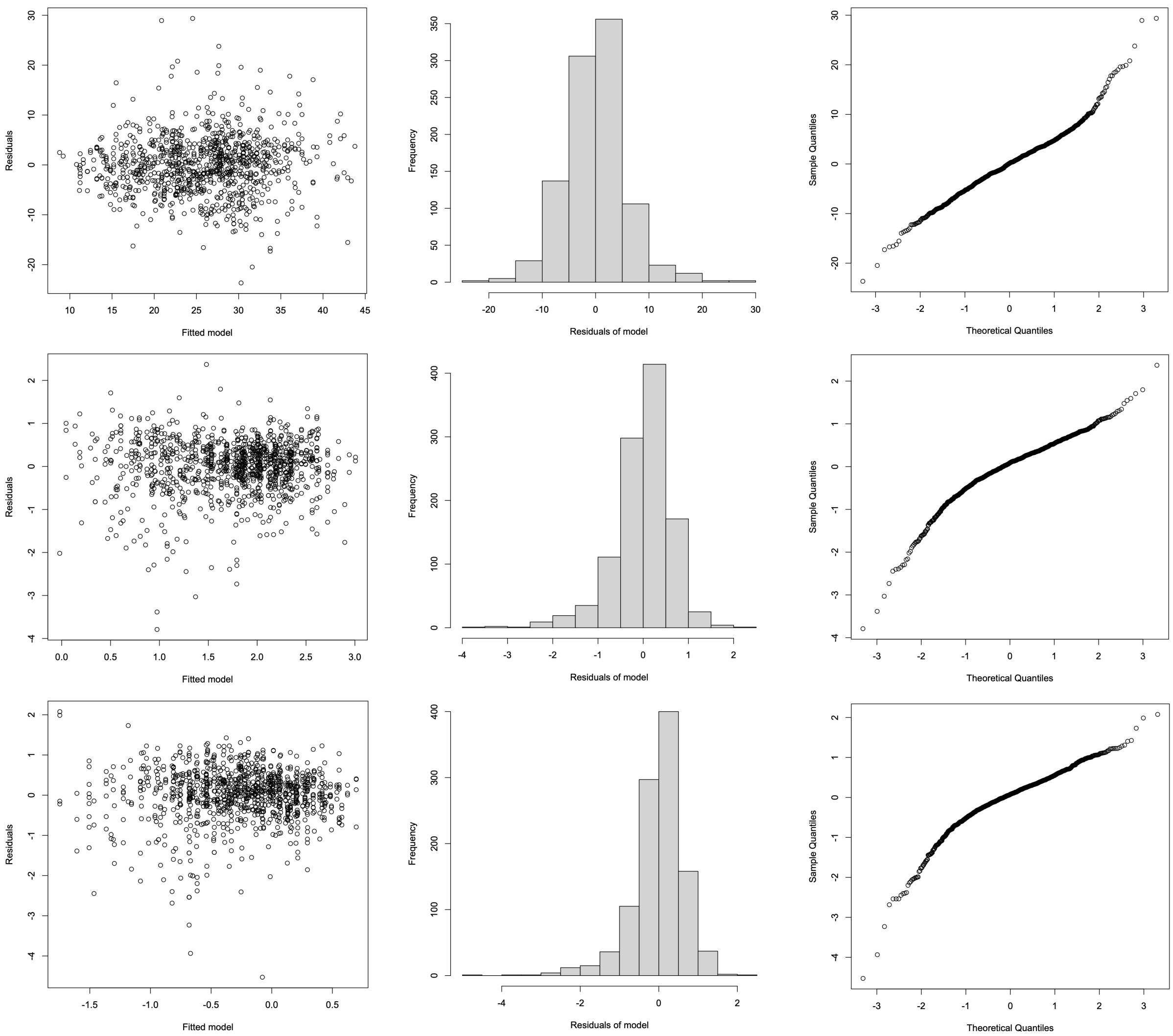


Figure 55: Assumption plots of LME models for knee (top row), hip (middle row) and torso (bottom row) RoF. Shown are the model residuals (left column), histogram (middle column) and Q-Q plot (right column) per segment.

Within the assumptions of Figure 55, it can be seen that the residual plots (left column) are randomly distributed between the predicted ("fitted") values and the residuals. This indicates linearity and a full capture of the RoF by the chosen effects of the model [126]. After data transformations of the hip and torso data, no heteroskedasticity is presented in the residual plots. For the torso RoF data and, to a lesser degree, for the hip RoF data, vertical stripes seem to occur within the residual plot, indicating that there is a small influence of categorical data. This could, however, not be solved with the use of logistics models and data transformations, thus indicating that the data is indeed affected by categorical influences. However, as the data points are still evenly distributed, the effect of categorisation is minimised and the model is able to predict values over the entire spectrum of the plot. For the normality of the data, the histograms (middle column) and Q-Q plots (right column) can be considered. Here, it can be seen that all histograms are relatively bell-shaped and the Q-Q plots indicate that the data fall relatively on a straight line, with the knee RoF data being the most normally distributed of the three segments.

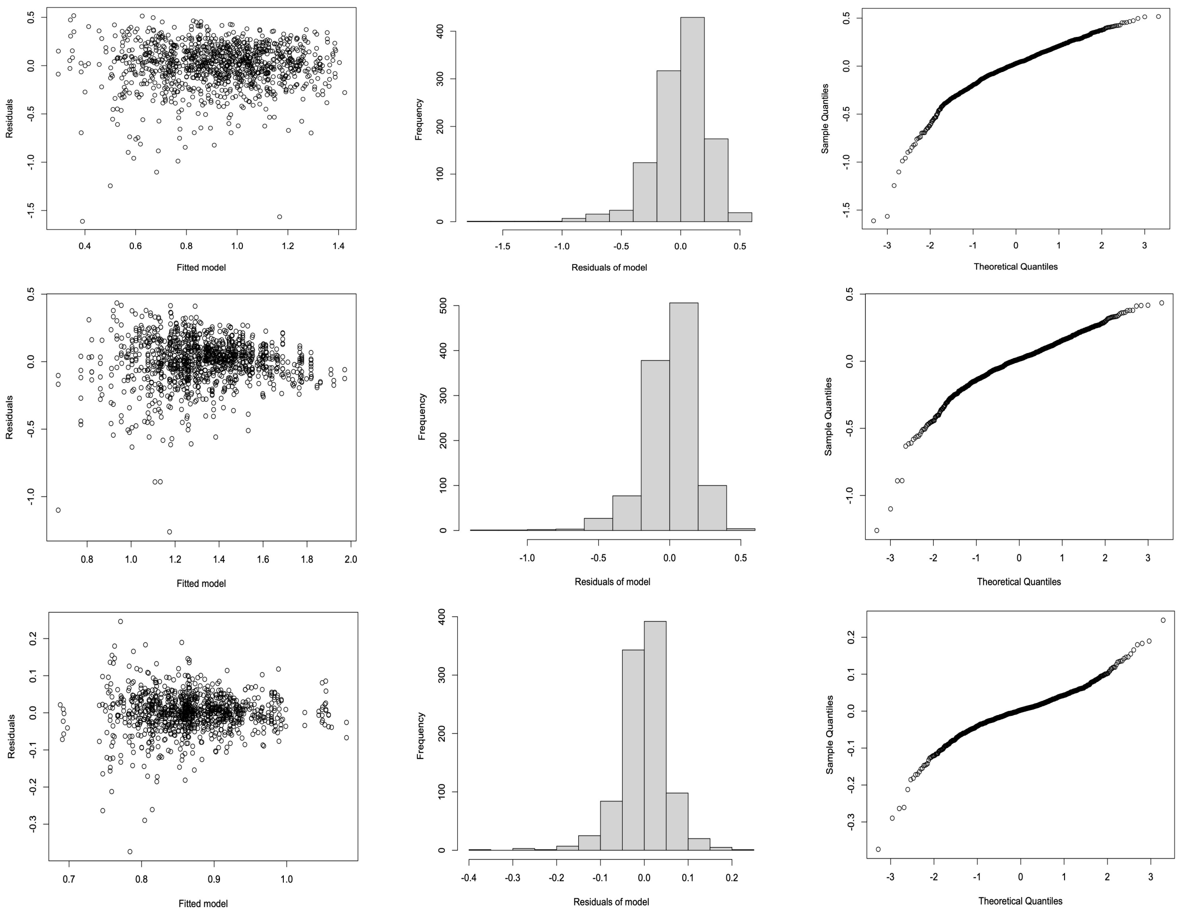


Figure 56: Assumption plots of LME models of toe-off phase for knee (top row), hip (middle row) and torso (bottom row) RoF. Shown are the model residuals (left column), histogram (middle column) and Q-Q plot (right column) per segment.

The assumption plots of the LME models of Section 6.4 are presented in Figure 57 for the landing RoF and Figure 58 for the toe-off RoF.

For the dominance effect measurement assumptions in Figure 57, it can be seen that the influence of categorical data is stronger than for the main dataset (shown in Figure 55). Because of this reason, data simplifications were used that resulted in a normal distribution for the knee segment residuals (top left plot), and a more distributed residual plot of the hip and torso (left middle and bottom plots). For the hip and torso data, it can also be seen that the histograms are less bell-shaped than the knee data, while the Q-Q plots of all three segments show similar normality. As no (non-categorical) fixed effects were found to be significant for the hip and torso data, these assumption plot results can be expected and might be removed by the addition of other fixed effects and further data gathering. For the current study, the effects do not influence the data analysis outcome.

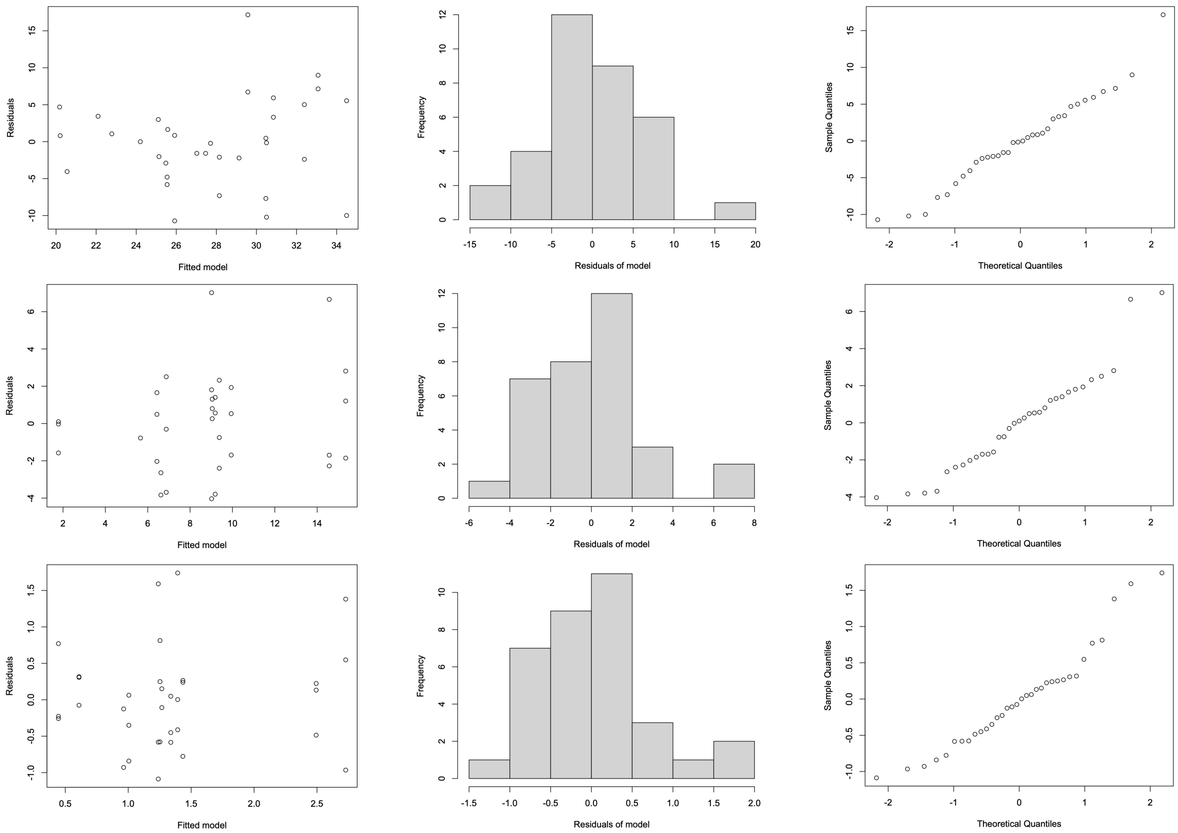


Figure 57: Assumption plots of LME models of the dominance effect measurement of landing RoF for knee (top row), hip (middle row) and torso (bottom row) RoF. Shown are the model residuals (left column), histogram (middle column) and Q-Q plot (right column) per segment.

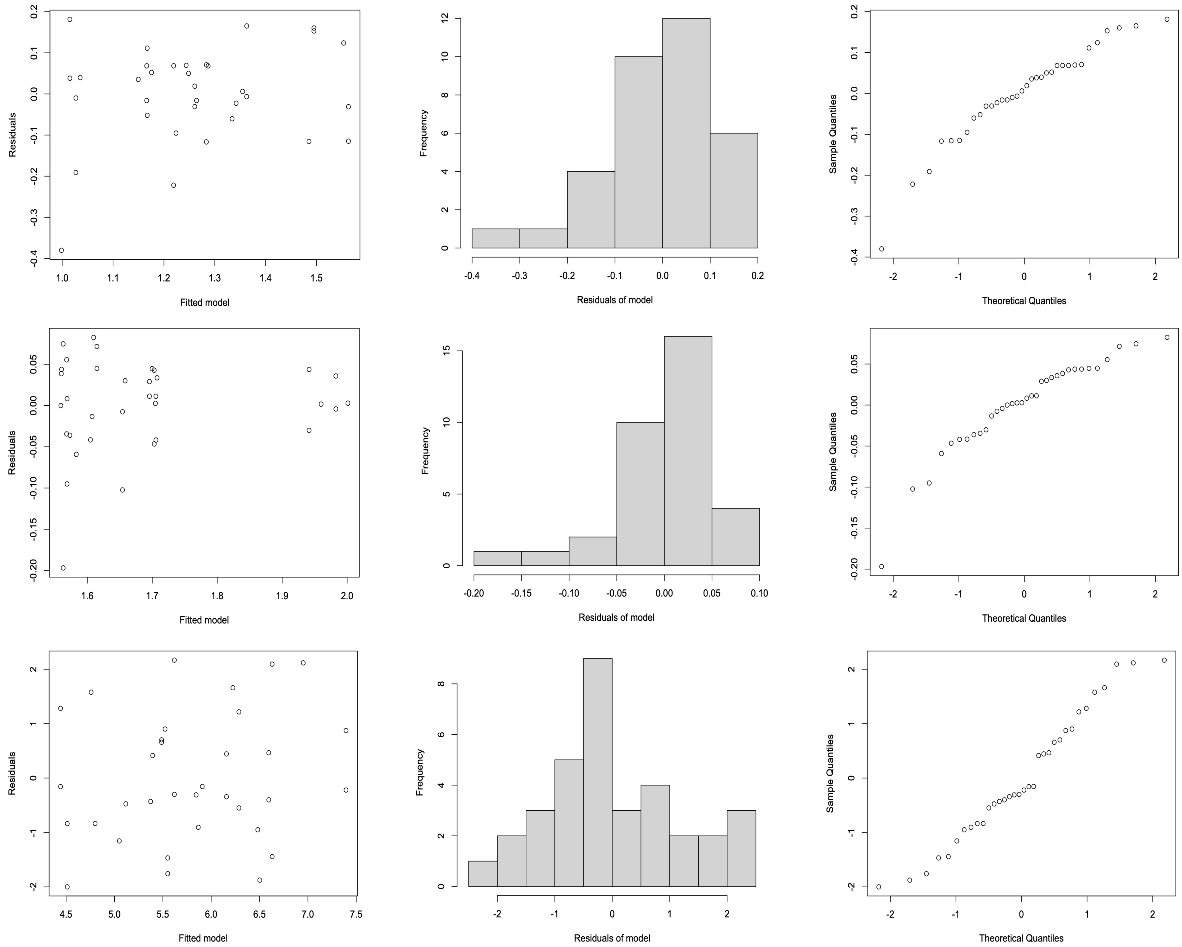


Figure 58: Assumption plots of LME models of the dominance effect measurement of toe-off RoF for knee (top row), hip (middle row) and torso (bottom row) RoF. Shown are the model residuals (left column), histogram (middle column) and Q-Q plot (right column) per segment.

The assumption plots of the LME models of the single leg distance analysis of the main dataset and the dominance effect measurement described in Section 6.5 are presented in Figure 59.

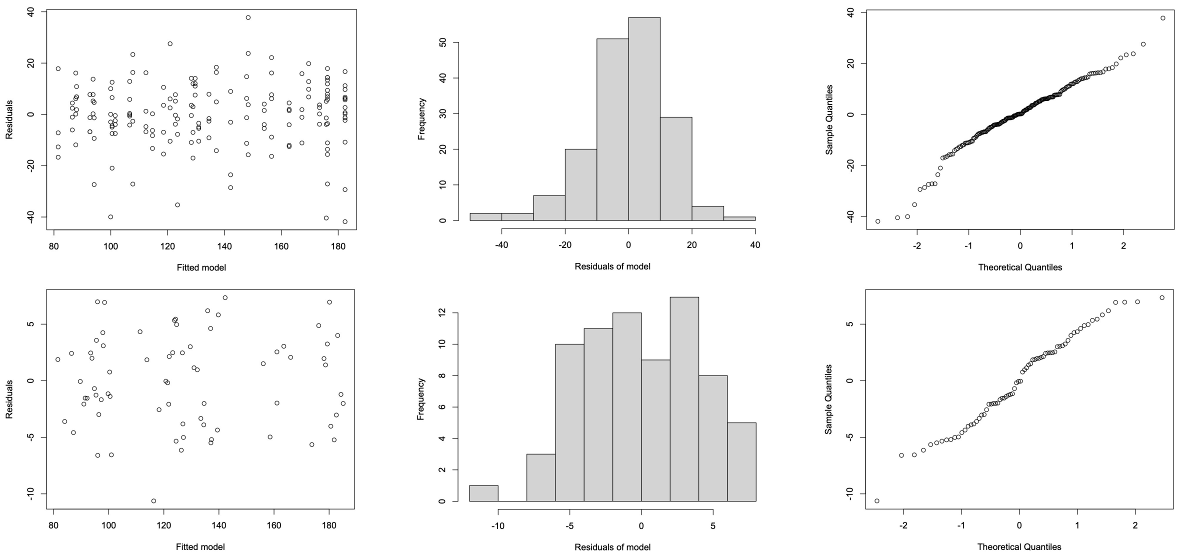


Figure 59: Assumption plots of LME models of single leg distance analyses for the main dataset (top row) and the dominance effect measurement (bottom row). Shown are the model residuals (left column), histogram (middle column) and Q-Q plot (right column) per segment.

The assumption plots of the LME models of the jump accuracy, lavaball hit accuracy and jump timing analysis described in Section 6.6 are presented in Figure 60.

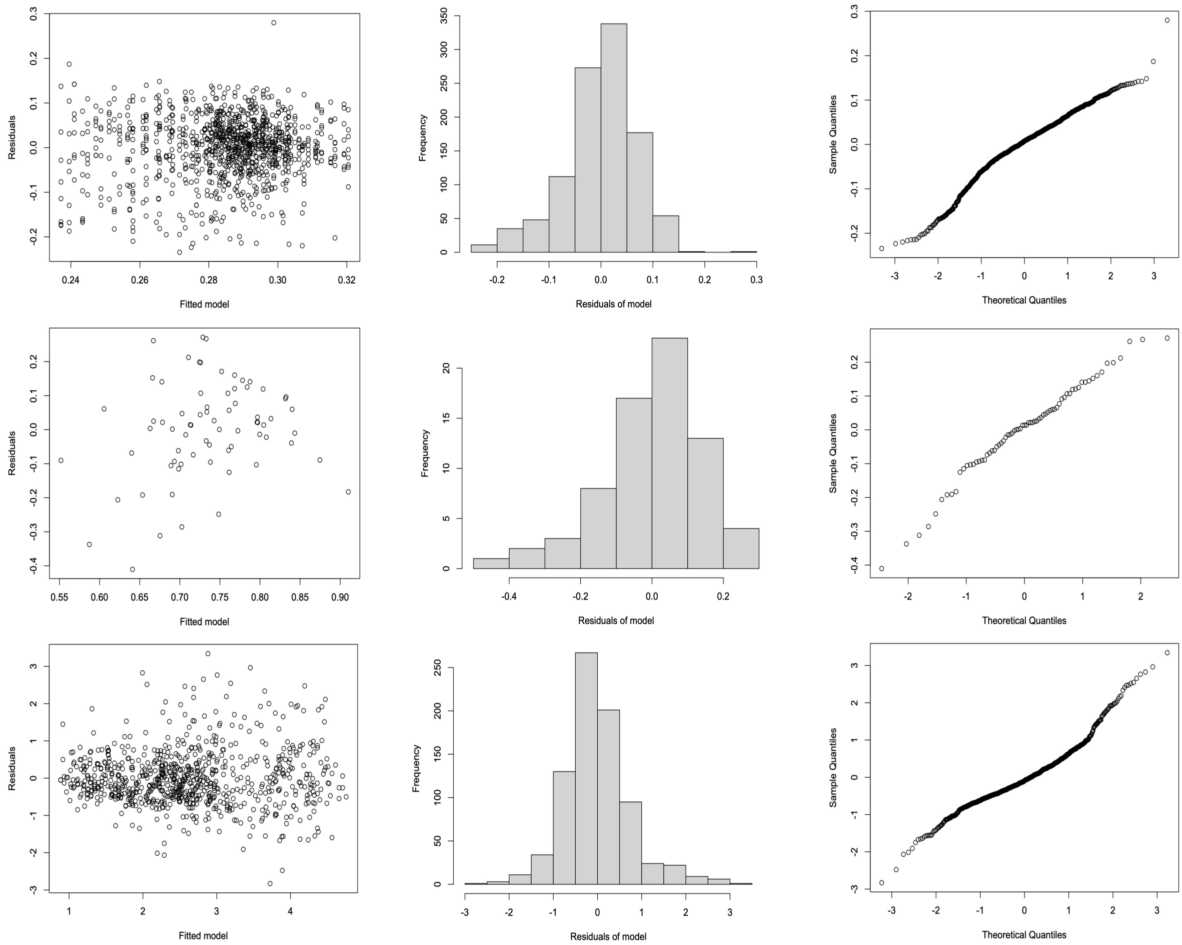


Figure 60: Assumption plots of LME models of jump accuracy (top), lavaball hit accuracy (middle) and jump timing (bottom) analyses. Shown are the model residuals (left column), histogram (middle column) and Q-Q plot (right column) per segment.