Inertial Measurement Unit-based post-surgery knee rehabilitation

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by

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Preface

This report presents the work done to complete the course BM51035 BME MSc Thesis and obtain the graduation from the MSc in Biomedical Engineering at the faculty of Mechanical, Maritime and Materials Engineering (3mE). This project has been supervised by Prof. dr. P. French and Ir. K. Rassels from TU Delft, and Ir. C. Lauwerijssen from 2M Engineering Ltd.

José López Hidalgo
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Contents

1 Introduction

Every year, nearly five million people undergo knee surgery[49, 63], making it one of the most common orthopaedic procedures. Sport-related and traumatic injuries, like torn menisci or ligaments, and age-related diseases, such as osteoarthritis, are the major causes that lead to a knee operation. To recover mobility, stability and muscle strength, the person must go through a post-surgical rehabilitation program.

The prize of these physiotherapy sessions increases the already high medical cost of the treatment. For instance, only in the USA, the expenditure on knee surgeries performed to treat degenerative diseases exceeds $3 billion per year[63].

Another inconvenience is that rehabilitation is repetitive. Patients repeat the same set of exercises over and over again. That might make them lose motivation and discourage them before finishing the whole program.

Lastly, this rehabilitation is inaccessible for some people, not only because of the medical cost. People who live far away from a hospital or rehabilitation centre, or in areas where the public healthcare system is saturated, cannot follow a rehabilitation protocol properly.

As a result, many people abandon their rehabilitation programs, so they do not fully recover the pre-injury state.

This can be solved through gamification, engaging these patients to get better results, allowing for telerehabilitation and providing the therapists with valuable information about the patient's performance.

1.1. Research Goal

The research goal of this project is to develop a game for post-surgery knee rehabilitation controlled with inertial measurement units (IMUs) to increase patient engagement, reduce medical costs and, ultimately, accelerate the rehabilitation process.

To achieve this goal, there are several tasks that need to be done:

- Literature research.
- Survey with physiotherapists and patients.
- Implementation of a new calibration tool.
- Implementation of a reporting system.

The literature review and the survey with the stakeholders will answer the medical and technical questions that result from the problem we want to solve. That knowledge will allow us to determine the best methodology we have to use for our solution.

The system used as the controller of the game implements a calibration tool that needs to be improved, as it does not work accurately with people with limited mobility. Therefore, we will have to develop a new calibration algorithm that suits our scope.

Lastly, the game needs to satisfy also the physiotherapist's requirements. For that reason, it is necessary to implement a reporting system that provides them with relevant medical information about the patient's progress.

1.2. Used Technologies

The sensor used in this project was the NODES System. It is a motion capture system to measure and record the orientation of human body segments, developed by 2M Engineering. Figure 1.1 shows the diagram of this system.

On the left, we can see the sensors used, that are IMUs. Several sensors are connected in series, forming a sensor string. Finally, these strings are connected to the main node or unit through sensor strings. The NODES unit contains five sensor string inputs.

The main unit processes the output of the sensors. We can differentiate three blocks inside it. Represented by the blue square, we have the preprocessing of the data. The input of this block is the raw data from the sensors. During this data preprocessing, there is a mounting frame calibration and noise compensation. Additionally, the data is converted to the International System of Units. This calibrated raw data can be stream as the output of the NODES System.

When the user requests the system to stream quaternions, the preprocessed data goes into the Sensor Fusion Algorithm (SFA) that the system implements, a Novel Madgwick algorithm modified by 2M. It corresponds to the green block shown in the diagram. This algorithm estimates the orientation of each sensor in quaternion form.

Finally, the red block corresponds to the sensor calibration. The user can carry out the calibration of the Inertial Measurement Unit (IMU)s at any time. As a result, the scale and offset values used in the preprocessing of each sensor will be updated.

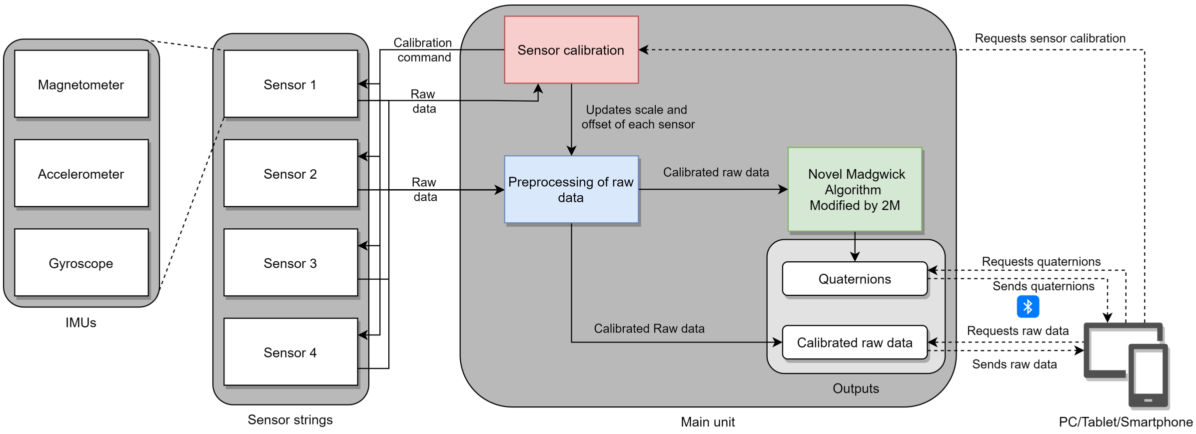

Figure 1.1: Diagram of the NODES System.

1.3. Report Outline

This report starts with a review of medical literature to analysed different aspects of knee rehabilitation and the survey with physiotherapists. Then, there is an overview of the state-of-the-art methodologies used to process the data from the type of sensors we use.

Chapter 3 will focus on the game developed. First, the concept of the game is presented. This includes an overview of the process followed to design the level and characters that appear in the game. The following section is about the algorithm created to convert the movement of the patient into a standard input for the game. After that, the save and load system of the game is explained. This system is needed to store the data recorded during the game so it can be visualised later by the patient or physiotherapist in the progress report. The next section is about the two user interfaces of the application, one for patients and another one for physiotherapists. Finally, the database created to manage those two users is explained, together with the scripts written to implement features like the login or registration of users, for instance.

Chapter 4 focuses on the second goal of the project, that is, a new calibration approach for the NODES System. In the first section, the current calibration tool is analysed and its problems are exposed. The following section explains the principles of the proposed calibration algorithm and shows the C# code created to implement it.

Chapter 5 focuses on the remaining goal, the reporting system to update the physiotherapist and show them the patient's progress. This system consists of two different reports. The first one is shown in the patient's user interface. On the other hand, the second report is for the physiotherapist.

In chapter 6, the experiment performed to validate the two algorithms that were developed is explained. First, the materials and methods used during the experiment are listed. Then, the results of the different tests are shown. Finally, these results are discussed.

Chapter 7 focuses on the voluntarily study made with employees from 2M Engineering and in the questionnaires created for physiotherapists and patients. The first two sections of this chapter correspond to the tests of the study. One test focuses on the calibration and the other on the game. The following section is about the questionnaire for the physiotherapists. This questionnaire was sent to the people that were interviewed at the beginning of the project. The last section shows the answers from the questionnaire created for people who had knee surgery before. This questionnaire was distributed among the interviewees' patients and on social media.

The last chapter of the report corresponds to the conclusion. In this chapter, the project and the results of the different tests and surveys are summarised. Additionally, the chapter ends with a section that focuses on the future work that could be done to improve what was done in this project.

2

Literature Research

Literature research was carried out to achieve the objectives mentioned in 1.1. This review has two scopes: medical and technical.

The medical literature review focuses on understanding the rehabilitation of the knee. It starts discussing the knee anatomy, the problems that can happen in this joint, and how are they solved through surgery. After that, the different phases, exercises and outcome assessment methods are explained. Finally, there is a review of rehabilitation technology, with an especial focus on the use of games in physical rehabilitation. This research also includes the survey with physiotherapists and patients and its outcomes.

The technical literature research, which tries to answer the questions mentioned above, starts with the type of sensor used and the different orientation representations. After that, the calibration process is explained. Finally, there is a state-of-the-art review of the sensor fusion algorithms used for motion tracking, with a comparison between the most important ones.

The requirements for the game, the calibration tool and the reporting system were extracted from the conclusions and experience gained after this research and the interviews with health professionals and patients.

2.1. Medical Scope

2.1.1. Anatomy of the knee

The knee is the largest and most complex joint of the body. It is located on the lower limb and joins the thigh and the leg or shank together. It consists of two joints: the tibiofemoral joint and the femoropatelar joint. Both of them are synovial joints, i.e., they have a matrix of connective tissue between the bones separating them. This matrix, that is the synovial cavity, forms the articular capsule.

Additionally, we can classify them according to the shape of their articular surfaces and movements permitted. The tibiofemoral joint is a modified hinge, while the femoropatelar joint is a plane. These two types of joint combined allow the knee to move with two degrees of freedom: flexion/extension and, only when the knee is at 90º of flexion, internal/external rotation. A healthy person shows a high range of knee flexion, limited predominantly by the contact between the thigh and lower leg. On the other hand, the maximum extension and rotations of the knee are typically low. Table 2.1 shows the average values of each movement for a healthy person.

Movement	**Range of motion (º)**
Extension	5-10
Flexion	120-150
Internal rotation[1]	10
External rotation[1]	30-40

Table 2.1: Range of motion of the knee joint in healthy people[44].

[1]Only when the knee is flexed 90º.

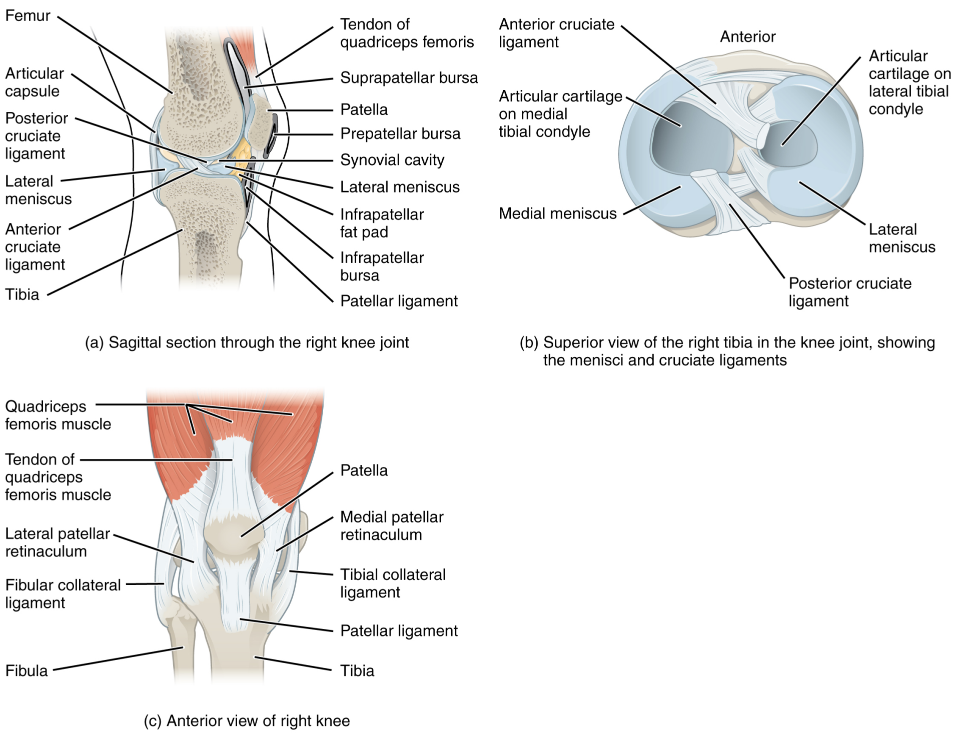

Figure 2.1: The knee joint. Sagittal section through the right knee joint (a), superior view of the right tibia showing the menisci and cruciate ligaments (b) and anterior view of right knee shoving the quadriceps and its tendons. Picture retrieved from [6].

The bones that form the knee are the femur, tibia, fibula and patella or kneecap. The femur presents two articular surfaces on its distal end: the medial and lateral condyles. They are two convex, ovoid protuberances separated by a groove known as the patellar surface that connects with the kneecap. The regions right above the condyles are the epicondyles. The condyles articulate with the concave medial and lateral condyles of the tibia. The proximal head of the tibia presents the intercondylar eminence that separates the condyles. Lastly, the head of the fibula connects with the inferior region of the lateral tibial condyle.

Apart from bone tissue, there are three other types present in the knee: cartilage, ligaments and muscles. The cartilage tissue covers the articular surface protecting the ends of long bones. It is inside the synovial capsule, which encloses the knee joint only partially. It is present on the posterior and lateral facets of the knee. Anteriorly, there are only tiny flattened sacs filled with a thin layer of synovial fluid, the bursa. The bursae provide a cushion between adjacent structures to reduce friction during knee movements.

Additionally, there are two crescent-shaped fibrocartilaginous tissues on top of the tibial condyles known as the menisci. The function of these tissues is to protect the knee. They are concave on the top and flat on the bottom, and they get thinner towards the centre. They are separated by the intercondylar eminence and attached only to the outer surface of the tibia. The menisci disperse and absorb the load to the knee joint and reduce friction. They also help to prevent side-to-side rocking of the femur on the tibia.

The ligaments that join the femur with the tibia or fibula are four, two outside and the other two inside the articular capsule. The outer ligaments are the fibular and tibial collateral ligaments. The first one runs from the lateral epicondyle to the fibular head, while the second one goes from the medial epicondyle to the medial condyle of the tibia. Additionally, the tibial collateral ligament fuses with the medial meniscus. The latter two ligaments are the Anterior Cruciate Ligament (ACL) and the posterior cruciate ligament. The ACL attaches to the anterior tibial intercondylar area and the medial side of the lateral femoral condyle, while the posterior cruciate ligament runs from the posterior tibial intercondylar area to the lateral side of the medial femoral condyle. Additionally, the patella is attached to the tibia and femur thanks to the patellar ligament and the medial and lateral patellar retinacula. These four ligaments stabilize the knee joint and prevent hyperextension of the knee and forward sliding of the tibia and femur.

Finally, the knee moves due to the action of the muscles in the thigh and lower leg. Some of them are monoarticular, i.e., they only act at the knee, but many others move the hip or ankle joints, too. The knee flexion is accomplished primarily by the action of the long and short heads of the biceps femoris, the semitendinosus and the semimembranosus muscles. These four muscles are known as the hamstring muscles. Additionally, other muscles like the sartorius, the gracilis, the gastrocnemius, the plantaris and the popliteus can also flex the knee. The popliteus muscle also unlocks the extended knee when flexion begins by rotating the leg medially. The extension of the knee, on the other hand, is the role of the quadriceps femoris, form by the rectus femoris and the vastus lateralis, medialis and intermedius. The patellar ligament and retinacula mentioned before are, in fact, the continuation of this muscle's tendons.

2.1.2. Knee pain

Problems with any of the tissues in the knee can introduce pain in the joint. Traumas, for instance, cause ligament sprain, tear of a meniscus, muscle strains, bone fractures, joint dislocations or inflammations of bursae (bursitis), tendons (tendinitis) or the synovial membrane (synovitis). These inflammations could also be the result of overuse, infections or other diseases. Common knee disorders are osteoarthritis, arthritis, osteomyelitis and tumours. Additionally, some disorders are associated with certain sports, like the iliotibial band syndrome or the patellofemoral pain syndrome, which is the most common sports-related knee disorder. Lastly, other causes of pain are deformities that affect the joint, like genu varum and genu valgum.

These knee problems are generally related to physical and occupational activity, sedentary lifestyles, obesity and age. There are non-surgical and surgical treatments to manage and heal this pain. Not all the disorders mentioned above require surgery. In some cases, this pain can be relieved with home remedies like the Rest, Ice, Compression and Elevation (RICE) method, alternative medicine such as acupuncture, physiotherapy or knee braces. However, more severe cases require the use of analgesic drugs and even a surgical operation. That is especially the case for traumatic injuries or fractures and worn out knee joints. Most of the knee surgeries performed are related to ACL injuries, fractures, torn menisci, bursitis, tendinitis, osteoarthritis and rheumatoid arthritis.

2.1.3. Surgical procedures

There are three types of knee interventions: knee arthrotomy, knee arthroscopy and knee arthroplasty. Each of them is intended for specific pathologies. Depending on the origin and severity of the pain, the patient will undergo one type or another.

An arthrotomy is a surgery where the joint is explored by opening a large incision. This type of intervention has been substituted almost entirely by arthroscopic knee procedures, as they are minimally invasive. In this second type, only two small incisions are needed, one for the surgical instruments and another one arthroscope, which is the specific endoscope used in this type of surgery. It is mainly performed to repair soft tissue, like a torn meniscus or an injured ACL, but also bone fractures.

On the other hand, an arthroplasty is the replacement of the knee joint with a prosthesis. It is primarily performed to repair the damage caused by osteoarthritis and for other diseases that worn out the knee, like rheumatoid arthritis. In either the partial or total knee replacement, the injured articular surfaces are replaced with implants typically made of metal, ceramic or plastic. Fractures or loosening of the prosthesis can occur after the operation, and they require a revision of the knee replacement. This surgery is needed as well when the lifespan of the knee implant is exceeded.

Many factors from the surgery have a considerable influence on the postoperative rehabilitation protocol, such as type of surgical procedure performed, graft choice, fixation method or size and location of the injury. While some interventions need only a couple of months, others take more than six months to rehabilitate. In either case, the knee gets swollen and painful after the surgery. While this situation continues, the motion of the knee is reduced or completely blocked, leading to muscle atrophy and joint stiffness. If this is not treated when the pain and inflammation have lessened, it may be impossible for the patient to return to the pre-injury state. Therefore, a rehabilitation plan is highly needed. Additionally, postoperative rehabilitation prevents also many other complications such as graft failure or thrombus formation.

2.1.4. Phases of the rehabilitation

The rehabilitation of an injury in the knee after surgery is a long process. It is typically divided into several phases that focus on recovering the skills lost, such as the complete range of motion or strength. An adequate rehabilitation program follows a functional progression, where the patient progresses through the different phases when they regain enough skills to do so. It is usually divided into five steps, from a maximum protection phase right after the surgery to the final return to sport phase[52, 53].

During the first phase, the injury has not healed, and the joint is still swollen. The primary goals at this point are to reduce pain and swelling and to recover some Range Of Motion (ROM) and muscle control.

When the patient advances to the second phase, the injury is almost healed, so the joint can bear more exercise than before. The aim now is to obtain full ROM, to increase muscle strength with light-weight exercises and to prepare the patient for walking.

In the third phase, patients build strength, power and proprioception. They also improve their confidence in their knee. Now, the patients can perform more demanding exercises like isokinetics or jogging.

The fourth phase corresponds to the return to activity stage. The goal of this period is to obtain maximum strength and muscle control. By the end of this phase, the patient should have the same balance, coordination and endurance in both knees.
Finally, the return to sport phase focuses on strength maintenance, endurance, and proprioception. When the patient is an athlete, this phase will also work towards conditioning the patient for a safe return to full participation.

2.1.5. Core exercises

A rehabilitation protocol combines different types of exercises. Some exercises focus on strength, while others are oriented to reduce swelling, improve ROM or gain more balance. Additionally, the same exercise can be adapted to follow a progression. For instance, the patient may start doing exercises assisted by another person or by a towel or other object, then without any help, and finally, increase the load by adding weights. Therefore, the possibilities are a lot. However, some exercises can be highlighted, for example, ankle pumps, different knee stretches, quadriceps sets, heel slides or squats.

All these exercises involved knee flexion or extension and the contraction of either the quadriceps or the hamstring muscles. Some exercises are done on a time basis, keeping the desire position for several seconds and then going back to the rest position, while others follow a repetition basis, where the exercise is repeated a fixed number of times. Additionally, these exercises can be grouped into active and continuous passive motion, open and close kinetic chain, or weight and non-weight bearing.

Active motion exercises, also known as Active Exercise Training (AET), are performed by the person alone, without any external assistance from a therapist or a device. On the other hand, Continuous Passive Motion Exercises (CPM) is performed by an assistant and not by the individual. The assistance may come from a physiotherapist or a device.

In an Open Kinetic Chain Exercise (OKC), the distal segment of the joint is free to move. Conversely, Close Kinetic Chain Exercise (CKC) don’t allow the distal segment to move, and the knee bears the body and/or external weight.

Lastly, exercises can be classified as either weight or non-weight bearing, depending on whether the load is applied to the knee joint or not.

2.1.6. Assessment of the outcomes

The results of the surgery and posterior rehabilitation are evaluated using subjective and objective data. The subjective elements are questionnaires such as the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC)[3] or the Knee Injury and Osteoarthritis Outcome Score (KOOS)[58], where the patient’s answers can show their satisfaction level after the surgery or pain during sport or daily activities, for example. On the other hand, the objective data consist of clinical examinations where the clinician measures the knee ROM[10, 17, 75], quadriceps strength[19, 36, 45] or knee girth[46, 60, 64], for example. There are also performance-based measures, such as hop tests; and imaging techniques, like radiography or magnetic resonance imaging, that can also be used to assess the progress of the rehabilitation.

2.1.7. Complementary therapies

Apart from conventional physical therapy, physiotherapists use several other methodologies in the rehabilitation of their patients. They are used to accelerate healing, augment strength or improve ROM, but also to help clinicians to diagnose and monitor their patients, for instance. The most relevant technologies are cryotherapy[8, 61], CPM[30, 37], electrical stimulation[22, 74], surface electromyographic biofeedback[2], shockwave therapy[70], electromagnetic tracking systems, and telerehabilitation.

2.1.8. Game-based rehabilitation

A special case of telerehabilitation is game-based rehabilitation. Conventional physiotherapy is repetitive and, for some people, even discouraging. However, a game can change that scenario into something motivating[9, 56, 66]. Additionally, games can distract patients and help them forget that they are in a rehabilitation session. This situation is known as flow experience[50]. People in that state are so focused on a game that they forget about everything else, even pain or other limitations related to their condition. The feedback from the game is also more dynamic than the one obtained from traditional rehabilitation, for example, with the use of mini-game objectives or different visual cues inside the game[32, 50].

Another significant advantage is the economy of scale[9]. We can individualise treatments to different patients and exercises to perform, while the hardware or assessment method can remain the same for all of them.

The use of software allows us to store high amounts of data from each session[9]. Additionally, this data can be accessed remotely by the therapist. Therefore, the clinician has more information available to evaluate the patient's progression.

It also has the advantage of providing consistent, unbiased and repeatable outcomes[56, 66].

Games may be beneficial in improving joint function, proprioception and dynamic balance, too[15, 26]. It might also help to change the movement patterns adopted after surgery into those of healthy people[27].

Telerehabilitation using a game reduces the time needed by the clinician to supervise their patients, the number of patient's visits to the rehabilitation centre, and the use of expensive equipment. Therefore, healthcare costs are minimised too. The Virtual Reality (VR) provides a low-cost, independent environment that the patient can use with little to no guidance from the therapist[9, 26, 56].

Several proposals have been made to control these games. Many studies have used commercially available options from the game industry, such as the Microsoft Kinect motion controller[42, 65], which is a device that can register the movement of the player, or the Nintendo Wii Fit video game[35, 48], that comes with the Nintendo Wii Balance Board (NWBB) and that provides a list of different yoga, strength, aerobic or balance games, for example. Another option is to control the game using their custom-made controllers, such as IMUs, potentiometers[51], Electromyography (EMG) sensors[39] or sphygmomanometers[16].

Some of the games are like virtual trainers [24, 43], showing how the prescribed exercise should be performed or showing feedback about the player's performance doing the exercise. On the other hand, other games take place in a setup that does not have anything to do with the rehabilitation but uses knee exercises to control it. Some examples are a game where the player controls a diver that needs to avoid shark[51]s, a fishing game[55] or a game where the player moves an aeroplane up and down to explode balloons and avoid dark clouds[16].

Immersive Virtual Reality (VR) and Augmented Reality (AR) have also been used in knee surgery post-rehabilitation[4, 14, 28, 29, 31, 57, 72]. This technology allows for a higher level of abstraction than computer games do.

Overall, most of the games that have been developed focus on knee flexion and extension. More demanding exercises, like squats or lunges, are included in some games, too[34].

2.1.9. Interviews with therapists and patients

Five people were interviewed to gather knowledge, experience and different point of view. Most of them were physiotherapists, but there were interviews with patients and other professionals too.

Several interviewees stated that the rehabilitation game could be used for different demographic groups and different injuries and that focus on only one specific age or problem might be an error. Furthermore, some interviewees expressed that the elderly can find this rehabilitation tool very attractive and motivating, contrarily to what people might think.

Another idea that was mentioned by many of them was the use of VR. According to them, VR might be great to avoid or reduce kinesiophobia and hypervigilance because the patient is immersed in a different environment that detaches them from reality. The first concept refers to the fear of feeling pain doing some movements. On the other hand, the latter is an enhanced state of sensory sensitivity in the injury. Therefore, this technology makes the patient's readaptation easier. This immersion can also improve proprioception and readaptation. However, they think that VR should be used in later phases of the rehabilitation and not right from the beginning.

It was made clear that the most important movement is knee flexion and extension and that it is the one that should be used in the game. Additionally, some interviewees pointed out that the foot should also be involved in the game. Several muscles in the lower leg that bend the knee do also control the ankle joint. Therefore, exercises like the ankle pumps are interesting to take into account for the game too.

Regarding the report, the ROM is the most significant parameter for all of them. Some people suggested that measuring quadriceps force would be interesting too. However, that cannot be measured with the sensors used in this project.

Lastly, one of the physiotherapists suggested that the game should adapt itself to the patient's progress. In that sense, it should focus more on improving extension when the patient has recovered faster the total flexion of the knee, and vice versa.

2.2. Technical Scope

2.2.1. Sensors used in this project

The NODES System uses Inertial Measurement Units (IMUs) An IMU is a system used to measure the orientation and displacement of the body where they are attached. They are used to navigate cars, aeroplanes, satellites or other vehicles and spacecrafts. Other applications that make use of this type of system are robotics and human motion tracking. An IMU typically integrates three sensors: accelerometer, magnetometer and gyroscope.Therefore, the output of an IMU will have nine components: the triaxial linear acceleration $\vec{a}$ measured with the accelerometer, the triaxial angular velocity $\vec{\omega}$ given by the gyroscope, and the triaxial strength of the Earth's magnetic field $\vec{m}$ obtained with the magnetometer. The readouts of the three sensors can be modelled as follows[47]:

$$y_a = K_a(\mathfrak{a} + g) + b_a + \mathfrak{v}_a \tag{2.1}$$

$$y_\omega = K_\omega \omega + b_\omega + \mathfrak{v}_\omega \tag{2.2}$$

$$y_m = K_m m + b_m + \mathfrak{v}_m \tag{2.3}$$

where y_a, y_ω and y_m are the readouts of accelerometer, gyroscope and magnetometer, respectively; b_a, b_ω and b_m are the accelerometer bias, the gyroscope bias and the magnetic distortion in that order; $\mathfrak{v}_\mathfrak{a}$, $\mathfrak{v}_\omega$ and $\mathfrak{v}_\mathfrak{m}$ are the white Gaussian noise terms of each sensor and K_a, K_ω and K_m are the scale factor matrix of each sensor. The scale factor matrix is a 3×3 matrix, where each row corresponds to the sensitivity of one sensor's axis. Ideally, it is equal to the identity matrix. Besides, the acceleration measured by the accelerometer can be decomposed into gravitational g and external non-gravitational $\mathfrak{a}$ accelerations.

They are cheap thanks to their small size, low weight and little battery consumption. However, this type of device has several disadvantages.

The sensor attitude can be estimated with or without the information from the magnetometer. In either case, we have to integrate the accelerometer and gyroscope signals to obtain the orientation. By doing that, we are also integrating their noise. Finally, the magnetometer can introduce errors in the measure due to magnetic disturbances produced by ferromagnetic materials.

Overtime, the errors accumulate and the estimated value of the sensor starts drifting from the true value. For that reason, it is not recommendable to use the accelerometer, gyroscope or magnetometer alone. Therefore, to compensate the the IMU's bias and increase its accuracy we need to combine the readouts of at least two of these sensors. This way, we obtain a meassure with less uncertainty. This is done using a Sensor Fusion Algorithm.

2.2.2. Orientation representations

There are three methods to express the orientation of the sensor in space, and each of them has its advantages and disadvantages [18, 54].

The first approach is to represent the orientation as Euler angles (EA): roll, pitch and yaw. It is the most computationally expensive of the three, but it is the most intuitive, too. The Euler angles represent three rotations, one per axis, performed in a specific order to go from one reference frame to a different one.

Another alternative is the quaternion representation. Quaternions typically require the lowest computational load. They can be represent as a quadruple where q_0, q_1, q_2 and q_3 are scalars, and **i**, **j** and **k** denote the unit vectors for the x-, y-, and z-axes, respectively:

$$q = q_0 + \mathbf{i}q_j + \mathbf{j}q_2 + \mathbf{k}q_3$$

They also have the advantage that they are not vulnerable to gimbal lock, unlike Euler angles. Gimbal lock occurs when two axes become aligned after rotating one of them, leading to the loss of one degree of freedom. However, due to their four degrees of freedom, the physical meaning of the motion is lost. Additionally, we need a constraint to reduce it to the three dimensions of the Euclidean space.

Lastly, orientations can be expressed as a Direction Cosine Matrix (DCM). It is a $3x3$ rotation matrix, where each column represents the projection along the reference base of unit vectors in another frame.

$$DCM = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \tag{2.4}$$

Computationally, its performance is in between the other two methods because the rotation matrix is immediately obtained. Moreover, the equations to find the propagated direction are linear. However, a drawback is that there are significantly more parameters than in the other representations. Therefore, it is necessary to include several constraints to estimate the rotation matrix.

2.2.3. Sensor calibration

An IMU needs to be calibrated before using it. This procedure is required to cancel out sensor offsets or orientation errors of the three sensors and to find the relations between sensor, mounting and global frames[7]. The calibration process has three phases.

The first step is the sensor frame calibration. Sensors convert a physical measurement into an electrical signal. Between the axes of the sensor, there might be differences in their gain or offset and misalignment between them. Therefore, to convert the electrical signal back to the physical domain, we need to compensate for those differences. Additionally, the resulting measure is converted to the International System of Units. It is performed during the sensor's assembly at the factory. Exceptionally, the magnetometer needs to be calibrated before every use due to magnetic distortions from the environment. The way to do that is to solve the ellipsoid-fitting problem[25] to find new and correct values for these gains and offsets.

After the sensor frame calibration, the axes of the sensor are orthogonal to each other. However, they may not have the same orientation as the casing. Therefore, the second step is the mounting frame calibration to find the rotation that relates both coordinate bases. This calibration also occurs at the factory. Three well-known approaches to do this are the Local Level Frame (LLF) method, the six-position static method and rate tests[62, 67]. They all use precise turntables to find the offset and errors in the sensors when specific static positions or dynamic movements are performed.

The last procedure is to find the geometrical relation between mounting and anatomical or world frames. This calibration needs to be done every time we use the sensors. This calibration can be performed in either static and dynamic conditions.

During static calibration, the rigid body where the IMU is attached is not moving, and the rotation matrix is obtained by comparing several vectors in the mounting frame with their equivalents in the global one. In general, the vectors used here are the gravity vector and the Earth's magnetic field vector. Additionally, the body segment where the IMU is mounted needs to be in a fixed position so that the anatomical frame is known.

On the other hand, in the dynamic scenario, the sensors are rotated along the axes of the limb. Using the gyroscope, we can obtain the axis around which the sensor is rotating.

Furthermore, both cases can be combined, for instance, by measuring the gravity vector in a static condition and then performing a rotation to obtain an axis perpendicular to gravity. In either case, only two axes are needed, as the third one is obtained using the product of both vectors.

2.2.4. Sensor fusion algorithms

A Sensor Fusion Algorithm (SFA) is a method used to merge the information of a set of sensors to obtain a combined output. It is possible to get an estimated measure using the sensors individually. However, as it was mentioned before, changes in environmental conditions, such as the temperature, introduce errors in the estimated measure that might accumulate overtime and produce a noticeable deviation from the true measure. By combining the signal of different sensors, we can compensate the drift of one of the sensors by comparing its information with the value estimated using the other sensors. Thanks to that, and the resulting information has less uncertainty.

There are two main algorithms used for orientation tracking: Complementary Filter (CF) and Kalman Filter (KF). Additionally, there are two algorithms that, although they are not SFAs, are present in most CFs and KFs implementations. They are Strap-Down Integration (SDI) or rate gyroscope integration, which calculates the orientation using only the angular velocity measured by the gyroscope; and Vector Observation (VO), finds the orientation by comparing at least two vectors in the sensor frame with their equivalent vectors in the global base. In applications using IMUs, the vectors used are typically the normalized direction of acceleration due to gravity g measured by the accelerometer and the normalized Earth's magnetic field b measured by the magnetometer.

In a CF, two different noisy measurements are combined to produce a single filtered output. In general, the signals have low and high-frequency noise, respectively. Hence, the transfer function of a CF contains a low-pass ($L(s)$) and a high-pass ($H(s)$) filters with a combined gain equal to the unit.

$$L(s) + H(s) = 1 \tag{2.5}$$

These transfer functions can take any form, being a first-order proportional filter, with cut-off frequency k_p, the least complex one.

$$L(s) = \frac{k_p}{k_p + s} \tag{2.6}$$

$$H(s) = \frac{s}{k_p + s} \tag{2.7}$$

Most CFs approximate these transfer functions using only the first-order term, although there are some implementations of second[33] and higher-order filters.

There are many different CFs, but among the most important implementations are Mahony filter[20, 41], which is a Nonlinear Complementary Filter (NCF), and Madgwick filter, that uses a Gradient Descent Algorithm (GDA) to minimise the error in the estimated orientation and also includes steps to compensate for magnetic distortion and gyroscope bias. There are three different formulations of the latter algorithm: original[40], improved[1] and novel[71] versions.

On the other hand, a KF is a recursive filter. First, the state is predicted from the previous iteration using the dynamic equations of the system. Then, that a priori state is updated using the information from the measurements. This update is done to minimise the estimated error covariance. Two steps can be distinguished: the propagation phase and the update phase. KFs are mainly used in guidance, navigation and control of vehicles, and human motion tracking.

The filter aims to solve the following discrete equations:

$$x_{k+1} = Ax_k + Bu_k + w_k \tag{2.8}$$

$$z_k = Hx_k + v_k \tag{2.9}$$

where x_k and z_k are the state and measurement vectors of the system at time k, A and H are the transition and observation matrices between states, B is a matrix relating the control input vector u_k with to the system states and w_k and v_k are the process and measurement noise vectors. Both w_k and v_k are assumed to be white noise processes independent of each other and stationary over time. Their covariances are Q_K and R_k, respectively. In the standard KF, also known as discrete or linear KF, solving the system gives us the following five equations. The equation to find the new estimate using the a priori state vector and the measurement data is

$$\hat{x}_k = \hat{x}'_k + K_k(z_k - H\hat{x}'_k) \tag{2.10}$$

where K_k is the Kalman Gain. This gain is updated every time using the following equation.

$$K_k = P'_k H^T (HP'_k H^T + R)^{-1} \tag{2.11}$$

Lastly, the equations to update the a posteriori covariance and to propagate the estimates to the next time step are

$$P_k = (I - K_k H)P'_k \tag{2.12}$$

$$\hat{x}_{k+1} = A\hat{x}'_k \tag{2.13}$$

$$P_{k+1} = AP_k A^T + Q \tag{2.14}$$

There are many linear and nonlinear variants of the standard KF, being the Extended Kalman Filter (EKF) the most relevant one performance-wise.

Many publications use the three filters outlined before, i.e., Mahony, Madgwick and EKF, as references to test the algorithms they develop. Bergamini et al. [5], Caruso et al. [12], Cavallo et al. [13], Fan et al. [21], Feng et al. [23], Ludwig and Burnham [38], Rosario et al. [59], Valenti et al. [68, 69], Young [73].

Table 2.2 was created using the results of those studies. It shows the trade-off criteria to see which algorithm is more suitable for this project. The aspects compared are computational load, complexity, estimation errors in noiseless and noisy measures, power consumption and memory requirement. For all of them, low values are desired.

	Computational load	**Complexity**	**Estimation errors in noiseless measures**	**Estimation errors in noisy measures**	**Power consumption**	**Memory requirement**
Madgwick	Low	Low	Medium	Medium	Low	Low
Mahony	Low	Low	Medium	High	Low	Low
EKF	High	High	Low	Low	High	High

Table 2.2: Comparison between the three main SFAs.

Both Mahony and Madgwick are filters with low values for all the parameters. In general, they have a similar performance. However, when the magnetic disturbances are strong, the estimation error using the Mahony algorithm is higher.

On the other hand, the EKF has the lowest estimation errors of the three algorithms, thanks to its flexibility. However, most of the studies cited above used the original version of the Madgwick filter, and the novel formulation of this algorithm, which is the one that the NODES System uses, has a better performance. Therefore, if we were to compare the EKF with the novel Madgwick filter, the difference in accuracy would not be significant. Additionally, the flexibility of the EKF comes at the cost of increased complexity and the necessity of an accurate model of the system. With a higher complexity, the computational load needed increases too. Furthermore, the power consumption and memory requirement also increase with respect to the other two filters.

To sum up, the comparison between these three SFAs shows that the Madgwick algorithm is the best option for this project. Moreover, as the version used in the NODES System is an improved formulation of the Madgwick filter, it can be expected that its performance will be even better than with the other options.

3
Rehabilitation Game Design

This project's goal is to develop a post-surgery knee rehabilitation game to accelerate the rehabilitation of these patients, increase their motivation and reduce medical costs. Using gamification in this medical context brings us two main benefits. On the one hand, using game principles such as points or objectives, we can create an engaging virtual environment. This setting can motivate patients to follow their rehabilitation program and get better results.

On the other hand, the game could be play at home, allowing for telerehabilitation. Therefore, it would reduce medical expenses and the number of visits to the physiotherapist that the patient has to do.

Additionally, the game we are going to create is controlled with a sensor system developed by 2M called the NODES System. It uses IMUs to capture the motion of one or more limbs. Using this type of sensor, we can save information from the patient's movement while playing. This data would then be processed and sent to the physiotherapist in a report. Thanks to this, the physiotherapist can keep track of a patient's progress and modify their rehabilitation program accordingly.

Figure 3.1 shows an overview of the system and the user interactions.

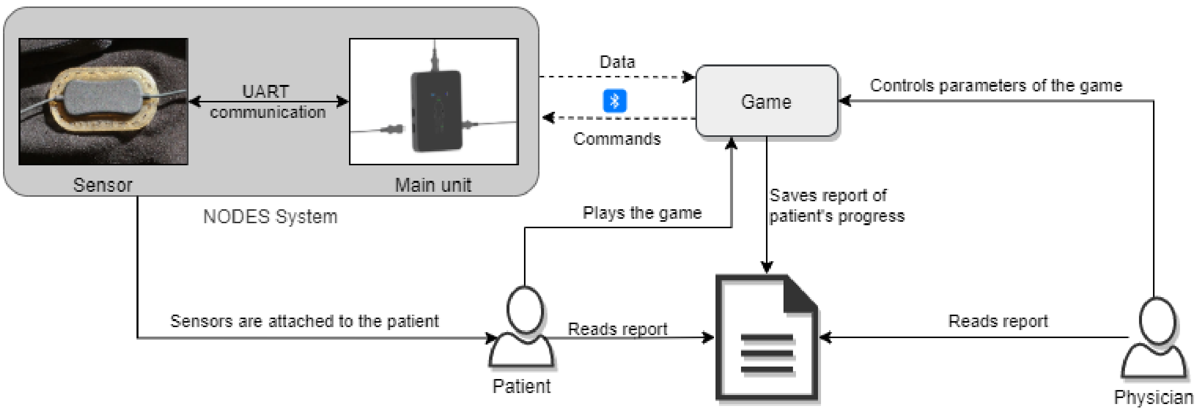

Figure 3.1: System overview.

3.1. Design Process

The design process started with the literature research and survey discussed in the previous chapter. The first thing that was decided was the focus of the game. The exercises of a rehabilitation program focus on several parameters, such as stability, range of motion or strength. However, the sensors we use limit our possibilities. Taking that into account and after finding which were the main elements in knee rehabilitation, it was decided to focus on improving range of motion. The NODES System monitors the patient's movement. Therefore, we can obtain the maximum extension and flexion of the patient at every session and see how it evolves.

Then, we had to select the exercise or exercises to include in the game. We saw that the best exercise we could use in the game was the flexion and extension of the knee in different positions. The reason is that it is directly related to the range of motion. Additionally, it can be performed at any stage of the rehabilitation. In the beginning, the patient may practice lying on the bed and facing up or down. When the pain and range of motion allow it, the patient can start playing sitting. In the last stages of the rehabilitation, the patient can perform the exercises standing. This way, although the game does not change during the different rehabilitation phases, its difficulty can still be adjusted to the patient's progress.

With the focus and exercise clear, it was time to decide the type of game we were going to implement: 2D, 3D or VR/AR. We studied their advantages and disadvantages and, although the use of VR was promising according to both the literature and some of the physiotherapists we interviewed, this option also had significant drawbacks like motion sickness, for instance. For this reason, the final decision was to create a 3D game. After interviewing physiotherapists and patients, the concept of the game was selected.

In parallel to the previous steps, the functional and non-functional requirements of the game were defined.

The developing phase started with the user interface. There are two different interfaces, one for the physiotherapists and one for the patients.

Following the user interface, we designed the game scene and implemented all the features we had conceived. This will be explained in more details in section 3.2.1. At this point, we also implemented the algorithm that takes the output of the NODES System and uses it as the controller of the game.

The last step in the design of the game was to implement the reporting system. This process had several iterations. In each iteration, the stakeholders gave their feedback about the reporting system. With that feedback, the report was improved and then shown again in a new iteration.

3.2. Concept of the game

Many game concepts were considered during the literature research, like 2D side-scrolling games like Flappy Bird and 3D/VR basketball or archery games, for instance. In the end, the chosen option was a 3D kart racing game where the player competes against non-player characters to win a race. To control the car, the patient needs to bend the ankle and knee. Acceleration and braking/moving backwards are done by extending and flexing the ankle. Lastly, extending or flexing the knee will turn the car right or left, respectively.

The game runs at 60 frames per second. Therefore, the game takes, on average, 17ms to update the screen after receiving the sensor's data. As this delay is below 20ms, the input lag will be unnoticeable for the player because the human eye cannot perceive it[11].

The game's track was designed to make the patient exercise like in a standard rehabilitation exercise list. This is done by introducing as many right and left turns as repetitions we want the patient to make of these exercises. Therefore, the course of the game gives us the possibility to create different modalities of training in just one game. There could be circuits that focus more on the knee extension, tracks focusing more on knee flexion and others where both exercises are balanced.

However, that is not the only aspect that can specialise the training for the patient. The ROM of the patient is used to translate the movement of the leg into acceleration, braking and turning inputs. Thanks to that, the game will always force the patient to reach their maximum extension and flexion. By default, the threshold will be set to exercise the whole range of motion. However, the physiotherapist can modify it at any time. That way, when the physiotherapist thinks that the patient has recovered enough knee flexion but still lacks some extension, they can change the threshold, so the patient only exercises the knee extension and vice versa.

Additionally, the game can be played in many different positions: lying face down or up, seating and standing. Therefore, the difficulty can be adjusted to the current status of the patient.

The interface of the game is simple. There is a panel at the top of the screen showing the current lap, position of the player and current lap time. At the bottom left corner, there is an image of a steering wheel that rotates according to the movement of the patient's leg. This image is used to make it easier for the player to visualise the direction they are turning when they bend their knee. Finally, there is a button to exit the game.

When the patient finishes the race, a new panel appears on the screen. It shows the final position and the best lap time of the patient, and it has two buttons, one to play again and another one to exit the game.

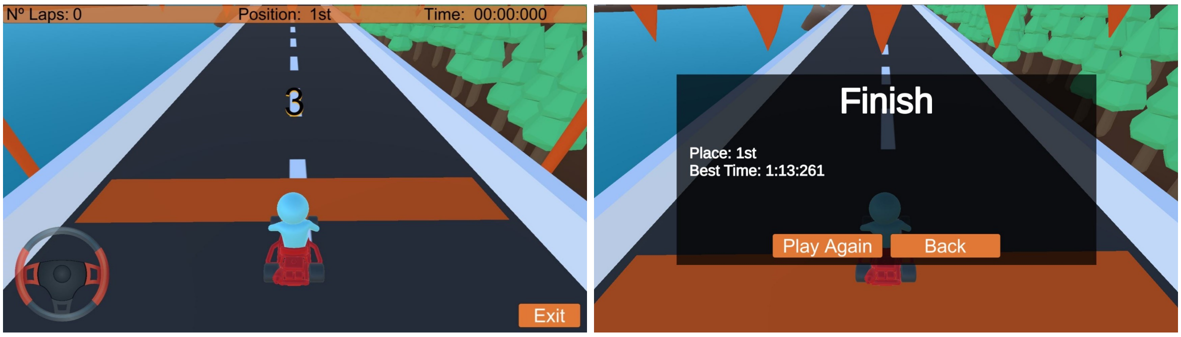

Figure 3.2: Pictures of the karting game. The left image shows the user interface during the game, while in the right one, the end game screen can be seen.

3.2.1. Track design

As it was mentioned before, the track was designed to simulate the exercises in a rehabilitation session. Therefore, it has as many left and right turns as knee flexion and extension repetitions we want the patient to do. It was created using Unity and Blender together. First, a Unity asset, called Bézier Path Creator, was used to create the track. The benefit of this tool is that we can access from a script the path that the road follows. Thanks to that, we can check if the players are going in the opposite direction or re-spawn a player when it goes outside of the track, for example.

Then, this game object was exported to Blender, where several other items were created, such as guardrails, a bridge and invisible walls for the AI players. The reason is that Blender provides many more features to design 3D models than Unity does. Back in Unity, a start line and checkpoints along the road were added too. The checkpoints are required by the non-player characters. They are used together with the invisible walls to teach how to drive around the track.

Lastly, a terrain with mountains, trees and water was added as decoration. This terrain was created using the Unity Terrain game object. This tool allows us to create different landscapes and add trees, rocks or grass to them. Additionally, the trees added to this terrain are rendered only when the player is at a certain distance. Rendering all the trees and other adornments in the level would slow down the game. Therefore, with Unity Terrain, the performance of the game can be improved.

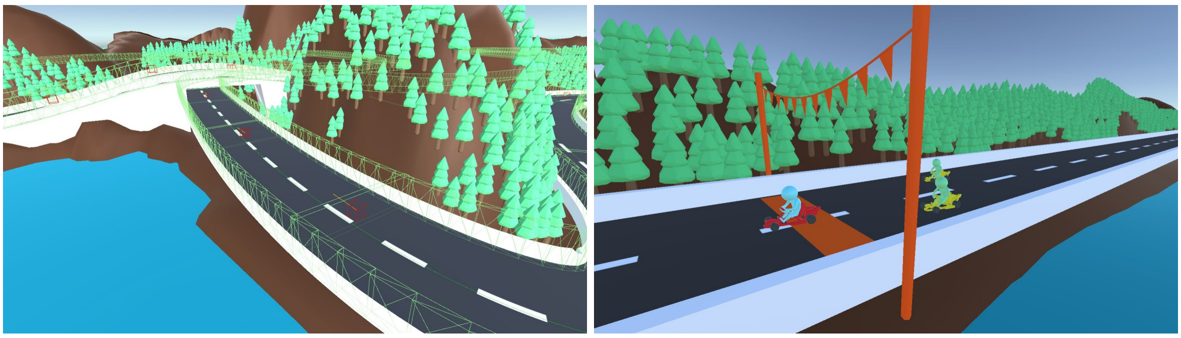

Figure 3.3: Course and characters of the game. On the left, the road, terrain, guardrails and, represented by green lines, the checkpoints and invisible walls. On the right, the start line, the player character (red kart) and the Non-Player Character (NPC)s (yellow karts).

3.2.2. Characters

There are two types of characters: player and non-player characters. The player character is controlled by the patient, while the Non-Player Characters (NPCs) are controlled by a trained AI.

Both player characters and NPCs were created using the Karting Microgame from Unity Learn. This project is one of the examples available when you download Unity and contains many prefabricated objects like cars, buildings, tracks and other decorations.

These objects, known in Unity as prefabs, already have C# scripts attached to them, providing all kinds of functionalities and behaviours. Therefore, there is no need of creating these models and scripts from scratch.

Conversely, we can partly modify these scripts, adding or removing lines of code for those game objects to behave as we want in this game. These modifications added several fields and properties to know their current position and number of laps, and to set if they can move and the type of input they will use.

Player character

The player character was created using the ”KartClassic_Player” prefab and and generating a modified version of its original script. This script contains the modifications mentioned above and a new input system. An algorithm was created to convert leg movements into the standard inputs of the game. Therefore, this game object can only be controlled with the NODES System.

Additionally, an invisible game object was added to this prefab’s model. This item is used to detect overtaking.

Non-player characters

The NPCs are instances of the ”KartClassic_MLAgent” prefab. This prefab has all the scripts of ”KartClassic_Player” plus several other scripts to make these characters move by themselves. To do that, we have to teach the AI how to drive around the course using machine learning. To do this training, we need checkpoints along the track and walls. When the NPC is set to training mode, it will generate a neural network model that will be able to follow the track by reaching each checkpoint and trying not to collide with the walls. With that model and in inferencing mode, the AI will drive as it was trained.

As it happened with the model of the player character, an object that is not visible in the game was added to be able to detect when a character overtakes another one.

3.2.3. Game features

In order to give the patient a good game experience, several features or elements were implemented.

- Race information: there is a panel at the top of the screen that shows the current lap, position and lap time of the patient.

- Exit button: it gives the patient the option to quit or restart or the game at any time, even if the race has not finished. When the player clicks this button, they are asked if they want to exit the game or to restart it.

- Steering wheel: there is a steering wheel on the bottom left corner that rotates according to the patient’s knee. This element is a helping aid for the patient, so they can more easily relate the movement of the knee with the rotation of the car.

- Initial animation: it tries to mimic the start sequence that happens in real car races.

- Finish line: every time the patient crosses it, the lap count is incremented. When the last lap is finished, the end game menu is shown, and the control of the character is disabled.

- Overtaking: a system to recognise when a character passes another one was implemented. Additionally, this system is able to recognise when one character has finished more laps than other, so the overtake does not count.

- Opposite direction detection: in order to prevent the patient from cheating or the NPCs to drive in the opposite direction, the game detects when a character is moving in the wrong direction and rotates it back to the correct heading.

- End game menu: it shows the patient their final position and best lap time, and allow them to play again or go back to the main screen.

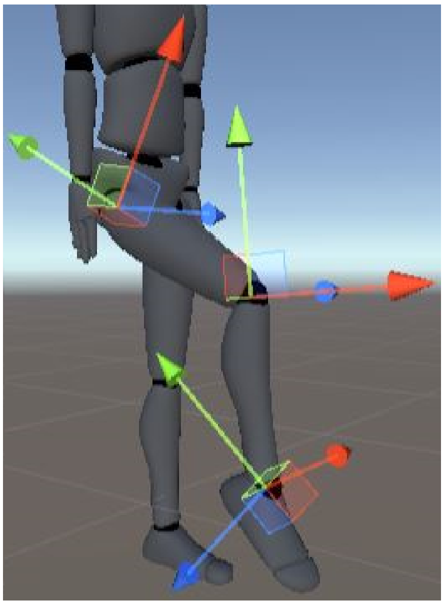

Figure 3.4: Axes of the puppet's leg segments. The foot is rotated -90º around the Y-axis (green).

3.3. Input system

The original input system of the original ”ArcadeKart” script uses the arrows of the keyboard. This input system consists of two Boolean variables, *Accelerate* and *Brake*, and one float parameter, *Turn*, that ranges from -1 to 1. *Accelerate* and *Brake* are true only when the up or down arrow is being pressed, respectively. When the left or right arrow is pressed, the value of *Turn* becomes -1 or 1. After realising the key, its value goes back to zero at a certain speed specified by the developer.

The input system in the modified code contains the same three variables but uses the virtual avatar to calculate their values instead of the keyboard. This way, the avatar that replicates the patient's movements in the virtual world will act as the input. The values of *Accelerate*, *Brake* and *Turn* will be derived from the angles between the virtual limbs, than can be seen in figure 3.4. The green arrow represents the longitudinal axis. Then, the red arrow is the forward axis. Lastly, the blue arrow corresponds to the lateral axis. However, the axes of the foot are rotated -90º around the longitudinal axes. Therefore, the red and blue axes are interchanged.

3.3.1. Input Conversion Algorithm

This algorithm receives the angle θ that the lower leg forms with either the foot or the thigh, and converts it into the values of the input system mentioned above. These angles are computed as the angle between the longitudinal axes of both limbs around the lateral axis of the virtual lower leg. The formula to find this angle with the correct signed is the following:

$$\theta_{unsigned} = \arccos \frac{v_1 \cdot v_2}{|v_1||v_2|} \tag{3.1}$$

$$sign = \begin{cases} 1 & \text{if } v_3 \cdot (v_1 \times v_2) > 0 \\ 0 & \text{if } v_3 \cdot (v_1 \times v_2) = 0 \\ -1 & \text{if } v_3 \cdot (v_1 \times v_2) < 0 \end{cases} \tag{3.2}$$

$$\theta = \theta_{unsigned} \cdot sign \tag{3.3}$$

where $\theta_{unsigned}$ is the unsigned rotational difference between limbs, v_1 and v_2 are the vectors from and to which the angular difference is measured, and v_3 is the axis around which the rotation is calculated. Therefore, v_3 is always the lower leg's lateral axis, while the other two vectors vary for each angle. For the knee angle, v_1 is the longitudinal axis of the sensor in the thigh, v_2 is the lower leg's negative longitudinal axis. On the other hand, the ankle angle is found using the lower leg's negative longitudinal axis and the foot's negative longitudinal axis.

Additionally, the knee angle is converted to keep the convention of extension and flexion angles. The extension is given with a positive sign, while the knee flexion has a negative sign. The origin is set to the neutral position, that is, a straight leg.

$$\theta_{knee} = \begin{cases} 180 - \theta & \text{if } \theta > 0 \\ -180 - \theta & \text{else} \end{cases} \tag{3.4}$$

Once that we have both θ_{ankle} and θ_{knee}, we can estimate the values of *Accelerate*, *Brake* and *Turn*.

$$Accelerate = \begin{cases} true & \text{if } \theta_{ankle} > \tau_{ankle} \\ false & \text{else} \end{cases} \tag{3.5}$$

$$Brake = \begin{cases} true & \text{if } \theta_{ankle} < \tau_{ankle} \\ false & \text{else} \end{cases} \tag{3.6}$$

$$k = \frac{8}{\left(\tau_{knee,\,1} - \tau_{knee,\,2}\right)^3} \tag{3.7}$$

$$Turn = \begin{cases} 1 & \text{if } \theta_{knee} > \tau_{knee,\,1} \\ -1 & \text{if } \theta_{knee} < \tau_{knee,\,2} \\ k * \left(\theta_{knee} - \frac{\tau_{knee,\,1} + \tau_{knee,\,2}}{2}\right)^3 & \text{else} \end{cases} \tag{3.8}$$

where τ_{ankle} is the threshold used to decide if the patient is accelerating or breaking from the ankle angle, and $\tau_{knee,\,1}$ and $\tau_{knee,\,2}$ are the current peak extension and flexion of the patient. When the bending of the knee is between the maximum extension and flexion, the equation corresponds to that of a cubical parabola, where k is the scale of the parabola and the negative term of the equation is the root, that is, the point where the value of *Turn* is equal to zero. The values for the maximum extension and flexion are recorded at the beginning of every session. Following the sign convention, the maximum flexion is negative.

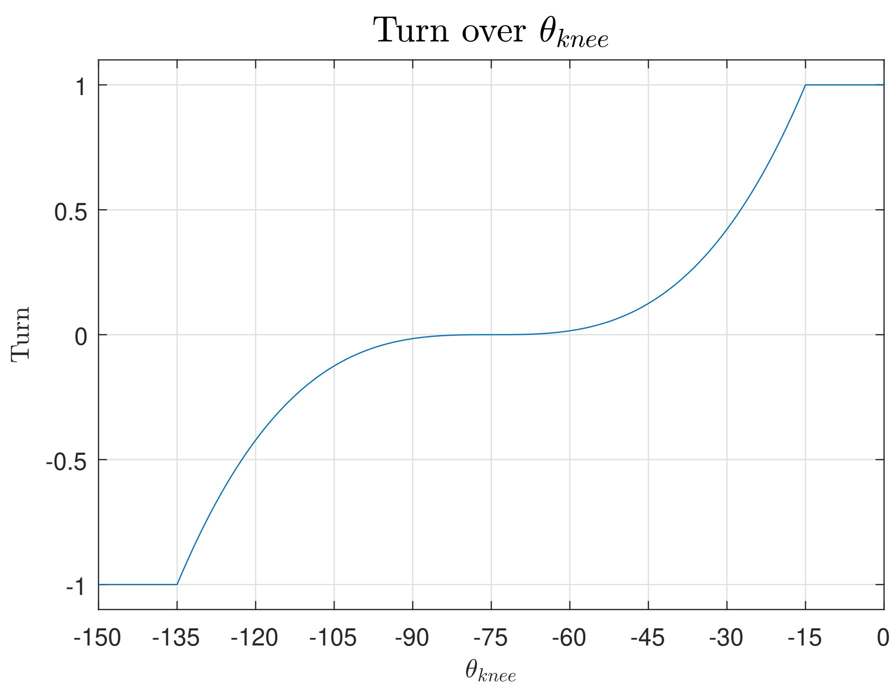

Figure 3.5: Value of *Turn* over θ_{knee}. The maximum extension was set to -15º and the maximum flexion to -135º.

3.4. User interfaces

There is one interface for each type of user. They only share the start and registration menus, each of them with its scene. The StartMenu scene acts as the master scene of the game. When it is loaded, it destroys all objects that do not belong to that scene, and it is used to transmit information between different menus using the singleton pattern. A singleton is a class without a public constructor. The only way to create an instance of a singleton is by calling the GetInstance method, which prevents the user from having more than one instance of an object.

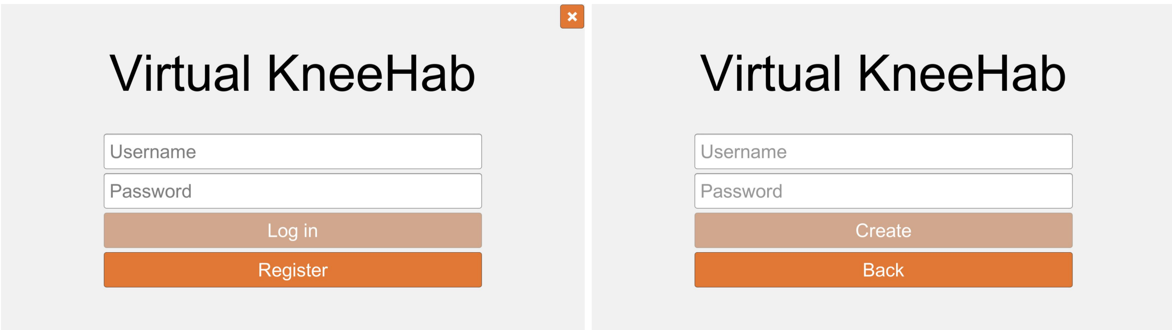

Figure 3.6: Start and registration menus of the application.

Both scenes are controlled with the StartMenu and Registration scripts, respectively. StartMenu has two input fields for the username and password and two buttons, one to log in and another to register a new user. When the user logs in, the application recognises whether the user is a patient or a physiotherapist and loads the correspondent screen. The script that controls this scene contains properties that allow to get and set the user's ID, the ID of the patient whose report the physiotherapist has requested and the exercise the patient will train more. The reason to include these parameters in this class is to keep them between scenes and use them when it is necessary. Additionally, there is a small button on the top right corner to quit the application.

The registration menu is nearly the same as the start menu. The only difference is the functionality of the buttons. Additionally, it does not have the quit button. One button returns to the start screen, and the other creates a new user and then returns to the main menu. The users created in this menu are only physiotherapists. To create a patient's account, the physiotherapist in their charge has to do it from their user interface. This account will have a default password that the patient can change afterwards.

The login button of the start menu and the create button of the registration screen are only enabled when the username and password both have at least eight characters.

3.4.1. Patient's user interface

The patient's interface consists of six different screens: main menu, calibration, ROM recording menu, controller guide, game, new password and report. Except for the first three, each menu corresponds to one scene in Unity. The reason why the first screens are in the same scene is that they share several game objects. This method saves execution time and memory, as we do not have to duplicate these objects.

The game and report screens are explained in sections 3.2 and 5.1, respectively.

Main menu

It has six buttons, the first five takes the user to the other menus from the patient's user interface, and the last button logs the patient out of the system, taking them back to the start menu. The button to play the game is only enabled when the NODES System is already connected to the application.

Calibration menu

The calibration menu has several elements. On the left side, there is a list of the devices available, a drop-down menu to select the calibration pose and five buttons. One button is to connect to the NODES System or to disconnect it. Then, the following two buttons are to calibrate the magnetometer and the virtual avatar, respectively. The last two buttons are used to go to the ROM recording menu or back to the main menu. These last two buttons cannot be active at the same time. When the avatar

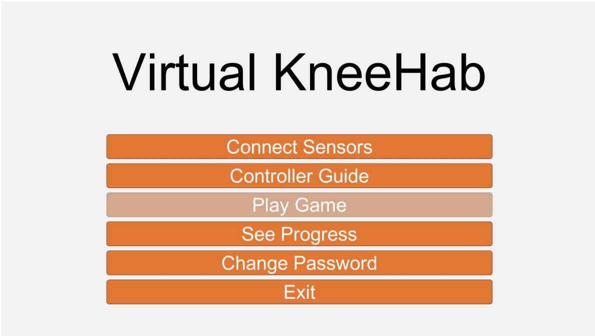

Figure 3.7: Patient's start menu.

is calibrated, the "Accept" button is enabled and the "Back" button disabled. The rest of the time, only the second button is active. Additionally, the buttons to calibrate the magnetometer and avatar are only interactable when the NODES System is connected.

On the right side, there is a view of a room with the avatar that the patient controls with their movements and a smaller avatar at the right bottom corner that shows the calibration pose selected.

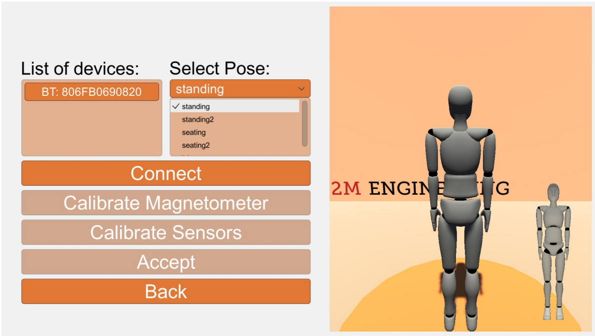

Figure 3.8: Calibration menu.

Range of motion recording menu

This screen shows the same room and avatars that are in the calibration menu. However, on the left side, it only has a text box and a button. The text box shows the instructions that the patient must follow. The button is used to continue measuring and to go back to the main menu. It is in this screen where the current ROM of the patient is measured and saved. This ROM will be used as the threshold of the algorithm that generates the inputs of the game, as it was explained in section 3.3.1.

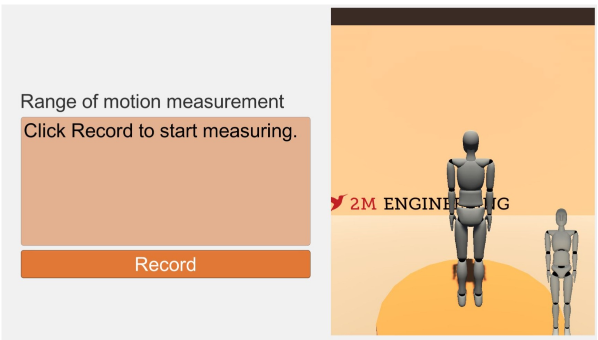

Figure 3.9: Range of motion recording menu.

Controller guide
This screen is used to show the patient how to play the game. It shows a panel with some text at the top of the screen, a picture of the lower body of the virtual avatar on the right side and two buttons at the middle bottom. Additionally, the camera shows an empty room with the kart the patient controls in the actual game. By pressing the button on the left, the puppet will show the patient step by step how to accelerate, brake, turn left and turn right the kart. The other button takes the patient back to the main menu at any moment.

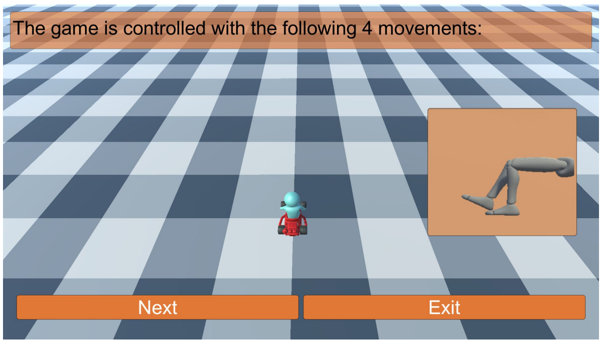

Figure 3.10: Controller guide screen.

New password
This screen lets the patient change their password. There are two input fields to enter the old password and the new one, a button to make this change and a button to go back to the main menu without changing the password. The first button is only interactable when both input fields contain more than eight characters.

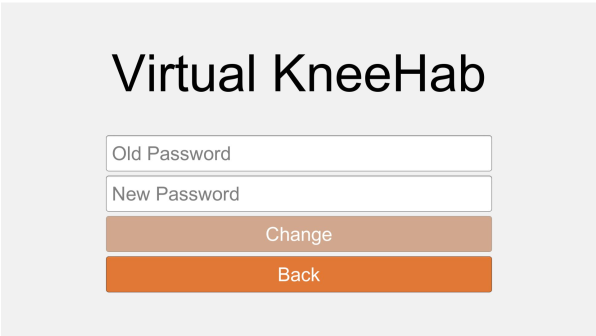

Figure 3.11: New password menu.

3.4.2. Physiotherapist's user interface

It contains only three screens: the main menu, the progress report menu and a screen to create new patients.

The main menu shows a list with the physiotherapist's patients on the left side and four buttons on the right side. The list shows the name and surname of the patient and a checkbox to select the patient. The buttons are used to remove patients from the database, see their progress, add a new patient or exit the application. The first two buttons are only interactable when a patient is selected.

On the other hand, the add patient menu contains three input fields for the username, name and surname of the patient, and two buttons. One button creates the patient in the database, and the other goes back to the main menu without adding any patient. The first button is only active when the username is at least eight characters long, and the other fields are not empty.

The report menu will be explained in section 5.2.

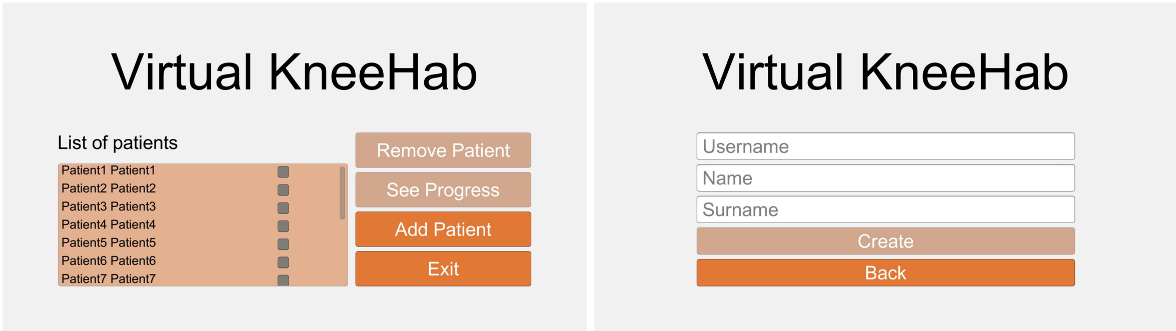

Figure 3.12: Screens of the physiotherapist's user interface: start menu (left) and new patient menu (right).

3.5. Database

As the application is intended for two types of users, patients and physiotherapists, and a physiotherapist would typically be in charge of more than one patient, a database is needed. This database lets us differentiate the user using the application and show them the correct user interface. Additionally, it allows the physiotherapist to manage their patients and to see their progress.

A local server environment was built using the XAMPP software. XAMPP allows us to create a web server where we can add and manage databases. The databases can be created and modified using a portable web application.

Figure 3.13 shows the diagram of the system architecture. When a patient or physiotherapist uses the game, it connects to the web server where the database is. This connection takes place using the Hypertext Transfer Protocol (HTTP). When the web server receives a request from some user, it passes this request to the Application Programming Interface (API) created in this project. This API checks that the information received is safe and sends back the information from the database that the user requested.

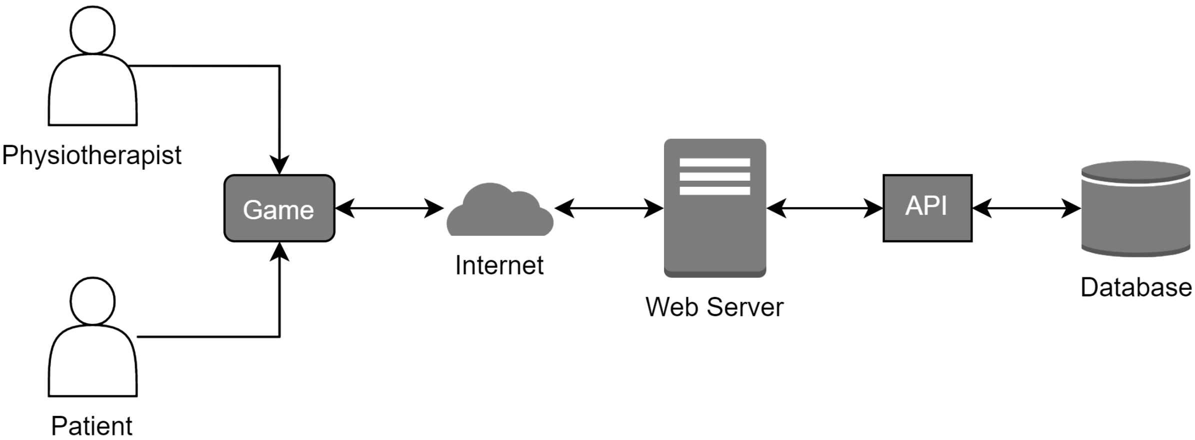

Figure 3.13: System architecture diagram.

4
Calibration Tool

In order to use the NODES System as the game's controller, we have to find the relationship between the orientation of the sensors in the real world and their counterparts in the virtual game. This virtual world or avatar calibration needs to be done every time the patient uses the game. The reason is that each time that the patient attaches the sensors to their leg, they will be in a different position and orientation, and the relationship between real and virtual sensor orientations will change.

The NODES System already includes a calibration procedure. However, there is a need to improve this current approach to make it more accessible for impaired or injured patients. As the game developed in this project is intended for people with limited mobility after surgery, one of the main tasks in this thesis is to propose a new calibration tool.

4.1. Current Calibration Approach

In the current method to calibrate the NODES System, developed by 2M, the user selects one of the predefined poses, and the person wearing the sensors copies it. When the calibration of the virtual avatar is initiated, the first quaternion or raw data sent by the NODES System to the computer is read and saved as the initial orientation. Then, the application extracts the forward direction from the sensor selected as the reference. The virtual world and avatar are then rotated, synchronising the forward direction of all three of them. This rotation takes place only around the upward axis.

Once that the virtual avatar is facing the same direction as the reference sensor, the orientation of each virtual sensor is synchronised with their real counterpart's initial one, and the limbs are rotated to match the selected pose. By doing this, the offsets and misalignments in the sensors' orientation with respect to the body limb are corrected.

Nevertheless, this approach presents two problems. The calibration poses are usually incompatible with people with impairments, like the patient in our scope. In the predefined poses, the limbs are either straight or at 90º of flexion. Therefore, their limited mobility makes it difficult for them to copy the requested postures completely.

Additionally, in this approach, the error in the calibration pose is coupled with the error introduced by the misalignment of the sensors. That means that when the application corrects the offset in the sensors' orientation, it adds the difference between the calibration pose and the actual pose of the person. Therefore, the offsets are not corrected properly.

Then, the goal here is to design an almost pose-free calibration tool that solves those two problems. By doing that, the patient will be able to calibrate and use the sensors at any moment of the rehabilitation, and the physiotherapist will receive more precise and reliable data.

4.2. Proposed Calibration Tool

The approach presented in this project considers the problems listed in the previous section and the condition of the people who will use the game. In consequence, this calibration should be valid during all phases of the rehabilitation. Essentially, that means that it should work when the patient can only lie in bed, when they can seat and when they can stand. However, the problem of the user not being able to copy the pose is still not solved.

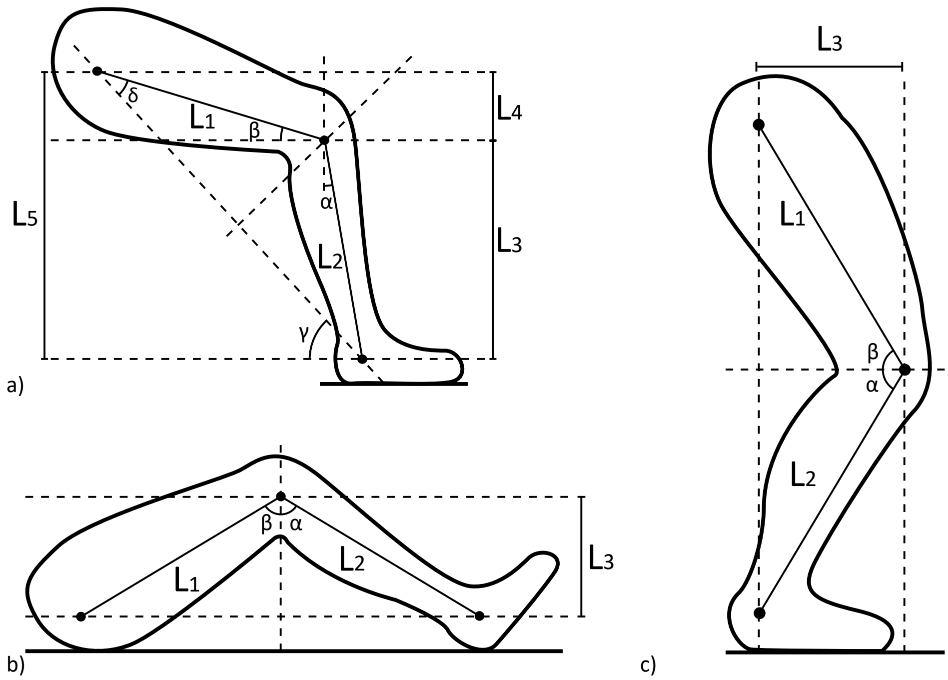

Figure 4.1: Poses to calibrate the system taking into account the patient's level of disability: sitting (a), standing (b) and lying (c).

To solve the second problem of the current approach a new step will be added to the calibration algorithm at the beginning. This step consists in update the pose of the virtual avatar to match the person's true pose, before synchronising real and virtual worlds. With this extra step, the error between the actual posture of the user and the calibration pose is rectified before the offsets of the sensors are corrected. Not only that, but now the first problem is also solved, as a slight difference between the two poses will not affect the calibration anymore.

4.2.1. Virtual Avatar Calibration Algorithm

For the proposed calibration procedure, we will make two assumptions. First, the sensor in the lower leg is placed in the desired position without errors. Then, we can correct the pose of the virtual puppet before synchronising the forward direction of the virtual and real body frames.

Additionally, we will assume that the thigh and the lower leg have approximately the same length. To understand the importance of this assumption, we have to analyse the three cases. After a look at the diagrams for each scenario shown in figure 4.1, it can be seen that the problem of a person standing and lying are algebraically the same. In the picture, α, β, δ and γ and are the angles present in the knee at different poses, L_1 and L_2 are the lengths of the thigh and lower leg, respectively, and L_3, L_4 and L_5 are the remaining distances of the triangles formed by the segments of the leg. Therefore, using the second premise, for the case of a person either lying or standing, we can extract the following equations from the diagram:

$$L_1 = L_2 \tag{4.1}$$

$$\begin{cases} L_3 = L_2 \cos\alpha \\ L_3 = L_1 \cos\beta \end{cases} \tag{4.2}$$

Substituting equation 4.1 in 4.2, the relationship between both angles is obtained.

$$\beta = \alpha \tag{4.3}$$

Therefore, estimating the initial knee flexion in those two cases is quite simple. However, the remaining case is not as straightforward as the other two. From figure 4.1a, we derive the following equations:

$$L_3 = L_2 \cos\alpha \tag{4.4}$$

$$L_4 = L_1 \sin\beta = L_5 - L_3 \tag{4.5}$$

$$\beta = \gamma - \delta \tag{4.6}$$

Now, in order to obtain the value of β, we have to find γ, which is the angle between the horizontal axis and the axis crossing hip and ankle, and δ, which is the angle between that last axis and the thigh.

$$\delta = \arccos\left(\frac{L_2}{2\sin\gamma} \cdot \frac{1}{L_2}\right) = \arccos\left(\frac{1}{2\sin\gamma}\right) \tag{4.7}$$

$$\begin{aligned} \gamma &= \arctan\left(\frac{L_5}{\sqrt{L_1^2 - L_4^2} + \sqrt{L_2^2 - L_3^2}}\right) = \\ &= \arctan\left(\frac{L_5/L_2}{\sqrt{1-(L_5/L_2)^2 + \cos\alpha(2(L_5/L_2) - \cos\alpha)} + \sin\alpha}\right) \end{aligned} \tag{4.8}$$

In the sitting scenario, L_5 denotes the height of the seat. To simplify equation 4.8, we will consider that the ratio between L_5 and L_2 is approximately the unit, that is, the user is sitting comfortably, with the seat at popliteal height. Then, the value of gamma is reduced to

$$\gamma = \arctan\left(\frac{1}{\sqrt{\cos\alpha\,(2 - \cos\alpha)} + \sin\alpha}\right) \tag{4.9}$$

Once that we have found γ, we can substitute it in equation 4.6.

$$\beta = \begin{cases} \arccos\left(\frac{1}{2\sin\gamma}\right) - \gamma - \frac{\pi}{3} & \text{if } \frac{\pi}{3} \leq \alpha \leq \frac{\pi}{2} \\ \gamma - \arccos\left(\frac{1}{2\sin\gamma}\right) & \text{else} \end{cases} \tag{4.10}$$

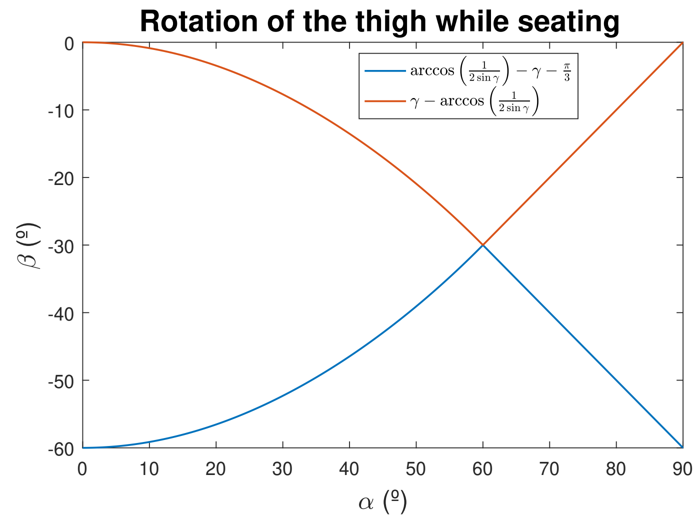

Figure 4.2: Value of angle β over α. The equations showed in the graph corresponds to equation 4.10.

It can be seen that equation 4.10 α includes a new case, for values of α between 60º and 90º. The reason for this is that, in that range, the previous formula does not work. When α is greater than 60º, the absolute value of β decreases. That is equivalent to the knee moving up. However, the reality is that β keeps increasing in value until the leg is completely straight. A plot of the equations in 4.10 can be seen in figure 4.2.

To sum up, by assuming that the thigh and lower limb have the same length and that the sensor in the lower limb has no errors in orientation, we can find the angle between the thigh and an axis perpendicular to the knee, provide that we know the one for the lower leg. Using the estimated quaternion of the sensor in the lower leg, we can find α as the rotation in the lateral axis between that quaternion and the unity. Knowing the true flexion of the knee, we can correct the pose of the virtual puppet. Finally, the orientation of the thigh sensor, which may be inaccurate, is corrected. Then, the steps of this new calibration algorithm can be summarized as:

1. Estimate the real angle of the knee
2. Introduce that angle into the virtual model
3. Synchronise the orientation of the virtual world with the sensor in the lower limb
4. Correct the misalignments of the sensors in the thigh and foot.

5

Reporting System

In order to be a valuable asset for patients and physiotherapists during rehabilitation, the game must save the data generated during each session so both patients and health professionals can see how the rehabilitation is progressing. For that reason, the reporting system is one of the most relevant parts of the project, especially the report for the clinicians.

Therefore, the game contains two different types of progress reports. Additionally, each of these reports has its requirements.

5.1. Progress Report for the Patient

The main benefit of the game for a patient is that it motivates the person to continue the rehabilitation. In order to do that, the report must present the patient with a clear goal. Additionally, it will be used by people of all ages, so the information must be easy to understand. Therefore,

Following those two points and the recommendations of the professionals that were interviewed during the literature research, it was decided to include three elements in the report: a bar chart, a pair of progress bars and a list.

The bar chart shows the improvements in degrees made at each session. This improvement is estimated using the ROM recorded at the start of the game plus the peak ROM accomplished in that session. Typically, the patient would see larger improvements at the beginning when the range of motion is more limited, and smaller results towards the end of the rehabilitation program. Therefore, this element could motivate the patient at the beginning of the process.

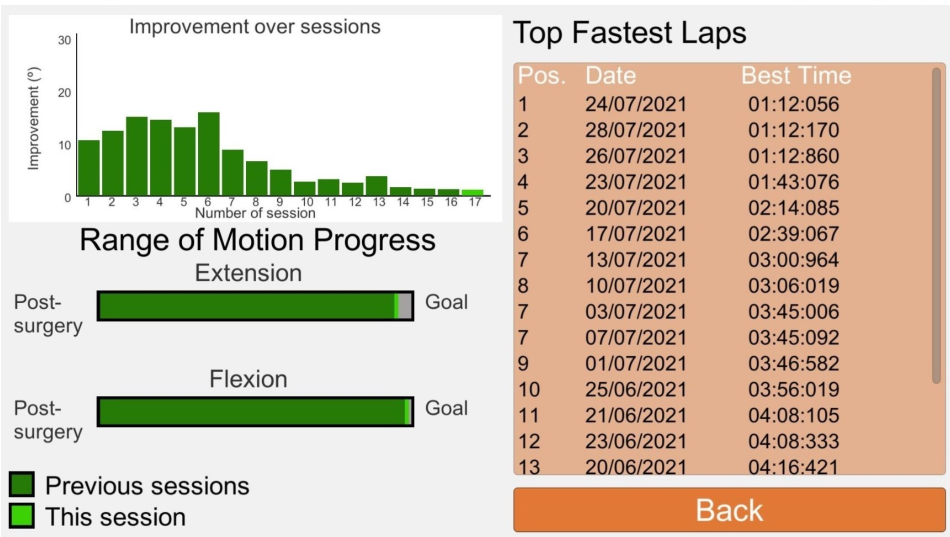

Figure 5.1: Progress report shown to the patient.

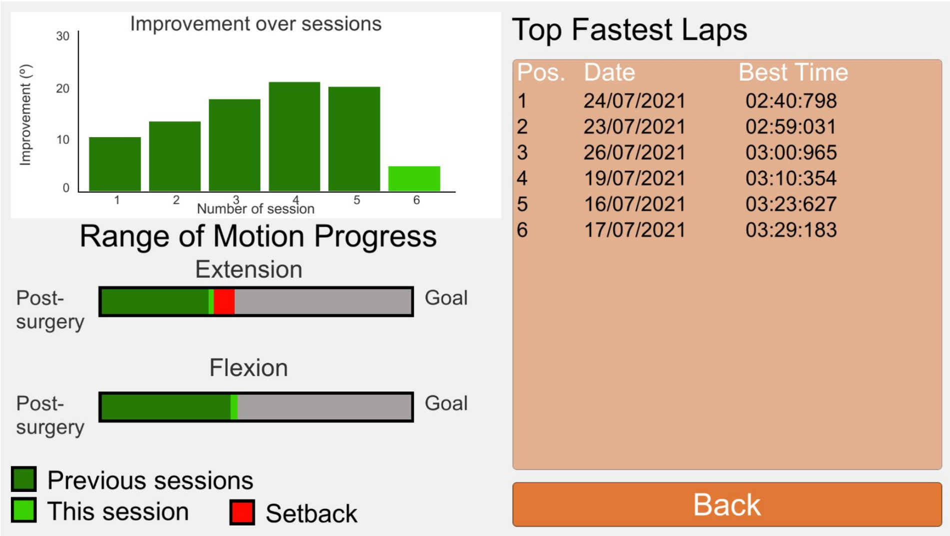

Figure 5.2: Progress report shown to the patient when there is a setback in the rehabilitation.

The progress bars are helpful to show explicitly how far the patient is from the end goal of achieving a full ROM. There are two bars, one for extension and one for flexion. This way, the patient can see on which exercise do they need to focus more. The progress bar's value will be the new ROM as a percentage, where the minimum value corresponds to the ROM recorded at the first session, and the maximum value is equivalent to the goal.

In order to differentiate the improvement made in the current session from the progress of the previous sessions, the bar graph and progress bars use different colours for each. A legend at the bottom left corner of the menu shows which colour corresponds to each of them. Additionally, setbacks along the rehabilitation are represented in red. During the rehabilitation process, the patient can lose some range of motion gained in previous sessions. When this occurs, the progress bars will show this regression, as seen in figure 5.2.

Lastly, the list is used to give another goal to the patient. However, in this case, the goal is related to the game itself. In the list, the best scores are shown. The score here is the best lap time at a session. Each line of the list contains the position, the date of the session and the best lap time. This way, the patient will try to improve their results in the game too.

To sum up, using just these three elements, the patient's report is concise, and the patient can clearly see the accomplishments made during the rehabilitation.

5.2. Progress Report for the Physiotherapist

The report that the patient sees needs to be motivating and show a connection between entertainment and rehabilitation. On the other hand, the information provided to the physiotherapist must be meaningful and complete, as regular visits to the physiotherapist would be substituted by playing this game at home. In order to define what meaningful information means in this context, several physiotherapists and other health professionals were interviewed during the literature study.

There was a consensus that the ROM is, without a doubt, the most relevant parameter to show in this report. According to the physiotherapists, this report should show how the patient moved the knee during the whole session, peak values reached during it and mean ROM values.

With that in mind, a report with five elements was created. First, there is a line chart that shows the complete movement of the knee during a session. This movement is measured in degrees. Negative values of the Y-axis correspond with knee flexion, while positive values are equivalent to complete knee extension. The X-axis shows the time of the game session in minutes.

The second element is also a line graph. It shows the progression of the patient over the sessions. There are four lines in this plot that correspond to peak and mean values of knee extension and flexion. The X-axis shows the number of sessions, and the Y-axis is the same as in the previous diagram.

Then, there is a list containing all the sessions that the patient has done. The lines in this list have a number for each session, the date and a checkbox. The checkbox allows the physiotherapist to choose the data that is printed in the first graph. When no session is selected, this graph will be empty.

Figure 5.3: Progress report shown to the physiotherapist.

Additionally, there is a drop-down list with three options: none, extension and flexion. During the interviews, some of the physiotherapists mentioned that the game had to let them change the exercises according to the patient's progress. With this drop-down menu, the physiotherapist can select if the game will focus on extension, flexion or both. For instance, when the patient has already recovered most or all the knee flexion, the game can be changed to focus only on the extension, which needs more improvement.

The last element is a picture showing an avatar's lower body. When a session is selected, the physiotherapist can play the patient's knee movement during that session in this picture. This animation can make it easier for the physiotherapist to interpret the first graph.

6

Validation of the algorithms

Two algorithms have been created for this project. The first one tries to improve the current virtual avatar calibration of the NODES System, and it was explained in chapter 4. The second algorithm converts the orientation of the sensors into angles that are later used as the input of the game, as shown in section 4. A study was performed to validate both algorithms.

The question we want to answer with these tests is how accurate and precise is the system. The initial hypothesis is that the output should be equal to the input.

Two different tests were designed for this validation, one for each algorithm. The first test studies the calibration tool and consists in calibrating the system at different angles. On the other hand, the second test examines the algorithm that converts the sensor's orientation into angles. In this test, the sensors are rotated 10º every 10 seconds until 180º have been covered.

6.1. Materials and methods

6.1.1. Materials

The materials used in both tests are three: the NODES System, two goniometers and tape to fix the goniometers to the table. Both goniometers are made of methacrylate. One of them has three degrees of freedom, while the other only moves around one axis. However, it let us replicate the movement of the leg, as the two segments can be rotated independently. The resolution of both goniometers is 1º.

6.1.2. Methods

In this section, all the information relative to the experiment is explained.

Variables and constants

The variables can be classified into three groups: independent, dependent and nuisance variables. For both tests, the independent variable is the quaternion rotation between the different sensors around the transverse axis of the body, that is, the Y-axis.

The dependent variables are the angles that the ankle and knee are bent over time, which are estimated by the algorithms. For the first test, only the knee angle matters, and it is equivalent to the sum of α and β. Additionally, in the seating position, 90º must be added.

As for the nuisance variables, the most important one is the magnetic distortion. Magnetometer calibration was performed at the beginning of each test to reduce the effect of this parameter. In addition, the experiments were done in a room with few ferromagnetic objects.

Lastly, the angular velocity when moving the goniometer and the frequency at which the sensors were rotated were almost constant.

Experimental design

The experiment consisted of two tests: one for the calibration tool and another for the algorithm that converts the sensor's orientation into angles for the game.

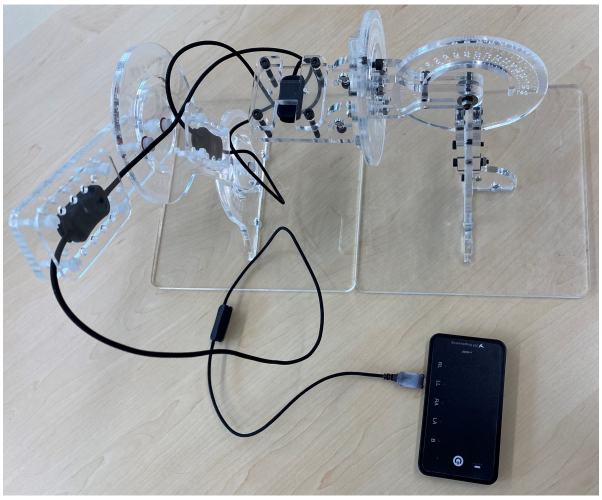

Figure 6.1: Setup of the experiment.

The experiment was designed considering the three possible ways to calibrate the sensors: lying, seating and standing. Additionally, the second test is also divided according to the two angles estimated by the algorithm: the angles from the lower leg to the foot and thigh, respectively.

Therefore, the first test is repeated three times, while the second one is replicated six times.

Experimental protocol

The setup for both tests can be seen in picture 6.1. The two goniometers are fixed to the table and each other using tape. The sensor representing the foot is attached to the goniometer with the three degrees of freedom, and the thigh and lower leg sensors are bound to the other goniometer.

The structure of the first test is the following. Initially, the sensors are calibrated at the calibration position. Then, we rotate 10º the thigh and lower leg sensors in opposite directions and calibrate the system again. These two steps are repeated until the sensors are rotated 90º with respect to the initial position. From here, the sensors are rotated back to the starting position in steps of 10º. The previous steps are repeated five times.

For the seating calibration pose, the sensor in the thigh is not rotated in increments of 10º. Instead, it is rotated according to equation 4.10, in chapter 4.

The second test follows a similar procedure. However, this time one sensor is rotated. To study the angle in the ankle joint, we move the foot sensor. However, to observe the knee angle, we rotate the lower leg sensor. Therefore, the test consists of the following steps. We start calibrating the system at one of the calibration poses. Then, rotate the sensor 10º and wait for 10 seconds. This is repeated until the sensor is has been rotated 180º. Due to the initial orientation of the sensors at each calibration pose and the orientation of the sensors fixed in the goniometer, the 180º range will be accomplished by rotating 90º in one direction, then going back to the start, and rotate in the other direction until we reach -90º of rotation from the initial point. All these steps are repeated five times.

The data of each type of test is saved into a text file. This file contains the quaternion orientation of each sensor and the estimated values of α and β or the ankle and knee angles, depending on the test. For the first test, only the data at the calibration is saved. In the second test, however, all the quaternions received since the avatar was calibrated are saved. Both files are saved when the main unit is disconnected.

Data processing

The data was processed using MatLab. In MatLab, the quaternions are multiplied to get the rotational difference between each other and converted into Euler angles. The values obtained from these quaternions are used as true measurements, and the values estimated by the algorithms are compared to them.

6.1.3. Statistical analysis of the data

Three statistical analysis methods were used to interpret the data recorded during the experiment. The relationship between input and output is studied using linear regression. With regression, we can find a model that will predict a certain percentage of the variance of the dependent variable. This value is called coefficient of determination and is represented as R^2. The closer R^2 is to the unit, the better the fit is.

Additionally, the arithmetic mean of the errors in the experiment and the standard deviation are used. Studying the measurements' average error, we can have an idea about the accuracy of the algorithms, that is, the distance between a measured value and a true or accepted value. On the other hand, with the standard deviation of the error, we can find the precision of the algorithm.

Linear regression models

The relationship between input and output can be modelled as $y = b_0 + b_1 x$, being y the dependent variable, x the independent variable and b_0 and b_1 the y-intercept and regression coefficient, respectively. Ideally, b_0 should be zero, and b_1 should be equal to one.

Arithmetic Mean of the Errors

The absolute error in the measurements was calculated and then averaged using the arithmetic mean, which is the sum of all the values of the data divided by the total number of data points.

$$\overline{x} = \frac{1}{n} \cdot \sum_{i=1}^{n} |\tilde{x}_i - x_i| \tag{6.1}$$

where $\overline{x}$ is the mean, n is the length of the dataset and x_i and $\tilde{x}_i$ are the actual and estimated measurements at index i.

When the true value of the measurement is close to zero, the absolute error is shorter. However, when the value of the measurement grows, the absolute error is larger too. For that reason, it is necessary to see the relative error, which gives us the error in the measurement as a percentage of the true value.

Standard Deviation

After calculating the mean, we can see how much the measurements spread around the average absolute error. To compute the value of the standard deviation s, we use the following formula:

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} |x_i - \overline{x}|^2} \tag{6.2}$$

The standard deviation is related to the uncertainty and precision of the measurement. When its value is small, the samples in the dataset are close to the mean value. Therefore, the measurement's consistency and precision are high. On the other hand, when the deviation in the data grows, the measurement's uncertainty increases too.

6.2. Discussion

6.2.1. Interpretation of the results

The analysis of the data recording using the statistical methods mentioned above gave us the following results. Figure 6.2 shows the regression of the two different tests. The second test is at the same time plotted in two graphs for ankle and knee angle, respectively.

If we look at the absolute errors of each test shown in figure 6.3, we can see that the amplitude of the errors in the calibration test is smaller than for the other two tests. However, its mean absolute error is higher than in the other cases, which can be seen in table 6.1. Another aspect that can be observed from these graphs is that the error has a periodic form. This is due to the procedure of the experiment.

It can be seen how the data samples with a high absolute error, on the contrary, have a low relative error. At the same time, the biggest values of the relative error correspond to small absolute errors, as the true value of the measurement is close to zero.

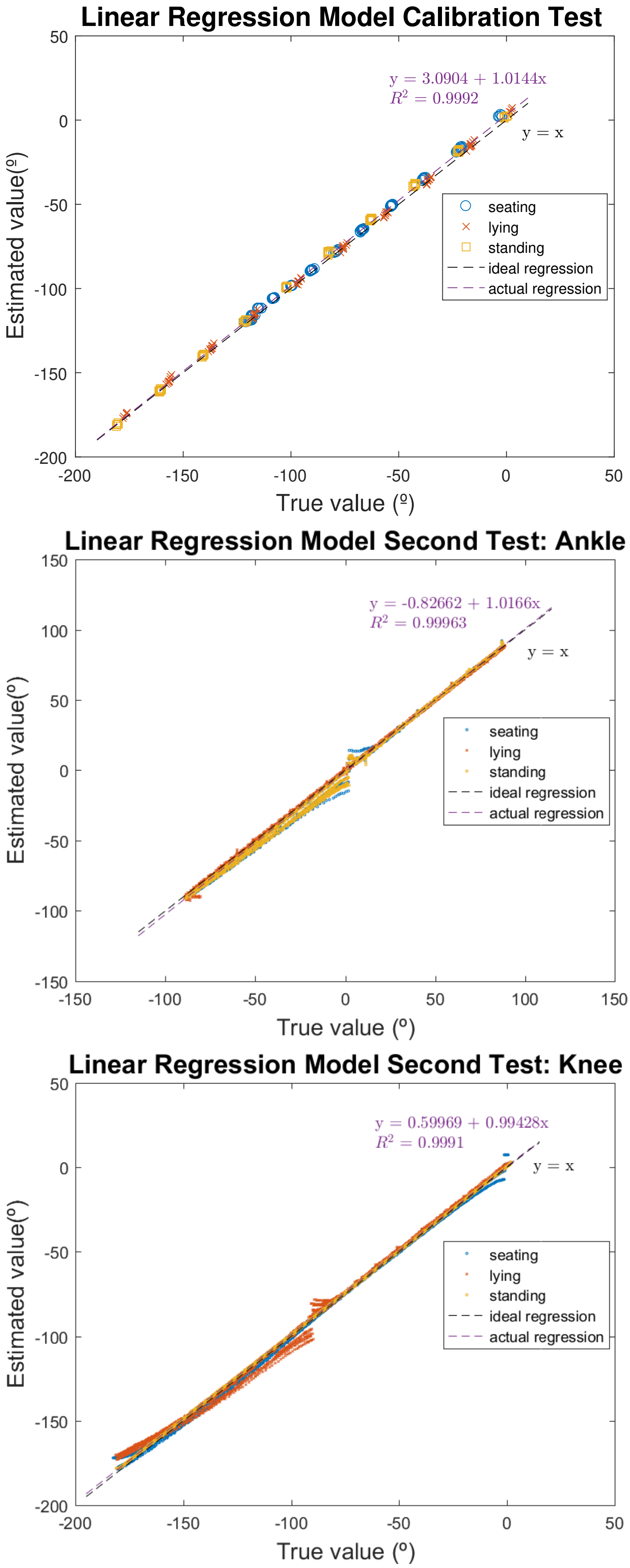

Figure 6.2: Linear regression relationship between true and estimated measurements of each test. Picture a) corresponds to the calibration algorithm test, and b) and c) correspond to the tests performed to validate the algorithm that estimates the ankle and knee angles, respectively.

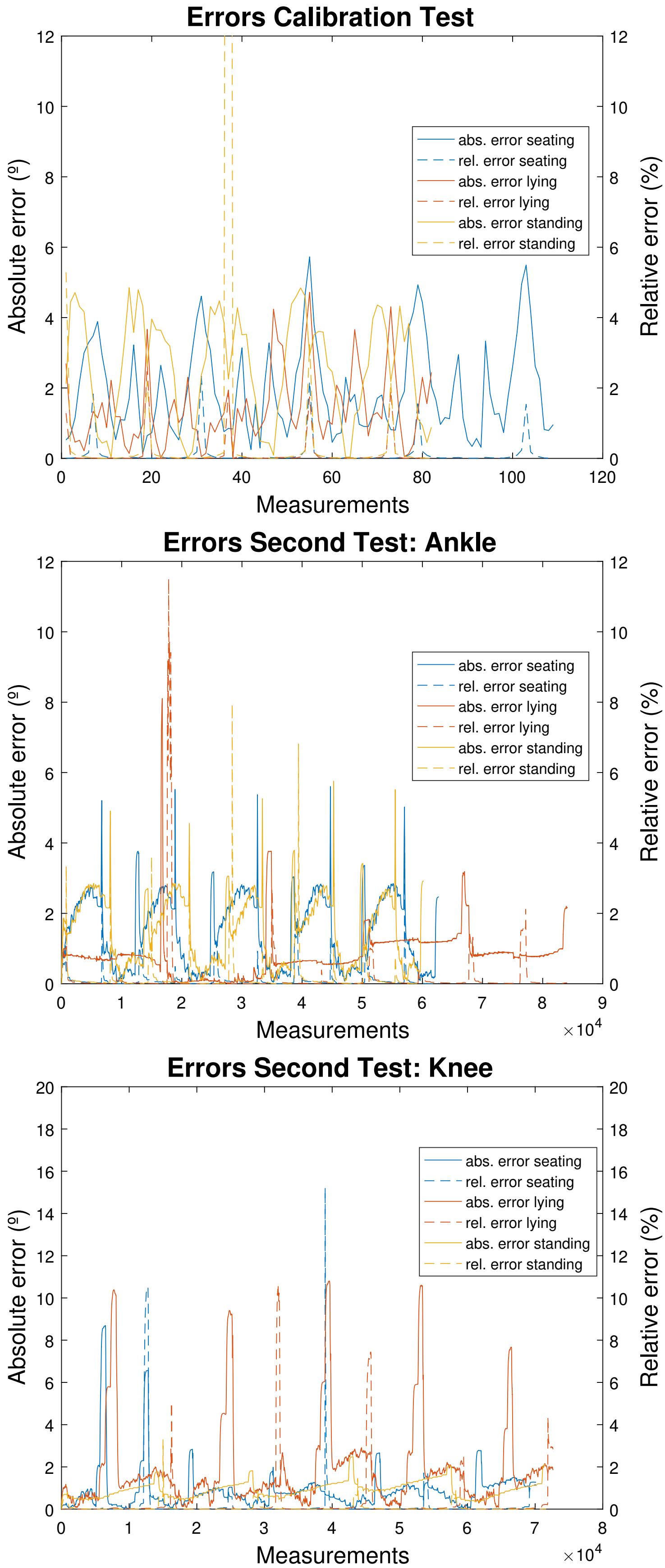

Figure 6.3: Absolute and relative errors of each test. Picture a) corresponds to the calibration algorithm test, and b) and c) correspond to the tests performed to validate the algorithm that estimates the ankle and knee angles, respectively.

Mean Errors				
	test cal	test ankle	test knee	total
seating	1.9461º	1.5141º	0.9103º	1.1960º
lying	1.4284º	0.8091º	1.9182º	1.3233º
standing	2.5977º	1.5571º	1.2593º	1.2188º
total	1.9863º	1.2403º	1.2414º	1.2504º

Table 6.1: Average error of each test.

Standard deviations				
	test cal	test ankle	test knee	total
seating	1.3010º	1.1086º	1.15658º	1.1738º
lying	1.0482º	0.7154º	2.1913º	1.6749º
standing	1.5041º	1.0473º	0.3897º	0.8260º
total	1.3712º	1.0133º	1.5289º	1.3016º

Table 6.2: Standard deviation of the error of each test.

Lastly, 6.2 contains the standard deviation of the error for each test. It can be seen that the models that approximate the relationship between the input and output of the experiment are close to the initial hypothesis.

The average errors of these models with respect to the true input in the range of motion shown on these graphs are 1.7966º, 0.9775º and 1.1142º, for the calibration test and second test for ankle and knee angles, respectively. Additionally, the coefficients of determination of the three models show that their fit is good, as the lowest value is 0.9991.

Therefore, we could use this model to re-scale the two algorithms and cancel their offsets. This way, the accuracy of the algorithms would be higher.

The study of the mean errors gave us a quantitative measure of the accuracy of the algorithms. If we look at table 6.1, we see that the experiments show that the algorithms have an accuracy of ±1.2504º. On the other hand, estimating the standard deviation of the experiment, we found that the fluctuation in the estimated values was ±1.3016º. This can be seen in table 6.2.

The resolution of the goniometers employed was 1º. For that reason, we have to round the previous values to their nearest integer. Therefore, we have a mean error of ±1º and a standard deviation of ±1º.

6.2.2. Limitations of the experiment

Some factors and complications occurred during the experiment that could be a source of error, and therefore the results could be invalid.

Magnetic distortions

Although the experiment took place in a room with few ferromagnetic elements, and placing the setup as far as possible of those elements, the effect of magnetic disturbances can be appreciated in the results. In the experiment, only a pitch motion is performed. However, when there are magnetic disturbances near the sensors, the readout of the magnetometer changes.

This is represented as a rotation around the yaw axis. A clear example of this behaviour happening in the experiment is shown in figure 6.4. It shows the input and output of one of the tests to validate the second algorithm. In the graph there are three lines: yaw, that is the rotation around the Z-axis, pitch, which is the rotation in the Y-axis, and the estimated value of the ankle angle.

The way the setup was designed, the estimated values should be equal to the pitch rotation, as we the sensors were rotated only around the Y-axis. We can see that the estimated value is very close to the pitch value. However, when the yaw rotation's value drifts from its initial value, the error in the estimated angle increases too. This effect is larger at ±90º of rotation.

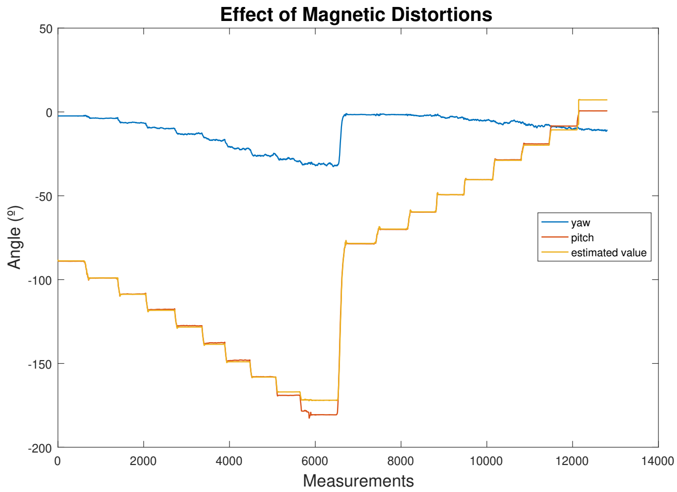

Figure 6.4: Example of the effect of magnetic disturbances in the output of the system. It corresponds to one of the runs of the second test focused on the angle of the ankle.

Mechanical errors
The goniometers used could have introduced mechanical errors as the attachment of the sensors is not completely precise.

The setup
Due to the different orientations of the sensors in each calibration position, the thigh and lower leg sensors had to be detached and fixed to the goniometers each time the calibration pose was changed. Therefore, this could have introduced random errors in each test.

Number of samples
Lastly, another deficiency of the experiment is the number of samples recorded during the calibration tests. As only one sample is saved every time the calibration is performed, getting as much data as in the other test would require repeating the calibration test hundreds of times. With fewer data points, it is more difficult to differentiate the random errors from the systematic errors.

6.2.3. Conclusions

Two algorithms were created in this project: one to calibrate the virtual avatar and another to translate the orientation of the sensors into angles. They were tested in an experiment to validate both algorithms. It consisted of three different tests, one for the calibration tool and two for the estimation of the angle between the leg segments. Additionally, the algorithms were tested once for each calibration pose: lying, seating and standing.

In the tests, the NODES System was attached to a pair of goniometers with a 1º resolution. The goniometers were fixed to a table using tape. The experiment consisted in rotating the sensors attached to the goniometers to simulate the different angles that the three limbs can form with each other.

The results were analysed using three statistical methods: linear regression models, arithmetic mean and standard deviation of the errors. The first method gave us several models that can be used to re-scaled the output of the algorithms and cancel their offsets. Then, with the mean value of the errors, we saw how accurate the system is. Finally, the standard deviation provided a quantitative measure of the system's precision. In the end, the results showed that the whole system has an inaccuracy of $\pm 1^{\circ}$ and a precision of $\pm 1^{\circ}$.

7

Voluntarily tests and questionnaires

The game and calibration tool were tested in healthy volunteers from 2M Engineering. These tests were used with two goals in mind. First, to see how well does the proposed calibration work in a setup. Then, to assess the clarity of the user interface and the playability and entertainment of the game. This subjective assessment is evaluated through a questionnaire that the volunteers filled after the test.

The test consisted of two parts. First, the new calibration algorithm was tested. The participants were asked to sit and keep the posture for 10 seconds to calibrate the virtual avatar. Then, they could move for another ten seconds and see if the avatar was following their movements. These two steps were repeated five times with different initial knee angles. In the second part of the study, the participants played the game once.

Additionally, two questionnaires for physiotherapists and patients were made. The first questionnaire was sent to the people that were interviewed for the literature research. The other test was shared among their patients and on social media, so people who have had knee surgery could fill it.

7.1. Calibration test

At the beginning of the each test, the initial seating position of the participant was photographed before calibrating. This was done to measured the initial angle of the knee. The data from the sensors was also saved in a file containing the orientation of each sensor over time in quaternion form.

Even though there are three calibration poses, only the seating position was tested. The reason is that to calculate the angles of the thigh and lower leg in this position, we had to make one more assumption.

From the pictures, the angle between the thigh and lower leg was measured using *ImageJ*, a computer programme for image processing. Then, the quaternion of the sensor in the lower leg was used to obtain the angle between the virtual thigh and lower leg, according to the algorithm described in chapter 4. The errors in the calibration of the virtual avatar can be found in figure 7.1. The line graph shows the absolute error of each sample and the mean value, while the bar plot shows the average error for each participant.

We can see how the error varies from person to person. There are two reasons for that. The first factor is the positioning of the sensor in the lower leg. This sensor acts as the reference sensor, and the algorithm expects that its position is as accurate as possible. Therefore, each participant could have introduced a different error when placing the sensors on the body.

The second and most important reason is the height of the participant. One of the hypotheses of the algorithm is that, in the seating position, the seat is at popliteal height. However, the experiment was performed in the same seat and with the same height for all the volunteers. Indeed, this was done to see how would the error of the algorithm grow when this hypothesis was not met.

There were some participants that were taller than the rest, to whom the seat was too low. In that case, the thigh was not parallel to the floor as the algorithm assumes, and an error is introduced. This problem could also have happened with shorter participants, that in order to touch the floor with their feet, they would have needed to rotate the thigh closer to the floor.

Additionally, another possible issue was the movement of the sensors between measurements, as the silicone rubber used to attached the NODES System can leave some space for sensors to move in the user does not place them straighten enough.

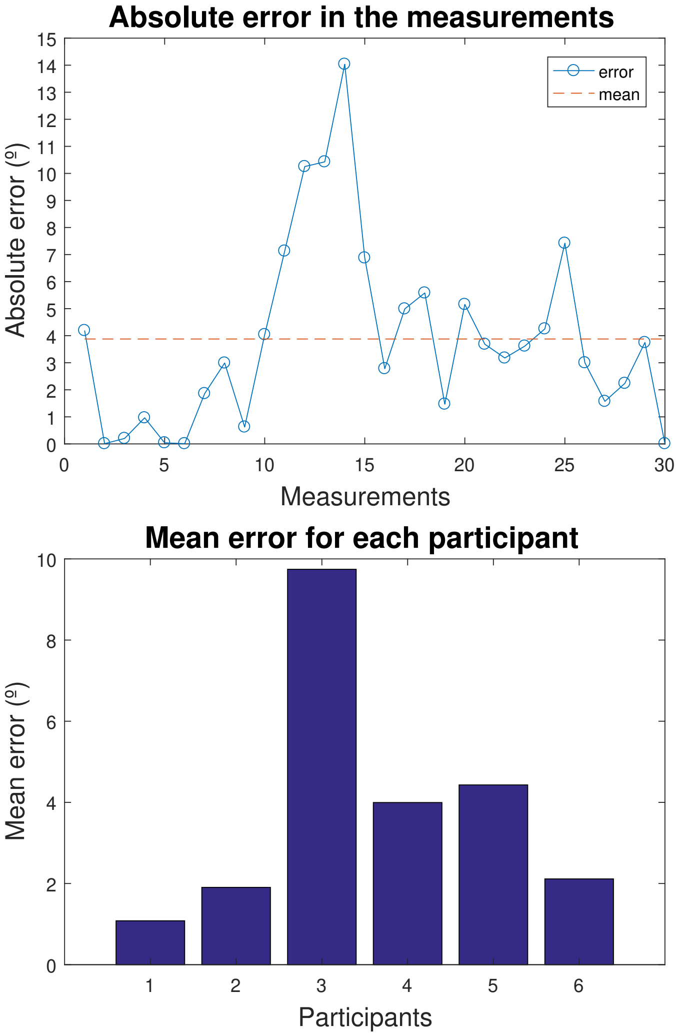

Figure 7.1: Errors in the calibration during the voluntarily tests.

7.2. Test of the game

Each participant was asked to play the game once. They had to log in, calibrate the system and record their range of motion first. Then, they learned the controls of the game and play. Finally, they saw their progress report.

In general, they were able to proceed without help. However, most participants experienced difficulties playing the game, partly because they could not get used to the controls. Additionally, they got stuck at some sharp curves.

To know their opinion about the game and their satisfaction, they were asked to fill in an online questionnaire after playing. The survey, which can be seen in appendix C.1, contains nine linear scale questions and four open-ended questions. The questions are related to six aspects of the game: user interface, calibration, controls of the game, entertainment, physical demand and progress report.

The participants found the user interface intuitive, although only half of them thought that the user interface was helpful during the game.

Almost all of the participants reported that it was absolutely easy to connect and calibrate the sensors.

Regarding the controller, for half of the participants, the controls were clear. However, in general, it was difficult for them to get used to them.

Almost all of the participants completely enjoyed playing the game, although they said it was slightly tiring.

Lastly, they found the progress report very helpful for the patient but moderately clear to understand.

In the open-ended question, some participants expressed how lifting the foot was quite straining after a while. Additionally, one of them would have liked to practice the controls before the actual game.

7.3. Physiotherapists' responses

The four people that were interviewed during the literature review phase were contacted again, and they were asked to fill in a survey with six open-ended questions. This questionnaire can be seen in appendix C.2. At the beginning of the form, there is a link to a video that shows the game developed. It shows first how a patient connects the sensors, play and sees their report. Then, it displays the physiotherapist's user interface and how they can see the patient's progress.

We wanted to know if they think that the game would indeed help and motivate their patients, if they would progress using the game, if it would reduce the number of check-up visits, and their opinions about the report shown to both the patient and physiotherapist.

All interviewees think that the game would surely make the patient practice more at home and progress playing it. The reason for that is its playful component. If the difficulty of the game is adjusted to the patient, they think that the game will stimulate them to exercise more and to reach bigger ROMs.

All of them answered that the report shown to the patient is adequate. According to them, it makes sense with the type of exercise that is done in the game, and it clearly shows the goal of the rehabilitation, the progress made and the evolution over time.

50% of the interviewees said that they would agree to see less frequently their patients using the game only at certain phases of the rehabilitation. The reason is that the game focuses only on improving the range of motion. However, this is not the only relevant aspect of the rehabilitation process. The strength or the new neurological adaptations need to be trained too. Therefore, the patient has to continue visiting the physiotherapist. The other 50% do not agree with reducing the number of visits, because they prefer to control their patients as much as possible.

Lastly, they all think that the information shown to them in the patient report could be used as additional help but never as the only reference.

7.4. Patients' responses

We wanted to know the opinion of people who had knee surgery too. For that reason, another questionnaire was made, where patients are asked if they think that they will practice more at home having the game, if they would agree to reduce the number of appointments with the physiotherapist, if the game would motivate them, about the difficulty of the game, if they would like to have several games instead of one and about the progress report. In this case, the questions were multiple-choice, except for the last one that is an open-ended question. The survey can be found in appendix C.3

At the beginning of this questionnaire, there is also a link to a video, but this video shows only the patient's user interface.

The questionnaire was shared among the interviewees' patients and on social media. By the time this report was written, 24 people had answered it.

66.7% of the people answered that they would practice more at home, and only 16.7% of them said they would not do it. Regarding the check-up visits, 41.7% of the patients would agree to reduce them, although there are more people that either said the are not sure (33.3%) or that they would not do it (25%).

There is a clear majority of people (66.7%) that think that the game will increase their motivation. There is also an agreement regarding the difficulty of the game, which 58.3% of the people would like it to increase during the rehabilitation. Regarding the number of games, there is not a majority in neither of the answers. 37.5% of the people answered that it is irrelevant for them, another 33.3% would like to have more games and 29.2% of them said that only one game was okay.

Lastly, less than half of the people answered the open-ended question regarding the report. 50% of them think that the information shown in the report is enough. Additionally, 50% also added that they care more about the information provided by the physiotherapist, so for them this information is not relevant.

8

Discussion and Conclusions

8.1. Discussion

In this project, a game using motion capture sensors was developed. The motion capture system used was the NODES System, developed by 2M Engineering. The game is intended for knee rehabilitation after surgery. This orthopaedic procedure is one of the most commons, and every year there are millions of people undergoing one. However, several reasons make the injured people never recovered the pre-injury state, like the cost of the rehabilitation and the loss of motivation and the discouragement produced by the rehabilitation program, which is very repetitive.

The principle of gamification was followed to solve those problems and improve the outcomes of the rehabilitation of those patients. Thus, a serious game was created to motivate those patients to continue practising the exercises and accelerate their rehabilitations. Together with the game, a new calibration tool for the NODES System and a reporting system were implemented to accomplish the project's goals.

During the initial phase of the thesis, a literature research was done. This review was used to select the best methods and options to create the game. Some aspects that were studied were the ideal sensor fusion algorithm for this project, the type of exercises and parameters that should be trained and the information to show in the progress report. Additionally, several interviews with physiotherapists completed the knowledge gained in the state-of-the-art review. With all that, we could decide each aspect of the game.

In the end, the concept chosen for the game was a karting game where the patient competes against other characters to be the first one to finish the race. The game is controlled using three sensors place in the thigh, lower leg and foot, respectively. The bending of the ankle accelerates and brakes the character while bending the knee makes it turn left or right. An algorithm was implemented to achieve that. It translates the angle of the knee and ankle in standard inputs for the game. This algorithm takes into account the patient's knee range of motion and only turns the kart when the angle is close to the peak extension or flexion.

The application created has two different user interfaces: one for patients and one for physiotherapists. It implements a database that manages both types of users and, depending on the type of user that logs in, it shows one interface or the other.

The patient's user interface consists of seven screens: the main menu, a screen to calibrate the sensors and virtual avatar, the controller guide, the game, the progress report and a menu to change the password. From the main menu, the patient can go to any of those screens or back to the start menu of the application. Every time the patient starts the application and wants to play, they need to calibrate the sensors first. Right after that, the current range of motion of the patient is recorded. It will be used to adjust the controls of the game to the physical status of the patient. When the patient finishes playing the game and comes back to the patient's main menu, the data recorded during the game is saved in two files on the device. This data will be loaded when either the patient or the physiotherapist want to see the progress report.

On the other hand, the physiotherapist's user interface consists of just three screens. In the main menu, there is a list showing their patients. Each line of the list has the patient's name and a check box. When this checkbox is checked, the physiotherapist can delete the patient from the database or see their report. Finally, physiotherapists can also create new patients.

The progress reports are different for each user, too. The patient's report has three elements. The first one is a bar graph with the improvements in degrees made over the sessions. It also contains two progress bars showing how far is the patient from achieving the maximum extension and flexion values. Lastly, there is an ordered list with the fastest lap times of the patient. In the bar plot and the progress bars, two different colours are used to clearly distinguish the progress made in the current session from the one made in previous days.

On the other hand, the physiotherapist's report has two line graphs, one with the movement of the patient's knee during a session and the other graph with the change of the peak and mean maximum values of both extension and flexion over the sessions. Apart from that, there is a list with all the sessions so the physiotherapist can select which session is plotted in the first graph, and a picture of the avatar's lower body where the physiotherapist can see animated the movement of the patient during the selected session.

The current calibration method of the NODES System was improved, as it had some limitations. The new algorithm to calibrate the virtual avatar introduces a new step at the beginning, where it takes the predefined calibration pose o¡selected by the user and updates each leg segment's position according to the orientation of the sensor in the lower leg. For that to work, the sensor must be attached as accurate as possible to the desired position. This algorithm works for the three poses that a patient with knee surgery can adopt: lying position for the initial phase of the rehabilitation, seating position when the patient has recovered enough mobility, and standing position, possible when the patient has enough strength and extension.

In order to validate the two algorithms created, two different tests were performed, one for each algorithm. The setup of the experiment consisted of two goniometers and the NODES System. The results showed that the system has an average error of $\pm 1^{\circ}$ and a standard deviation of $\pm 1^{\circ}$. In the interviews with physiotherapists that took place during the literature research phase, it was found that they were more concerned about the precision of the system rather than its accuracy and resolution. Provided the precision of the system found in the experiment, it can be seen that the system meets the requirements of the health professionals. Additionally, it is important to compare the proposed calibration algorithm with the previous one. The mean error of our algorithm was $\pm 2^{\circ}$. On the other hand, the original algorithm did not update the pose of the virtual avatar, so the error in the calibration would be at least the sum of α and β. This confirms that the calibration algorithm proposed in this project is more accurate than the previous one.

The calibration tool, game and reporting system were assessed in a study with volunteers from 2M Engineering and a survey with physiotherapists and patients. The participants of the study were used to test the calibration tool first. In the test, the participant had to seat and calibrate the sensors several times, changing the flexion of the knee every time. This was done to see the performance of the calibration algorithm in a real setup. We saw that the assumption of the seat being at the knee height has a big effect on the calibration. As the seat was the same for everybody, the error in the measurement was greater when the participant was taller than the other people.

After testing the calibration tool, the volunteers played the game and filled a questionnaire. The goal of this survey was to gather the opinion of the people who had tried the game. They were positive about the game, the user interface and the progress report, but had problems with the controls and the difficulty of the game.

Lastly, two more questionnaires were prepared. The first one was sent to the physiotherapists that were interviewed before. In general, they were happy with the results. They think that it would surely help patients to get motivated and to exercise more. They also praised the reporting system. However, even though they liked the game and the progress report, they still think the game should be used only as an accessory tool. The second questionnaire was shared between the interviewees' patients and on social media, so people that had gone through knee surgery could assess this game. Their answers were similar to what the physiotherapists reported. In general, they think that it would motivate and help patients in their rehabilitation. However, they would prefer to receive the progress report from their physiotherapists, so they do not care that much about the information shown in the game.

8.2. Conclusions

In this thesis, a post-surgery rehabilitation game was created after a state-of-the-art research and a survey to gather the opinion of several physiotherapists. The game was successfully tested in healthy volunteers from 2M, as the existing COVID-19 measures did not allow for tests in patients.

Additionally, it was validated with an experiment that evaluated the performance of the two algorithms created. Its results showed that the system has an accuracy of $\pm 1^{\circ}$ and precision of $\pm 1^{\circ}$.

The game, calibration tool and reporting system were assessed thanks to the people who tried the game, and also thanks to physiotherapists and patients, who answered a questionnaire that was created specifically for each of them.

The positive feedback received in the surveys demonstrated that the game is a promising tool to use together with traditional rehabilitation, and that it could fulfil our goal of accelerating the rehabilitation of these patients.

8.3. Future work

After the validation of the data, the voluntarily study and the answers to the questionnaires of patients and physiotherapists it was clear that there are several aspects of the game that could be improved.

- Most of the volunteers found the controls of the game complicated and the game a bit tiring. The relationship between turning and bending the knee is difficult to grasp, especially at the beginning. Two things can be done to solve this problem. One solution would be to add a menu where the patient can practise without any obstacles could help them get used to it before playing the actual game. Indeed, this was suggested by one of the volunteers and could be easily implemented by adding a new screen or by modifying the current controller guide menu. Another option would be to change the camera view. For instance, by putting the camera on top of the patient's character and rotating it 90º. From this perspective, turning would be equivalent to moving up or down. This movement in the game can be easily related to extending and flexing the knee, as those knee exercises are like a vertical movement from the patient's perspective.
- The difficulty of the game might be too high. This problem can be solved by designing more tracks with different lengths and number of sharp curves, and by tuning the speed, acceleration and similar parameters of the player's character.
- A wrong seat height can have a large negative effect on the calibration of the avatar. This problem is more difficult to solve, but one possible solution is to include a dynamic step in the calibration protocol. This new step could consist in moving the leg from side to side and up and down. That way, we could correct the misalignment of the error in the thigh. Then, we could use the corrected orientation of this sensor to rotate the thigh instead of using the angle estimated with the orientation of the sensor in the lower leg.
- The system could be improved by adding more features, be it more race modes or multiple games. It would not only satisfy those patients who requested more games, but it would also allow us to introduce more exercises. Therefore, it would make the game an even better tool for their rehabilitation.

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Glossary

List of Acronyms

ACL	Anterior Cruciate Ligament
AET	Active Exercise Training
API	Application Programming Interface
AR	Augmented Reality
CF	Complementary Filter
CKC	Close Kinetic Chain Exercise
CPM	Continuous Passive Motion Exercises
DCM	Direction Cosine Matrix
EA	Euler angles
EKF	Extended Kalman Filter
EMG	Electromyography
GDA	Gradient Descent Algorithm
HTTP	Hypertext Transfer Protocol
IMU	Inertial Measurement Unit
KF	Kalman Filter
KOOS	Knee Injury and Osteoarthritis Outcome Score
LLF	Local Level Frame
NCF	Nonlinear Complementary Filter
NPC	Non-Player Character
NWBB	Nintendo Wii Balance Board
OKC	Open Kinetic Chain Exercise
RICE	Rest, Ice, Compression and Elevation
ROM	Range Of Motion
SDI	Strap-Down Integration
SFA	Sensor Fusion Algorithm
VO	Vector Observation
VR	Virtual Reality
WOMAC	Western Ontario and McMaster Universities Osteoarthritis Index

List of Symbols

α, β, δ and γ	Angles in the knee for the calibration algorithm
$\mathfrak{a}$	External non-gravitational acceleration
$\overline{x}$	Mean
τ_{ankle}	Threshold used to decide if the patient is accelerating or breaking from the ankle angle
$\tau_{knee,\ 1}$	Maximum extension of the knee
$\tau_{knee,\ 2}$	Maximum flexion of the knee
q_0, q_1, q_2 and q_3	Components of the quaternion
θ	Rotational difference between limbs
θ_{ankle}	Rotational difference between lower leg and ankle
θ_{knee}	Rotational difference between lower leg and thigh
$\theta_{unsigned}$	Unsigned rotational difference between limbs
$\tilde{x}_i$	Estimated measurement
$\vec{\omega}$	Angular velocity
$\vec{a}$	Linear acceleration
$\vec{m}$	Strength of the Earth's magnetic field
A	Transition matrix
b	Normalized Earth's magnetic field
b_0	Y-intercept
b_1	Regression coefficient
b_a, b_ω and b_m	Biases of accelerometer, gyroscope and magnetometer
g	Normalized gravity vector
H	Observation matrix
$H(s)$	High-pass filter gain
k	Scale of the *Turn* formula
K_k	Kalman gain
k_p	Cut-off frequency
$L(s)$	Low-pass filter gain
L_1	Length of the thigh
L_2	Length of the lower leg
L_3, L_4 and L_5	Auxiliary distances
Q_K	Process noise vector covariance matrix
R^2	Coefficient of determination
R_k	Measurement noise vector covariance matrix

s	Standard deviation
u_k	Control input vector
v_k	Measurement noise vector
w_k	Process noise vector
x_i	True measurement
x_k	State vector
y_a, y_ω and y_m	Readouts of accelerometer, gyroscope and magnetometer, respectively
z_k	Measurement vector
i, **j** and **k**	Standard orthonormal basis for $\mathbb{R}^3$
Accelerate, *Brake* and *Turn*	Parameters of the input system
q	Quaternion
sign	Sign of the rotation

A

System Requirements

A.1. Functional Requirements

A.1.1. Requirements for all users

- The system shall allow a user to be a patient (player).
- The system shall allow a user to be a physiotherapist (administrator).
- The system shall allow a user to log in.
- The system shall allow a user to log out.

A.1.2. Requirements for the physiotherapists

- The system shall allow a user to register a new account as an physiotherapist
- The system shall prevent a physiotherapist from creating a new user with an already existing username
- The system shall allow a physiotherapist to see the list of patients under their supervision
- The system shall allow a physiotherapist to add a new patient to the database
- The system shall allow a physiotherapist to remove a patient from the database
- The system shall allow a physiotherapist to access a patient's progress data
- The system shall allow a physiotherapist to select the training session that is displayed in the report
- The system shall allow a physiotherapist to set the training parameters of a patient

A.1.3. Requirements for the patients

- The system shall allow a patient to connect the sensors
- The system shall allow a patient to play the game
- The system shall allow a patient to see their progress
- The system shall allow a patient to change their password
- The system shall allow a patient to select a device
- The system shall allow a patient to select a calibration pose
- The system shall allow a patient to connect to a selected device
- The system shall allow a patient to calibrate the magnetometers of the sensors

- The system shall allow a patient to calibrate the virtual avatar
- The system shall save the current range of motion of the ankle joint of a patient
- The system shall save the current range of motion of the knee joint of a patient
- The system shall display an avatar following the movements of a patient
- The system shall allow a patient to control the avatar with their leg
- The system shall allow a patient to accelerate by extending their ankle
- The system shall allow a patient to brake by flexing their ankle
- The system shall allow a patient to turn right by extending their knee
- The system shall allow a patient to turn left by extending their knee
- The system shall show the number of laps a patient has made
- The system shall increase the number of laps when a patient finishes a lap
- The system shall show the position of a patient
- The system shall update the position of a patient when there they pass or are passed by an AI player
- The system shall show the lap time of a patient
- The system shall reset to zero the lap time of a patient when a patient finishes a lap
- The system shall respawn a player at the middle of the road when the player falls to the water
- The system shall detect a collision between two players
- The system shall detect a collision between a player and an object in the environment
- The system shall detect when a player is driving in the opposite direction and rotate it to face the correct direction
- The system shall end the game when a player finishes three laps
- The system shall prevent a patient from moving the car when the game is finished
- The system shall destroy an AI player when the game is finished or when it completes the last lap
- The system shall display the final position and best time of a patient when the game is finished
- The system shall allow a patient to play again
- The system shall allow a patient to go back to the main menu
- The system shall save the data recorded by the sensors when a patient finishes the game

A.2. Nonfunctional Requirements

- The system must have a simple and intuitive user interface. Texts should have large font sizes and explain the function of the elements in the user interface they refer to.
- The system must work for different display resolutions. The elements in the user interface should keep the same position and relative size when the resolution of the device changes.
- The average frame rate must be greater than 60.
- The average response time between click and reaction must be less than 0.5 seconds.
- The controls of the game must be intuitive. A player should learn how to play during their first try.
- The progress report must be clear and easy to understand. The title, axes and legend of each figure should explain the information displayed on it
- The game must be safe for the patient. The movements a patient has to perform while playing should be controlled and within their capabilities.

B

Informed consent form for the study

Informed Consent Form for the Study: Testing of a Game and Calibration Tool for Pre- and Post-Surgical Knee Rehabilitation

Please tick the appropriate boxes	Yes	No
Taking part in the study		
I have read and understood the study information dated 11/05/2021, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	○	○
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	○	○
I have been informed of the criteria to be included in this study and I fulfil it as I do not have any pathology or any implanted device.	○	○
I understand that taking part in the study involves a questionnaire and participant's knees being photographed to measure knee angles while wearing sensors. Participant's name will not be recorded. Additionally, <u>no</u> personally identifiable characteristic of the participant will be shown in the photographs, only his or her knee.	○	○

Signatures

__________________________ ____________________ _________

Name of participant Signature Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

__________________________ ____________________ _________

Researcher name Signature Date

Study contact details for further information:

Name: José López Hidalgo

Telephone number: +31 645 339 815

Email: jlopezhidalgo@gmail.com

C
Questionnaires

C.1. Voluntarily study questionnaire

Virtual KneeHab questionnaire

This questionnaire is intended for participants of the study "Testing of a Game and Calibration Tool for Pre- and Post-Surgical Knee Rehabilitation" as a part of a master's thesis project. This survey aims to get a subjective assessment of the game from the participant's experience. You will answer questions about the user interface, calibration tool, game and progress report. These answers will help to measure the playability and entertainment of the game, the clarity of the user interface and the usefulness of the game and progress report.

*Required

1. Was the user interface intuitive for you? *

Mark only one oval.

	1	2	3	4	5	
Not at all	◯	◯	◯	◯	◯	Completely

2. Was the user interface during the game helpful? *

Mark only one oval.

	1	2	3	4	5	
Not at all	◯	◯	◯	◯	◯	Completely

3. Do you have any other comments about the user interface?

____

____

____

____

____

4. Do you think that it is easy to connect and calibrate the sensors? *

Mark only one oval.

	1	2	3	4	5	
Not at all	◯	◯	◯	◯	◯	Completely

5. Were the controls of the game clear to understand for you? *

Mark only one oval.

	1	2	3	4	5	
Not at all						Completely

6. Was it easy for you to get used to how the game is controlled? *

Mark only one oval.

	1	2	3	4	5	
Not at all						Completely

7. Do you have any other comments about the controls of the game?

8. Was the game enjoyable? *

Mark only one oval.

	1	2	3	4	5	
Not at all						Completely

9. Was the game physically demanding? *

Mark only one oval.

	0	1	2	3	4	5	6	7	8	9	10	
Not demanding at all												Extremely demanding

10. Do you have any other comments about the game?

11. Do you think that the progress report would be helpful for a patient? *

Mark only one oval.

	1	2	3	4	5	
Not at all	○	○	○	○	○	Completely

12. Do you think the the progress report is clear? *

Mark only one oval.

	1	2	3	4	5	
Not at all	○	○	○	○	○	Completely

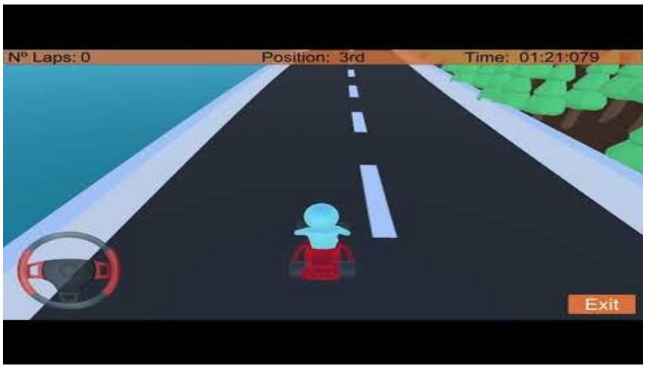
13. Do you have any other comments about the progress report?

C.2. Questionnaire for physiotherapists

Virtual KneeHab. Rehabilitation Game after Knee Surgery.

This questionnaire is aimed at those people who were interviewed at the beginning of this project. With the feedback from these interviews, a post-operative knee rehabilitation game was developed. It is called "Virtual KneeHab", which is controlled using motion sensors. The goal of this questionnaire is to collect the opinion of said interviewees about the final result of the game.

Video of the game showing the user interface of both the patient and the physiotherapist.



http://youtube.com/watch?v=ncg7f-a8eJo

1. Do you think patients would practice more if they played this game? Why?

2. Do you think patients could properly progress with this game? Why?

3. Do you think the progress report shown to the patient is enough? Or do you think, on the contrary, that it should contain more detailed information about rehabilitation?

4. Would you agree to see your patients less frequently, knowing that they use this game at home? Why?

5. Do you think the information displayed on the patient progress report is adequate? Why?

6. How would you use this information? As the only reference to the patient's progress? Or as extra help during a check-up appointment with the patient?

C.3. Questionnaire for patients

Virtual KneeHab. Rehabilitation Game after Knee Surgery.

This questionnaire aims to collect the opinion of people who have undergone knee surgery and subsequent rehabilitation on a game developed for said rehabilitation. This game is controlled by moving the knee and ankle, thanks to motion sensors placed on the thigh, lower leg and foot.

Video showing how a patient would use this game during his rehabilitation.

http://youtube.com/watch?v=UcNh4cEL1i8

1. Do you think you would practice more at home if you had a game like this?

Mark only one oval.

- Yes
- No
- Maybe

2. Would you be okay with having less frequent appointments with your physiotherapist if you could use this game at home?

Mark only one oval.

- Yes
- No
- Maybe

3. Do you think that using this game would increase your motivation during the rehabilitation?

Mark only one oval.

- Yes
- No
- Maybe

4. Would you like the game to increase in difficulty as you progress?

Mark only one oval.

- Yes
- No
- Maybe

5. Would you like to play more than one game?

Mark only one oval.

- Yes, I would like to play different games.
- No, one game is enough.
- It does not matter to me.

6. What do you think of the progress report that the game shows you? Does it contain enough information? Or would you prefer to see more detailed information about your progress?