Faculdade de Engenharia da Universidade do Porto

KneeRecovery
Rehabilitation Exercises for Knee Recovery at Home

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Abstract

Osteoarthritis is a disorder of the musculoskeletal system characterized by progressive loss of articular cartilage, not allowing free movement of the joint and causing painful experiences. The knee is the joint of the human body that is most often affected by osteoarthritis. When the disease is already in an advanced state, surgical intervention, called total knee replacement, is the common indicated procedure. After the surgery, the recovery phase is followed by rehabilitation exercises specially designed for the patient to regain strength and improve the parameters of knee kinematics. In recent years, there has been a growing demand for more efficient forms of health care delivery, which has resulted in increased home rehabilitation. However, performing home rehabilitation exercises can be compromised by the lack of real time feedback and adherence.

Several solutions have been explored in which technology can be used to enhance home exercise by providing essentially feedback to patients, however they still have some limitations, reasons that evokes the need of alternatives.

With this in mind, the KneeRecovery - Knee Rehabilitation Exercises Analysis System was developed with aiming to build an algorithm capable of measuring the evolution of the angle performed by the knee during the rehabilitation sessions to which the patient is subject at home, informing him/her if the exercises are being properly executed or not and reporting the progress throughout the rehabilitation process. In order to do that, two inertial sensors aligned with each other were placed on the thigh and shank and the lower limb was modeled. Data from inertial sensors were combined through a sensor fusion method in order to obtain the orientation of each lower limb segment. After finding the sensors' orientation, the vectors describing thigh and shank segments in Earth coordinate frames were defined through a method of conversion from sensor local reference frame to Earth reference frame. The knowledge of the vectors that characterizes the orientation of the thigh and shank segments allowed the calculation of the knee angle.

To evaluate the system, KneeRecovery was compared with two validation systems: camera motion tracking system and goniometer. Due to various factors, ranging from sensors' alignment to intrinsic sensors' characteristics, an offset problem was verified. To overcome this problem, a calibration method was developed. After the calibration has been applied, in spite of an acceptable performance has been achieved, 4,02 degrees of maximum mean absolute deviation of the absolute error was obtained when the camera was used as comparison. This amplitude error revealed to be characteristic of the exercises which involve faster movements. The results obtained when the goniometer was used as point of comparison were slightly higher and confirmed the conclusion that the velocity of the exercises influences the error obtained. In this case, 4,61 degrees of maximum mean absolute deviation of the absolute error was obtained. The experimental results demonstrated KneeRecovery can be considered a viable system to give feedback in home rehabilitation with the advantages of being portable, without occlusion problems, small-sized and low cost.

Although results were promising, further development of this project is required to potentially improve the knee angle estimation.

Keywords: Knee, Osteoarthritis, Total Knee Replacement, Rehabilitation Exercises, Inertial Measurement Unit, Sensor Fusion, Orientation Estimation, Knee Angle.

Resumo

A osteoartrite é uma desordem do sistema musculosquelético caracterizada pela perda progressiva de cartilagem articular, impedindo o movimento livre da articulação e desencadeando experiências dolorosas. O joelho é a articulação do corpo humano que mais frequentemente é afetada por osteoartrite. Quando a doença já se encontra num estado avançado, a intervenção cirúrgica, denominada artroplastia total do joelho, é o procedimento comum indicado. Após a operação, segue-se a fase de recuperação que se faz acompanhar por exercícios de reabilitação especialmente pensados para que o paciente recupere força e melhore parâmetros da cinemática do joelho. Nos últimos anos tem-se verificado uma crescente procura por formas mais eficientes de entrega de cuidados de saúde, o que resultou num aumento de reabilitação em casa. Porém, a execução dos exercícios de reabilitação em casa pode ser comprometida pela falta de feedback em tempo real e adesão.

Várias soluções em que a tecnologia é usada para possibilitar a reabilitação em casa, através da disponibilidade de feedback aos pacientes têm sido exploradas. Porém, estas ainda apresentam algumas limitações, razões que suscitam a necessidade de alternativas.

Com isto em mente, o KneeRecovery – Sistema de Análise de Exercícios de Reabilitação foi desenvolvido com o objetivo de construir um algoritmo capaz de medir a evolução do ângulo do joelho durante as sessões de reabilitação a que o paciente se sujeita em casa, permitindo informá-lo se os exercícios estão a ser executados corretamente ou não e relatar o seu progresso ao longo do processo de reabilitação. Com este intuito, dois sensores inerciais alinhados foram colocados na coxa e na perna e o membro inferior foi modelado. Os dados obtidos a partir dos sensores inerciais foram combinados através de um método de *sensor fusion* de forma obter a orientação de cada segmento do membro inferior. Depois de encontrada a orientação dos sensores, os vetores que descrevem a coxa e a perna foram definidos em coordenadas Terra através de um método de conversão da referência local do sensor para a referência Terra. O conhecimento dos vetores que caracterizam a orientação dos segmentos da coxa e da perna permitiram o cálculo do ângulo do joelho.

Para avaliar o sistema, o KneeRecovery foi comparado com dois métodos de validação: o primeiro é um sistema de *tracking* do movimento que utiliza uma camera e o segundo requere o uso de um goniómetro. Devido a vários fatores que vão desde o alinhamento dos sensores a características intrínsecas aos sensores, um problema de *offset* foi verificado. Para ultrapassar este problema, um método de calibração foi desenvolvido. Após a calibração ter sido aplicada, apesar de um desempenho aceitável ter-se verificado, um desvio médio absoluto de 4,02 graus de erro absoluto foi obtido quando a camera foi utilizada como termo de comparação. A amplitude deste erro revelou ser característica dos exercícios que envolviam movimentos mais rápidos. Os resultados obtidos quando o goniómetro foi usado como comparação foram ligeiramente superiores e confirmaram a conclusão de que a velocidade dos exercícios influencia o erro obtido. Neste caso, 4,61 graus de desvio médio do erro absoluto foram obtidos. Os resultados experimentais demonstraram que o KneeRecovery pode ser considerado um sistema viável para dar *feedback* na reabilitação feita em casa, com as vantagens de não ter problemas de oclusão, ser de pequenas dimensões e baixo custo.

Embora os resultados tenham sido promissores, desenvolvimentos adicionais a este projeto são necessários para potencialmente melhorar a determinação do ângulo do joelho.

Palavras-chave: Joelho, Osteoartrite, Artroplastia Total do Joelho, Exercícios de Reabilitação, Unidade de Medição Inercial, Fusão Sensorial, Estimação da Orientação, Ângulo do Joelho.

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Sara Oliveira

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List of Abbreviations

2D	Two dimensional
3D	Three dimensional
AICOS	Assistive Information and Communication Solutions
CPM	Continuous passive motion
DOF	Degrees of freedom
IMU	Inertial Measurement Unit
NMES	Neuromuscular Electrical Stimulation
OA	Osteoarthritis
OARSI	Osteoarthritis Research Society International
ROM	Range of motion
TENS	Transcutaneous Electrical Nerve Stimulation
TKR	Total Knee Replacement

Chapter 1

Introduction

Knee osteoarthritis (OA) is ranked as the 11th highest contributor to global disability, with sufferers commonly reporting pain, activity limitations and diminished health-related quality of life [1]. This disease is characterized by structural changes in and around the knee joint. The predominant structural changes are the loss of cartilage and the formation of osteophytes. The nature of this phenomenon's risk factors can be quite different. Age, gender, genetics, overweight and local biomechanical factors, such as joint injury and malalignment and muscle weakness propitiate OA progression. Abnormal mechanical loading in various sport activities or during heavy work may activate the biomechanical cascade that leads to joint degeneration and pain, but also even in normal mechanical loading if the cartilage is impaired [2]. OA causes inflammation, swelling, pain and subsequently reduced motion in joints. As a progressive disease, it gradually worsens with time being highly prevalent among obese and elderly people [3]. In advanced stages of knee OA, surgical intervention may be warranted due to a reduced effect of conservative treatment on symptoms. Total Knee replacement (TKR) is a promising management strategy for end-stage OA, with typically large improvements in pain and self-reported function [1]. Moreover, the use of this procedure has been steadily rising in recent years. In the United States, the annual number of TKR surgeries increased 162% over the past two decades among the Medicare population. Similarly, in Europe, there was a marked increase in the annual number of TKR surgeries in the past decade, with numbers tripling in Denmark and doubling in Spain. The increasing incidence and prevalence of TKR and knee OA in the developed world is likely to continue due to factors such as the ageing population and increasing prevalence of obesity [4]. Despite the apparent success of TKR, many patients continue to report difficulties in daily functional capabilities [5], which is reflected in altered knee kinematics when compared to the healthy joint [6]. Following discharge after a TRK, physical rehabilitation, comprising mainly physical therapy intervention, is widely advocated and provided as a standard of care [7].

Recent years have witnessed an increasing demand for more efficient health care delivery which has resulted in an increase in home based rehabilitation. However, rehabilitation exercises performance at home can be jeopardized due essentially to the lack of a real-time feedback and adherence. Many patients encounter various difficulties when performing their rehabilitation exercises at home. For instance, without the supervision of their therapist, patients may execute their exercises incorrectly. Incorrect alignment during exercise, incorrect speed of movement and poor quality of movement may have an impact on the efficacy of exercise and may therefore result in a poor outcome. Patient adherence is also a major problem associated with home based rehabilitation exercise. Up to 65% of patients' report being non-adherent or only partially adherent to their exercise programs, with over 10% failing to complete their programs. The degree to which patients adhere to their exercise programme may also influence the success of rehabilitation. Accurate assessments of adherence and exercise performance are therefore required in order to ensure that patients both adhere to and perform their exercises correctly [8].

To address this problem, knee kinematics as the knee angle obtained during rehabilitation have to be quantified and the need of a system able to give this information emerges to allow a rehabilitation process at home.

1.1 Problem Identification

There are several techniques being applied nowadays with the aim of enhance home exercise by providing essentially relevant information on exercise technique over the time about its correct or incorrect execution and encouragement to patients [8][9]. Solutions like electromyography, real-time ultrasound biofeedback systems or commercial videogames such as the Nintendo Wii and the Kinect from Microsoft have shown potential in rehabilitation. Despite this variety of biofeedback systems, they have some limitations, such as the high cost, the need of an expertise to operate them, the incapacity to track subtle movements, problems related with accuracy or occlusion [8].

In recent years, many researchers had proposed inertial sensors as a means of tracking movement during exercise, however studies focused on the motions of specific segments of the human skeleton, such as the knee, and for long-term are relatively rare [10]. In addition, in general, these methods only evaluate parameters such as the range of motion (ROM), not giving an extensive evaluation and analysis of the evolution and performance achieved by the patient.

The problem identified is the non-existence of a unique portable low-cost system, specifically suited for be applied in a long-term knee rehabilitation program, allowing a real-time feedback and a complete report of the patient's evolution.

1.2 Motivation and Objectives

Knee angle can be calculated using a wide variety of techniques and sensors. Several successful examples exist in literature for the application of inertial sensor based systems in the measurements of knee angles, motoring the recovery of patients who underwent TKR [10].

Considering the problem mentioned above and the drawbacks of the existing solutions, an inertial low-cost system suited for giving real-time feedback about the knee angle performed by the patients when a knee rehabilitation program is being performed at home should be the solution. The small size, the low cost, the usability and the unobtrusive nature of these sensors makes them an ideal solution to measure movement and therefore deliver feedback to patients as they perform their exercises [8]. Despite some disadvantages as fluctuations induced by noises and drift problems, once it is corrected, inertial sensors are well suited for recording recovery conditions during a home-based knee rehabilitation program [10].

Developing an inertial system that monitors patients' quality and accuracy of rehabilitation movements at home plays an essential role in the success of a patient's recovery process. With an inertial system, it is possible to obtain the knee angles, which can be evaluated in real-time. This information can be used not only to give feedback to patients about the exercises' execution, but also inform about the recovery progress, analyze if the recovery's expectations are being achieved and obtain a report about the evolution. In this way, the system has a very important role not only for the patients during the execution of the knee rehabilitation program at home, but also to the therapists who can obtain relevant information in order to control the recovery status and flexibly adjust rehabilitation programs [10].

As it can be seen, the development of an inertial system for being applied in home-based knee rehabilitation programs can be very useful and even fundamental.

Therefore, the objective of this dissertation is the development of an inertial sensor system capable of evaluating knee angles throughout the knee exercises rehabilitation execution at home and in real time, of patients who underwent a TKR surgery. This evaluation intends to give a feedback about the patient's exercises performance and also intends to analyze its progression, informing if the patient fulfil the criteria to progress for advanced phases of recovery and giving a report about the patient's evolution.

1.3 Dissertation Structure

This dissertation is organized in four chapters:

Chapter 1 – Introduction.

Chapter 2 – Background and Literature Review, the objective is to present an extended overview of the literature. This review covers the topics of lower limb anatomy, osteoarthritis, TKR, knee rehabilitation exercises and its effectiveness and the used methods for estimate knee kinematics.

Chapter 3 – KneeRecovery - Knee Rehabilitation Exercises Analysis System, the work developed in order to obtain the knee angle estimation will be described. There is a description of the methods implemented and how the system was evaluated, presenting and discussing its results and introducing future improvements.

Chapter 4 – Conclusions and Future Work, a description of what was achieved in this dissertation is shown and future developments are referenced.

Chapter 2

Background and Literature Review

Knee rehabilitation exercises involve many variables and the choice of appropriate ones requires basic knowledge about the lower limb and more precisely, the knee joint. Thus, an anatomical description of the lower limbs with great focus on knee is presented in this chapter, as well as the types of movements performed by the lower limb.

Since the need to perform knee rehabilitation exercises begins after a process of OA development, followed by TKR, a review about the disease and the common surgical procedure indicated is also presented in this chapter. Recovery from TKR is the next step. First, there is a phase of rehabilitation, which has to be adapted to the knee kinematics after TKR. So, a review about knee kinematics after the surgery and the effectiveness of rehabilitation exercises is presented, as well as a short description of others rehabilitation modalities applied. Since exercises therapy is the most common way of rehabilitation and is the main focus of this dissertation, a set of recommended exercises are shown. Then, inertial sensors are presented as an efficient option to estimate knee kinematics, as well as the way of representing object orientation, with emphasis on sensor fusion methods and quaternions. Finally, a set of variables capable of characterizing the knee kinematics evolution during rehabilitation exercises are presented.

2.1 Lower Limb Anatomy

In order to understand lower limb movements, it's of great importance to consider the body elements involved in this process. The lower limbs and its anatomical and physiological constitution are therefore the object of study in this section.

Bones, joints and muscles are three anatomical and physiological determinant factors for understanding lower limb movements. Bones and joints will be focused in this dissertation, since its concepts are fundamental to understand some contents that will be developed. The principle of a joint is the movement between two or more bones promoted by the muscles. Movement would not be possible without joints. However, not all joints provide motion, since the structure of a given joint is directly correlated with its degree of freedom (DOF). The knee joint joins the thigh with the leg (upper and lower part of the limb, respectively) [11]. To initiate this process of knowing the lower limb anatomy, next, the skeletal lower limb system is presented.

2.1.1 Skeletal System

Pelvic girdle and lower limb bones will be considered in this section. These bones (Figure 2.1) support the body and are essential for normal standing, walking and running [11].

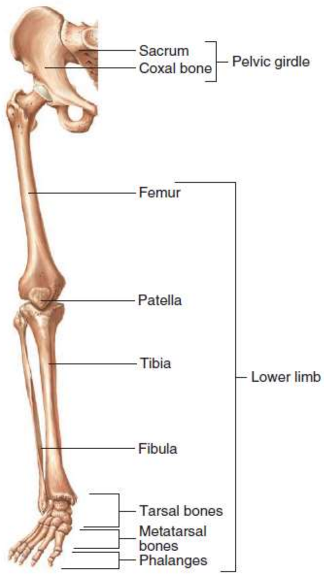


Figure 2.1: Anterior view of the bones of the right lower limb and pelvis [11].

The right and left coxal bones join each other anteriorly and the sacrum posteriorly to form a ring of bone called the pelvic girdle. The pelvis includes the pelvic girdle and the coccyx. Each coxal bone is formed by the fusion of three bones during development: the ilium, the ischium and the pubis. All three bones join near the center of the acetabulum, a fossa located on the lateral surface of each coxal bone and which is the point where the lower limb articulates with the girdle [11].

The thigh contains a single bone, the femur, which is the longest and strongest bone in the human body (Figure 2.2 a). Its upper extremity is composed of the head, neck, greater trochanter and lesser trochanter. The head of the femur articulates with the acetabulum of the pelvis to create the hip joint. The lower extremity is composed of the medial and lateral condyles, adductor tubercle, patellar surface and intercondylar fossa. It is larger than the upper extremity and articulates with the tibia and patella of the knee, forming the knee joint [11][12].

The patella, or kneecap (Figure 2.2 c) is a large bone located within the tendon of the quadriceps femoris muscle group, which is the major muscle group of the anterior thigh, forming part of the knee joint [11][12].

The leg is part of the lower limb between the knee and the ankle (Figure 2.2 b). It consists of two bones: the tibia and the fibula [11]. They are closely linked at the knee and ankle, but they are two separated bones [13]. The tibia is the larger of the two and has the function of support most of the leg's weight. The medial and lateral condyles articulate with corresponding femoral condyles at the knee. The fibula does not articulate with the femur but has a small proximal head where it articulates with the tibia [11].

The proximal foot consists of seven tarsal bones. The talus, or ankle bone, articulates with the tibia and the fibula to form the ankle joint. The calcaneus is the largest and strongest bone in the foot, it is located inferior to the talus and supports that bone. The metatarsal bones and the phalanges form the distal part of the foot [11].

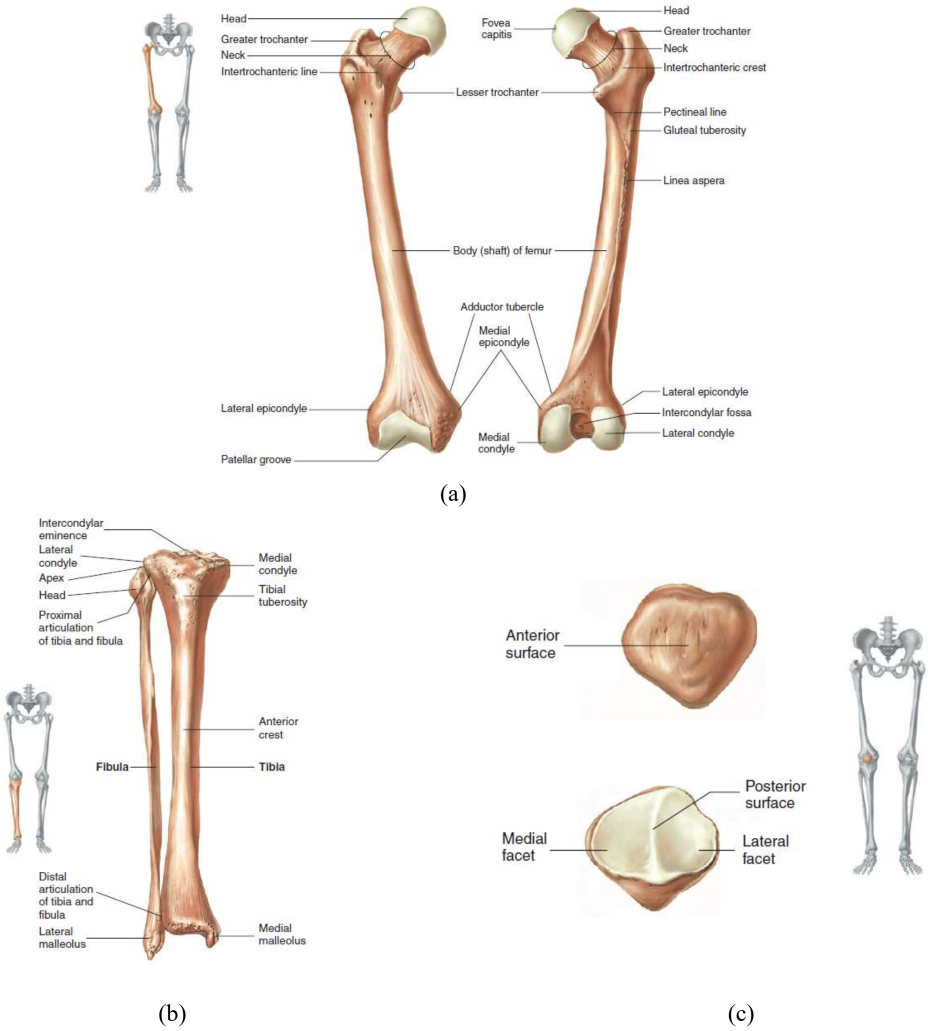


Figure 2.2: Right lower limb bones: (a) femur, anterior and posterior view (from left to right); (b) tibia and fibula, anterior view and (c) patella, anterior and posterior view (from top to bottom) [11].

2.1.2 Knee Joint

The knee joint is a synovial hinge joint located between the femur and the tibia. The illustration of a general structure of a synovial joint is represented on Figure 2.3, and the knee joint representation itself is presented on Figure 2.4. Actually, knee joint is a complex ellipsoid joint that allows flexion, extension, and a small amount of rotation of the leg. Like the other synovial joints, knee joint contains synovial fluid and allows the considerable movement between articulating bones. The articular surfaces of bones within synovial joints are covered with a thin layer of hyaline cartilage called articular cartilage, which provides a smooth surface where the bones meet. A meniscus is a fibrocartilage pad found in knee joints. It is much like an articular disk with a hole in the center. The circumference of the meniscus is attached to the fibrous joint capsule. The articular surfaces of the bones that meet the joint are enclosed within a synovial joint cavity, which is surrounded by a joint capsule. This capsule helps hold the bones together while still allowing for movement. The joint capsule consists of two layers: an outer fibrous capsule and an inner synovial membrane. Portions of the fibrous capsule may thicken, and the collagen fibers may become regularly arranged to form ligaments. In addition, ligaments and tendons may be present outside the fibrous capsule, thereby contributing to the strength and stability of the joint while limiting movement in some directions. The major ligaments that provide knee joint stability are the cruciate and collateral ligaments. Two cruciate ligaments extend between the intercondylar eminence of the tibia and the fossa of the femur. The anterior cruciate ligament prevents anterior displacement of the tibia relative to the femur, and the posterior cruciate ligament prevents posterior displacement of the tibia. The medial and lateral collateral ligaments stabilize the medial and lateral sides, respectively, of the knee. Joint strength is also provided by popliteal ligaments and tendons of the thigh muscles that extend around the knee [11].

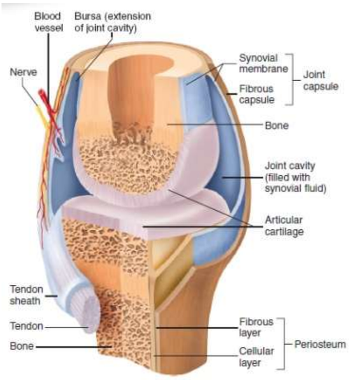
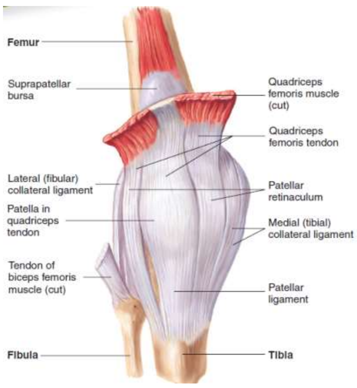
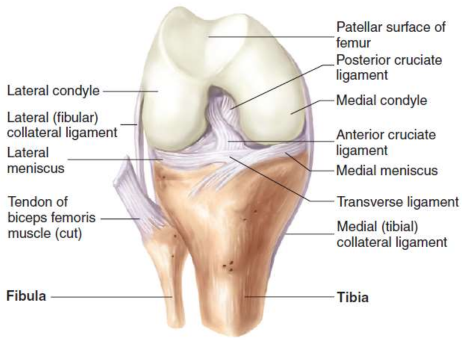


Figure 2.3: General structure of a synovial joint [11].



(a)



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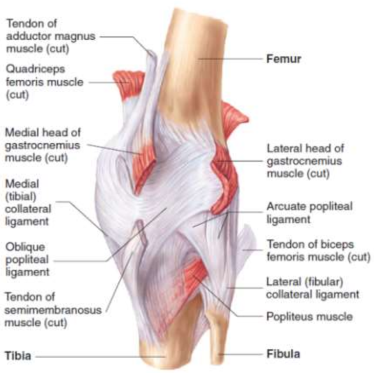

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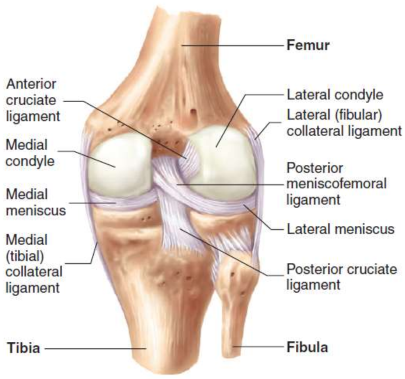
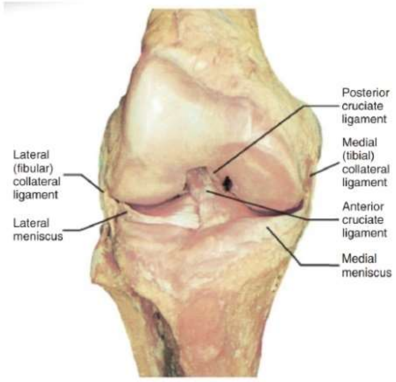
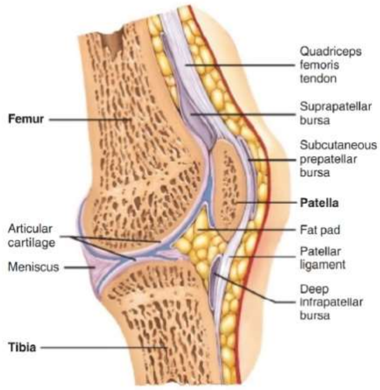


(d)

Figure 2.4: Right knee joint: (a) anterior superficial view; (b) anterior deep view; (c) posterior superficial view; (d) posterior deep view [11].



(e)



(f)

Figure 2.4: *(continued)* – Right knee joint: (e) photograph of anterior deep view; (f) sagittal section [11].

The synovial membrane lines the joint cavity, except over the articular cartilage. The membrane produces synovial fluid, a thin, lubricating film that covers the surfaces of the joint. Synovial fluid consists of a serum (blood fluid) filtrate and secretions from the synovial cells [11].

In knee joint, the synovial membrane extends as a pocket, or sac, called a bursa, for a distance away from the rest of the joint cavity. Bursae contain the synovial fluid and provide a cushion between structures that would otherwise rub against each other, such as tendons rubbing on bones. The largest is the suprapatellar bursa, which allows the anterior thigh muscles to move over the distal end of the femur. The knee bursae include the subcutaneous prepatellar bursa and the deep infrapatellar bursa, as well as the popliteal bursa, the gastrocnemius bursa, and the subcutaneous infrapatellar bursa [11].

A joint's structure relates to the movements that occur at that joint [11]. Next, the three main movements executed in knee rehabilitation exercises are presented.

2.1.3 Movements

The lower limb is modeled as a sequence of four rigid links connected by three universal rotary joints representing the hip, knee and ankle joints. Each joint is modeled as a sequence of three single axis rotational joints thus ascribing to the lower limb a total of twelve DOF [14].

Flexion and extension are common opposing movements. Flexion moves (bends) the leg in a posterior direction, and extension moves (straightens) it in an anterior direction [11].

Abduction (to take away) is movement away from the midline. Adduction (to bring together) is movement toward the midline[11].

Rotation is the turning of the lower limb around its long axis. It's a circular movement [11].

ROM describes the amount of mobility that can be demonstrated in a given joint. Active ROM is the amount of movement that can be accomplished by contracting the muscles that normally act across a joint. Passive ROM is the amount of movement that can be accomplished when the structures that meet at the joint are moved by an outside force, as when
a therapist holds on to a patient's leg and moves it toward the thigh, flexing the knee joint. The active and passive ranges of motion for normal joints are usually about equal [11].

There are some factors that influence the ROM of a certain joint: shape of the articular surfaces of the bones forming the joint; amount and shape of cartilage covering those articular surfaces; strength and location of ligaments and tendons surrounding the joint; strength and location of the muscles associated with the joint; amount of fluid in and around the joint; amount of pain in and around the joint and amount of use and disuse the joint has received over time [11].

2.2 Osteoarthritis

Osteoarthritis is the most common form of arthritis. According to the Osteoarthritis Research Society International (OARSI), OA is defined as a disorder that involves movable joints characterized by cell stress and extracellular matrix degradation initiated by micro- and macro-injury that activates maladaptive repair responses including pro-inflammatory pathways of innate immunity. The disease manifests first as a molecular derangement (abnormal joint tissue metabolism) followed by anatomic, and/or physiologic derangements (characterized by cartilage degradation, bone remodeling, osteophyte formation, joint inflammation and loss of normal joint function), than can culminate in illness [15].

OA can affect all the tissues of the joint, including the cartilage, bone, ligaments and muscles. Typically, this disease occurs later in life, usually after age 50, although it may start earlier in the case of joint injury [16]. Factors as age, gender, obesity, joint injury, joint abnormalities, genetics and abnormal mechanical loading in various sports activities or during heavy work are aspects that can increase the risk of OA [2][17].

The progression of OA may be charted by comparing a normal healthy joint with an osteoarthritic joint (Figure 2.5). In a healthy joint, protective cartilage caps the ends of joint bones. Around the bones and cartilage there is a further protective "wrapping", the synovial membrane which contains synovial fluid that allows cartilage-capped joint bones to glide smoothly for pain-free ROM [16].

In contrast, when a joint develops OA, some of the cartilage covering the ends of the bones gradually roughens and becomes thin, less elastic, more brittle and the bone underneath thickens [16][18]. All the tissues within the joint become more active than normal, since the body is trying to repair the damage:

- The bone at the joints edge grows outwards, forming bony spurs called osteophytes.
- The synovial membrane may thicken and produce extra fluid and consequently, it may cause the joint swelling.
- The capsule and ligaments (tough bands that hold the joint together) slowly thicken and contract as if they were trying to make the joint more stable [18].

Early in the disease process, the body has resources to repair detrimental changes within an OA joint. However, as the disease progresses, the body's repair system can no longer keep up with these processes. The cartilage becomes so thin that it doesn't cover the ends of bones. These ones rub against each other and start to wear away. The loss of cartilage, the wearing of bone and the bony spurs can change the shape of the joint, forcing the bone out of their normal position [16][18].

The main symptoms of OA of the knee can vary in severity, but in its severe forms, OA is a painful condition that restricts mobility. It may cause a feeling of stiffness after rest and crepitus, a creaking, crunching sensation at the same time as the joint moves. The swelling may be hard (caused by osteophytes) or soft (caused by synovial thickening and extra fluid). The knees become bent and bowed and the muscles around the joint may look thin or wasted [19].

Knee OA has a big impact in patient's daily life, becoming more difficult the performance of normal everyday activities, such as walking or climbing stairs. It is a major cause of lost work time and a serious disability for many people.

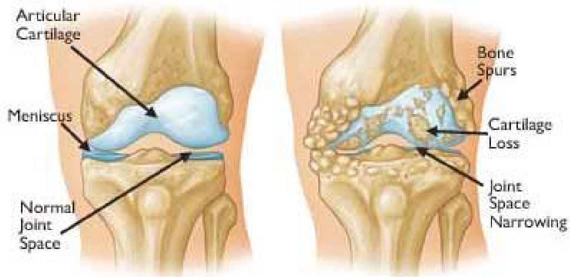


Figure 2.5: Anatomic comparison between a normal knee (left) and a knee with OA (right) [20].

2.3 Total Knee Replacement

Total Knee Replacement is a commonly performed surgical procedure indicated for patients affected by severe knee OA. Orthopedic surgeons began performing TKA in the 1970s. Today it is a commonly performed surgical procedure that is beneficial to a majority of patients and is cost effective for quality of life assessments [21]. The aim of TKR is the re-establishing of joint function and mobility and the alleviation of pain [22] with a stable prosthesis that is well fixed. This is achieved by bone resection, soft tissue balance [23] and replacement of the bone damage parts with a knee prosthesis.

2.3.1 Knee Prosthesis

The knee prosthesis is usually composed of three components, femoral, tibial and patellar components (Figure 2.6). The femoral component is made of metal, generally in cobalt-chrome alloy, and it is fixed to the distal femur. The femoral component mimics the anatomy of the distal femur and presents an asymmetrical flange, reproducing the patellar groove and avoiding possible patella dislocation. The tibial component is typically a flat metal platform with a polyethylene insert. It is usually stabilized through a short stem which is fitted into the tibial bone. Between these two metal components there is a polyethylene insert as the bearing surface, the patellar component, which replicates the kneecap surface [22][24].

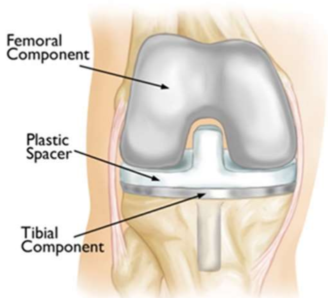


Figure 2.6: TKR prosthesis [24].

2.3.2 TKR Operative Procedure

TKR is a complex process, which requires an orthopedic surgeon to make precise measurements and skillfully remove disease portions of the bone, in order to shape the remaining bone to accommodate the knee implant. The surgeon builds an artificial knee inside the leg, creating a highly realistic artificial joint [25].

The first step consists in making the knee incision to get access to the patella [25]. Usually, a large open incision is performed to safely permit both exposure of the articular surfaces and dislocation the patella without damage to the collateral ligaments or extensor apparatus [26]. However, this conventional way of performing total knee surgery leads to greater blood loss and has the potential for inaccuracy. So, a less invasive TKR surgery can be performed with a smaller incision. The disadvantages of minimally invasive TKR are related to the restricted visibility resulting in tibial component malalignment and a higher early failure rate [22]. Once the knee is open, the patella is the first knee part exposed and the one which the surgeon will rotate outside the knee area, allowing the area need visualization to perform the surgical intervention. The surgeon starts for resurfacing the femur. For that, careful measures and precise cuts are done in the bones. The damaged bone and cartilage from the end of the femur is cut away. The end of the femur is cut and resurfaced to fit the first part of the artificial knee, the femoral component. Next step consists in introducing the femoral component implant, attaching the metal part to the end of the femur, finalizing with cement addition to seal these both elements. The following bone to resurface is tibia. As previously done in the femur, the damage bone and cartilage from the top of the tibia is removed in order to shape it to the metal and plastic tibial components. Once the tibia is prepared, the tibial component is fitted to this bone and secure into place through the bone cement. Once the tibial component is in place, the surgeon will snap with a polyethylene (medical-grade-plastic) insertion to sit between the tibial and the femoral components, and act as a kind of buffer. This step is important, since its function is to support the body, allowing bending and flexing the knee. Next, the patella will need to be adjusted, fitting it with an additional plastic component, using cement, in order to ensure a proper fit with the rest of the implant. Before finalizing, the surgeon needs to ensure that the implant is working as expected, and that alignment, sizing and positioning is suitable. With this purpose, the surgeon bends and flexes the knee. Then, the incision needs to be closed with stitches or staples [25]. After the surgery, the small incisions will be covered with a bulky dressing and knee immobilizer. The surgeon usually puts a local anesthetic in the knee at the time of surgery for pain relief after surgery, which lasts for about six or eight hours [27].

The average hospital stay after TKR is usually one to four days, depending on the recovery speed [9]. Most patients leave the hospital using a front-wheeled walker, which should be used until muscle knee strength returns. When the patient feels strong enough to walk without the assistance of the walker, a cane can be held in the hand opposite to the replaced knee. These two assistive devices should be used for the first six weeks after the surgery [28].

2.4 Recovery from TKR

Outcomes following TKR remain dependent on the adequacy of rehabilitation and subsequent functional recovery following surgery [29]. Understand the evolution that occurred in the knee, the improvements achieved or the limitations that still remain, when comparing with healthy joints are an important step that will help clinicians to perform the best rehabilitation program and to the patients approach and develop their normal knee kinematics patterns. Some conclusions obtained by studies that compared knee kinematics before and after TRK are described in section 2.4.1 and they help to understand that the normal knee function is not obtained in the following months. These same results support the idea that an integral and routine intervention following TKR directed toward restoring knee functions is an important step to help patients to recover their normal activities.

Besides exercise therapy is the most common way of rehabilitation and there are clinical effectiveness proves, some studies question the truly efficacy of this kind of therapy. So, an investigation of exercise therapy success is performed, as well as the investigation of other rehabilitative modalities currently available are done in sections 2.4.2 and 2.4.3, respectively. The effectiveness of this kind of exercises is essential to know the best way to help the patients to achieve their normal daily activities. In section 2.4.4 there is also a set of common exercises, suggested by a guide plan.

2.4.1 Knee Kinematics after TKR

In most cases, TKR surgery relieves pain and makes possible to perform daily activities more easily. Despite experiencing significant reductions in pain, many TKR patients do not achieve normal joint function when walking following surgery. Several studies refer changes in joint kinematics and gait analysis patterns after TKR compared to healthy control subjects[1] [30][31][32][33][34][35].

After surgery, patients spent a decreased percentage of time in single-limb stance[2] and had abnormal sagittal plane knee motion, with decreased flexion and ROM during walking [22][36]. Shorter stride length[3], reduced mid-stance[4] knee flexion and abnormal patterns of external flexion/extension moment of the knee are also verified [30].

The results of a study that had investigated the knee kinematics three months after TKR showed that after this range of time, patients already improved their normalized stride and step length, but not their gait speed. Furthermore, the patients' gait velocities were always slower than the control group at their comfortable speeds. Thus, all spatio-temporal parameters in the patient group remain below the normal values at three months after surgery. In relation to kinematics of the operated limb, the results showed that the knee function during gait is not yet restored three months after TKR. Patients walked with significantly less knee extension during the stance phase, which can be linked to the flexion deficit and lack of muscular control and strength. In general, patients demonstrated decreased knee movement in the sagittal plane compared to the control group, with a decreased in knee flexion range during the loading response[5] and a decreased in

[1] Healthy subjects are considered to have normal walking pattern, no injuries and a similar age to the patients with TKR.

[2] Single-limb stance: phase within the gait cycle during which the body mass is carried by a single limb [81].

[3] Stride length: distance between two successive placements of the same foot, consisting of two step lengths [82].

[4] Mid-stance: gait period between foot flat and heel off, or the time at which the swing phase leg passes the stance phase leg and both feet are side by side [83].

[5] Loading response: the doubled supported period of time in gait when the whole foot is on the ground. It ends when the opposite foot rises. The weight of the body shifts between the legs [84].

knee ROM during the gait cycle. It was also observed that, in the coronal plane, the patients walked with less knee adduction/abduction misalignment during the stance phase of the gait after TKR, suggesting that the knee alignment in the coronal plane was restored. The knee pain level after TRK procedure was also reduced, indicating a positive effect of the surgery on the patients' pain. A decreasing symmetry was observed, which means that the kinematic changes induced by the prosthesis cause a significant imbalance between the operated and non-operated limbs during the early stages after surgery in terms of the step length, knee ROM and maximal extension during stance phase. Therefore, it is possible that the non-operated limb is used more by the patients to protect their new prosthetic joint during walking and to avoid pain, increasing the dependence on this limb [6].

Another study investigated the knee kinematics of patients who have undergone TKR when walking at self-selected comfortable and fast speeds, twelve months after the surgery, comparing these findings to a control population. In this study, differences in the knee kinematics between TRK patients and controls were also verified in both the sagittal and transverse planes, and these differences indicate that knee kinematics are not restored to normal, twelve months after TKR. In the sagittal plane, the TKR group walked with reduced knee flexion during the stance and swing phases of gait. It was also reported that the patients continue to walk with less knee extension during stance phase than controls. TKR group walked with significantly reduced cadence (steps per minute) and reduced stride (long steps) length. This study also allowed to conclude that TKR patients walked with greater external knee rotation and less internal knee rotation than controls, which suggests that TKR patients walk with a knee that is offset into more external rotation than controls. This conclusion approximates from the decreasing symmetry also verified three months after the surgery [5].

These investigations conclude that following TKR, patients present knee kinematics that are different to a control population, which means the need of a recovery plan that focuses on retraining the knee kinematics. So, a better understand of the evolution, impairments and functional knee limitations following surgery is very useful and helps clinicians designing more specific rehabilitation programs, the phase after the surgery [6].

2.4.2 Rehabilitation Effectiveness

Rehabilitation, with a particular emphasis on physiotherapy and exercise is widely advocated and provided as a standard of care for patients with TKR [7]. Physiotherapy is defined as the process by which movement and physical function are treated when an individual experiences some injury [37].

During the hospital stay, physiotherapy targets mobilization and achievement of functional goals relating to hospital discharge. Further post-discharge physiotherapy and exercise-based interventions promote re-training and functional improvement [38], with a great focus on recovery knee ROM, restoration of knee muscle strength and performance, development of functional independence and ability to participate in daily activities, thus improving the patient's quality of life [37]. These functions are usually reported by patients to evaluate and assess postoperative, and therefore, are often the focus of rehabilitation. Without rehabilitation, functional independence and activity levels may not be recovered [29].

In fact, rehabilitation exercises at home are a trend of the future because of the aging population and limited funding for public health care [39].

However, not all the studies show guaranties of the rehabilitation effectiveness. The following references have reached a common conclusion: effectively rehabilitation shows short term[6] improvements in physical functional, while in long term[7], benefits are not identified.

The first reference that shows this conclusion searched evidences for effectiveness of multidisciplinary rehabilitation[8] following TKR. Its results did not identify studies that provided direct evidence that multidisciplinary rehabilitation following TKR achieved better outcomes compared with no treatment. However, this same reference found good level evidence that early and/or organized multidisciplinary rehabilitation led to more rapid attainment of functional milestones in short term, as well as fewer post-operative complications and shorter hospital stay. For multidisciplinary rehabilitation at home, there was no home care improving quality of life in medium-term[9] and disability in persons following TKR [40].

Another report mentioned that physiotherapy and exercise interventions after TKR provide some evidence for short term effectiveness. Comparing patients who received a programme of physiotherapy exercise with those receiving no intervention there were short term benefits for physical function and pain. No benefit was apparent regarding longer term improvements [38].

Still another study referred that rehabilitation attendance post-TKR was associated with an increase in self-report physical function. Among patients who attended rehabilitation, a modest-response relationship was observed between the number of sessions and functional outcomes [7].

An important problem that home-based physiotherapy exercise may address is that uptake of rehabilitation is frequently low and that patients who do not attend are more likely to be those with poorer functional health. A review reported show term evidence of effectiveness of exercise adherence strategies and little evidence that home-based interventions are associated with good adherence. Optimizing uptake and adherence to interventions are important issues in rehabilitation [38] and overcoming this issue can be a step in the right direction to obtain better results in long term rehabilitation effectiveness.

By the other side, rehabilitation following TKR continues to pose a challenge for both patients and providers. In addition, guidelines vary considerably between institutions, which often leave therapy regimens to the discretion of the provider [29]. Little information is available describing content of physical therapy services following TKR although there is consensus for the need to increase strength and knee ROM [41].

The lack of clear guidelines for rehabilitation may contribute to inadequate recovery of strength and ROM, resulting in less optimal functional outcomes [29].

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[6] Short term: up to four months [40].

[7] Long term: up to twelve months [40].

[8] Multidisciplinary rehabilitation: Rehabilitation programme delivered by two or more disciplines, and target towards improvement at the levels of mobility or participation in daily live activities, or both. These programs can include elements of medical, nursing, physical therapy, occupational therapy, social work, psychology, orthotics, recreation and vocational therapy [40].

[9] Medium-term: up to six months [40].

2.4.3 Rehabilitative Modalities

Nowadays, there are several modalities applied after TKR to regain strength and function, such as physical therapy, aquatic therapy, ice/compression, transcutaneous electrical nerve stimulation (TENS), neuromuscular electrical stimulation (NMES) and instrument-assisted soft tissue therapy [29]. Its main functions are variable: some are better suited to relieve pain, others are used to increase strength or to improve knee biomechanics.

Exercise Therapy

Exercise Therapy refers to performing repeated movements as part of a goal directed training program, specifically directed at altering some physical or physiological characteristic and enhancing overall functional ability [37]. This therapy plays an important role in postoperative rehabilitation of patients after TKR. The primary purpose of exercise therapy is to maximize ROM, improve strength and pain and to normalize gait mechanics. For reach these goals common elements in post-TKR exercise therapy include, but are not limited to: passive knee ROM exercises, lower extremity stretches (for the quadriceps, hamstrings and calf muscle), ice/heat application, gait training and functional training [29].

Aquatic Therapy

The concept of aquatic therapy is based on the idea that the buoyancy of water attenuates the effects of gravity, decreasing shear, and compressive forces in joints, which may allow patients to experience some relief of pain. In addition, the water resistance improves strength, particularly as its intrinsic property to resist movement’s increases with speed. This may be more advantageous in the early postoperative phase when patients are limited by pain, so these kind of therapy programs can begin anywhere from four days to eighteen months after TKR. Typical exercises include ROM stretches for the knee, single leg balance, mini-squats, cycle kicks and leg swings [29].

Balance Training

Balance training may be supplemented into therapy sessions in an effort to restore joint proprioception and postural control. Patients often have impaired balance after TKR as a result of ligamentous damage that alters mechanoreceptors. This has consequences on joint proprioception and posture control, which influences knee stability. These deficits affect the ability of patients to perform activities such as twisting, pivoting, walking on uneven surfaces and changing direction. To aid with this, balance training may be employed, which includes lower extremity ROM exercises and functional task-oriented exercise with resistance bands, side stepping, tandem walk and use of a tilt board or balance beam [29].

Continuous Passive Motion (CPM)

CPM is a machine that repeatedly provides passive movement of the knee joint through a controlled ROM and has been a frequent modality in the recovery of TKR patients. This procedure has healing effects on articular cartilage and ligaments, as well as decreases the length of hospital stay, improves ROM and leads to fewer circulatory complications. With the use of CPM, the patient should have the capability of achieve at least 0 to 90 degrees ROM upon hospital discharge and 0 to 120 degrees upon conclusion of postoperative rehabilitation [29].

Cold Therapy and Compression

The aim of using cold therapy (or cryotherapy) and compression after TKR is essentially moderate pain, swelling and inflammation of the affected joint. This procedure is applied at the end of each therapy session due to its positive effects on inflammation, edema and pain relief. These effects are possible, since the metabolic activity of local tissues decreases and vasoconstriction of the perioperative tissues is induced. The leukocyte migration is also reduced and nerve signal transmission is attenuated, producing a temporary anesthetic and analgesic effect. External compression intends to prevent edema by increasing interstitial pressure and reducing the flow of fluid into the interstitial space [29].

Neuromuscular Electrical Stimulation (NMES)

Patients who are unable to voluntarily activate the quadriceps muscle immediately after TKR may benefit from early intervention with NMES. The concept of this therapy is the use of dosed electrical currents delivered through cutaneous electrode pads to stimulate muscle contraction, which may potentiate the muscle strength and functional performance, by overriding deficits in muscle activation caused by central nervous system impairments. In this process, a greater proportion of type II fast-twitch muscle fibers exists, which generates higher levels of force production and may correspond to better functional performance and recovery [29].

Transcutaneous Electrical Nerve Stimulation (TENS)

TENS is a device in which adhesive electrodes are placed on the skin, sending controlled electrical impulses to local sensory nerves. It acts as an analgesia mechanism, so it is used to relieve pain. This capacity is achieve since TENS acts on central and peripheral nervous system mechanisms to promote an analgesic effect [29].

Instrument Assisted Soft Tissue Therapy

Instrument-Assisted Soft-Tissue Therapy is a noninvasive technique that stimulates the regeneration of soft-tissue through the application of pressure to the affected area. This helps in fibroblast recruitment and activation from dysfunctional capillaries, which stimulates the endogenous release of growth factors and cellular mediators, leading to tissue regeneration [29].

2.4.4 Rehabilitation Exercises

Since the exercise therapy plays a fundamental role in the postoperative rehabilitation and it is the traditional used method, next a set of exercises proposed by [28], in different recovery steps are presented.

Phase 1 – Immediate Post-operative phase
This phase goes from the first postoperative day through 2 weeks.

Straight Leg Raising Exercise

The patient lies on his/her back with the operative leg straight. The non-operative knee is bent to reduce pressure on the low back. The patient performs a quadriceps setting exercise (he/she tightens the quadriceps muscle on top of the thigh by pressing the knee straight down into the bed) to fully straighten the knee. The leg is kept completely straight and the hip is bended, so the operative leg rises from the bed to reach the level of the opposite knee. The leg is held for 3-5 seconds and then is lowered slowly. This exercise is depicted in Figure 2.7. 2-3 sets of 10 repetitions each should be executed, 3-5 times daily.

Figure 2.7: Straight Leg Raising Exercise example [28].

Sidelying Hip Adduction Exercise

The patient lies on his/her knee replacement side with the opposite foot placed on the bed either in front (or behind) the operative leg (the operative leg should be on the bottom). The patient tightens the muscles on his/her inner thigh and lifts the operative leg off the bed towards the ceiling as high as possible. The position should be held at the top of the exercise for 5 seconds. Then, the leg is slowly lowered. This exercise is depicted in Figure 2.8. 2-3 sets of 10-20 repetitions should be executed, 3 times per day.

Figure 2.8: Sidelying Hip Adduction Exercise example [28].

Standing Hip Abduction Exercise

The patient stands and holds on to a solid object for balance and support. The operative leg is raised out to the side and slightly backwards. The leg is held for 3 seconds and slowly lowered. 2-3 sets of 10-20 repetitions should be executed, 3 times daily. After each set, the patient stands on the operative leg with the replaced knee joint as straight as possible when bearing weight solely on this leg. This exercise is depicted in Figure 2.9.

Figure 2.9: Standing Hip Abduction exercise example [28].

Long-Arc Knee Extension Exercise

The patient sits on the edge of the bed or chair. With the knee bent at a right angle off the bed/chair, the patient straightens the operative knee as fully as possible and holds for 5 seconds. This exercise is depicted in Figure 2.10. 3 sets of 10-15 repetitions should be executed, 3 to 5 times per day.

Figure 2.10: Long-Arc Knee Extension Exercise example [28].

Phase 2 – Motion Phase
This phase goes from the week 2 through week 6.

Hip Extension Exercise

The patient lies on his/her stomach in bed and raises the operative leg straight up towards the ceiling. The leg is lifted just to the point in which the kneecap leaves the bed and no higher. This exercise is depicted in Figure 2.11. 2-3 sets of 10-20 repetitions should be executed, 3 times daily.

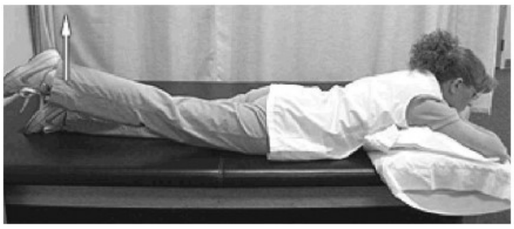


Figure 2.11: Hip Extension Exercise example [28].

Phase 3 – Intermediate Stretching and Strengthening Phase
This phase goes from the week 7 through week 12.

Prone Quadriceps Stretch

The patient lays the stomach in bed with 2-3 pillows under the abdomen. A belt or tie-down is strapped around the ankle of the operative knee. A towel should also be placed under the operative knee to raise the level of the knee above the hip joint. The patient tightens the stomach muscles and bends the knee until feels a stretch in front of the thigh. Then, he/she pulls on the belt attached to the ankle until feels an intense stretch, holding for 30 seconds. This exercise is depicted in Figure 2.12. The exercise should be repeated 10 times, 2-3 times per day.

Figure 2.12: Prone Quadriceps Stretch example [28].

Single Leg Balancing

The patient stands with feet shoulder width apart and bears full weight through the operative leg with the knee completely straight. Then, he/she brings the opposite knee upwards towards the ceiling by bending at the hip to balance on the operative leg, balancing for 10 seconds. This exercise is depicted in Figure 2.13. A comparison between the non-operative and the operative sides allows determining balance differences.

Figure 2.13: Single Leg Balancing Exercise example [28]

2.5 Knee kinematic estimation method during rehabilitation exercises

Recent years have witnessed an increasing demand for more efficient health care delivery which has resulted in an increase in home based rehabilitation. However, rehabilitation exercises performance at home cannot be an easy task. The absence of a therapist may allow that patients execute their exercises incorrectly, because of incorrect alignment, incorrect speed of movement or poor quality of movement. These facts may have a negative impact on the exercise efficacy and may therefore result in a poor outcome [8].

Several solutions have been explored in which technology can be used to enhance home exercise by providing essentially feedback to patients. Biofeedback systems have been acquired, since they are able to provide relevant information on exercise technique and accuracy, allowing patients to identify if they are performing correctly the movements, in real-time. Electromyography and real-time ultrasound biofeedback were considered an interesting option in rehabilitation. However, these systems are expensive and need an operating expertise, which difficult its use at home. Nintendo Wii and Kinect from Microsoft have shown interest by the consumers of rehabilitation tools, mainly because they are inexpensive alternatives, which can be operated at home. The idea behind Nintendo Wii is a wireless, accelerometer-enable controller, which is held by the user to track their movement. Wii Fit uses a balance board to measure movements. The disadvantage of these systems in rehabilitation exercises context is that they can only measure gross body movements and do not have the capability to track all the subtle movements performed during rehabilitation exercises. The Kinect consist of an RGB (red-green-blue) camera and a depth sensor, which provide full body three-dimensional (3D) motion capture and joint tracking capabilities. The Kinect accuracy decreases as the distance from the camera increases, and it also struggles with occluding body parts or objects in the scene, which represents a big disadvantage to its use at home rehabilitation [8].

An alternative to these technologies for the estimate of joint kinematics is the using of inertial sensors [9]. Many successful examples exist in the literature for the applications of inertial sensor-based systems in the measurement of a variety of kinematic variables and related parameters to analyze information about the mechanics of human's motion and activity.

The small size and unobtrusive nature of these sensors make them an ideal solution to measure movement and therefore deliver feedback to patients as they perform their exercises [8].

Depending upon their application, inertial sensors are generally embedded with Bluetooth/wireless transmitters or SD cards for a real-time data streaming or non-board for long term data recording, respectively. Inertial sensors can be fixed on a single body segment, or a network of two or more inertial sensors can be used to retrieve data from multiple body segments asynchronously so that knee kinematics can be estimated [9].

In addition, the low cost and the usability of these sensors have resulted in a number of researchers developing inertial sensor-based systems to address the problems associated with home exercise therapy proposed to aid rehabilitation [8].

Inertial sensors are described below, and due to their advantages, they have been widely used for estimating joint kinematics. Taking into account the main objective of this dissertation, an algorithm that uses inertial system will be developed in order to be applied by any patient during knee rehabilitation exercises performance at home, obtaining information about knee kinematics and in this way, understand the evolution of patient's recovery and if the patients are executing the exercises correctly or not.

Next section will enable a better understanding of how an Inertial Measure Unit (IMU) operates through its inertial sensors and how it will be applied to determine a set of knee biomechanics characterizing variables.

2.5.1 Inertial Measurement Unit

The first study which formalized the problem of estimating joint kinematics by using inertial sensors dates back to 1990. Since then, a variety of methods have been presented throughout 25 years for the estimate of 2D (two dimensional) and 3D joint kinematics by using wearable inertial sensors [9].

Inertial systems are normally a family of sensors represented by accelerometers, gyroscopes and magnetometers. The term "inertial" refers to the fact that this typology of sensors is able to measure their movement (or the movement of a rigid body to which the sensor is fixed) by exploiting the reluctance of a free mass to move (inertia) when contained in the sensor, while the latter is accelerated by an external force (accelerometer) or is rotated by a force couple system (gyroscope) [9] or directed by the magnetic field (magnetometer).

IMU is a device which usually contains two sensors: accelerometer and gyroscope.

Next, a brief description of each sensor is described.

2.5.1.1 Accelerometers

Accelerometer is a three axis sensor which provides acceleration measurements in meters per second squared (m/s^2) along each of x, y, z axes [42]. Accelerometers respond to gravity as well as to their acceleration, and it can be used to estimate the inclination of a body segment, body sway, or for measuring activities levels. However, accelerometers have some limitations such as noisy signals and difficulties in estimating the gravity vector accurately during dynamic movements because the movement itself also contributes to the acceleration measurement, not just gravity [39]. The most important source of error of an accelerometer is the bias. The bias of an accelerometer is the offset of its output signal from the true value. It is possible to estimate the bias by measuring the long term average of the accelerometers output when it is not undergoing any acceleration [42].

2.5.1.2 Magnetometer

Magnetometer sensor measure the magnetic field in micro Tesla (μT) in x, y, z axis. It can be used in combination with accelerometer to find the direction with respect to North when linear acceleration is zero. The main source of measurement errors are magnetic interference in the surrounding environment and in the device [42].

2.5.1.3 Gyroscope

Gyroscope sensor provides the angular velocities in radians per second (rad/sec) along each of three axes. It can be used to get the correct orientation of the device while in motion. If there is a magnetic interference in the surrounding environment, the heading calculated from the magnetometer is not accurate. Moreover, x and y axes calculated from accelerometer sensor are only accurate when mobile is stationary or its acceleration is zero. In this situation, gyroscope can be used to get the correct orientation. But the problem with gyroscope is that there are bias and numerical errors.

The bias of a gyroscope is the average output from the gyroscope when it is not undergoing any rotation (i.e.: the offset of the output from the true value). The gyroscope bias shows itself, after integration as an angular drift, increasing linearly over time. Another error arising in gyroscope is the calibration error, which refers to errors in the scale factors, alignments, and linearities of the gyroscope. Such errors are only observed whilst the device is turning and they lead to the accumulation of additional drift in the integrated signal, the magnitude of which is proportional to the rate and duration of the motions [42].

2.5.2 Sensor Fusion for Orientation Estimation

In geometry, the orientation, also called angular position or attitude, of an object, such as a line, plane or even a human body, is part of the description of how this object is placed in space [43]. By combining the information provided by the IMU, through sensor fusion methods, one is able to calculate and estimate the orientation of an object [44]. The task of an sensor fusion filter is to compute a single estimate of orientation through the optimal fusion of gyroscope, accelerometer and magnetometer measurements [45]. Sensor fusion methods combine sensory data or data derived from sensory data in a way that should ideally give better performance than that achieved when each source of information is used alone. The design of systems based on sensor fusion methods requires the availability of complementary sensors in order that the disadvantages of each sensor are overcome by the advantages of the others [46][47]. The achievements of sensor fusion are robustness, extended spatial and temporal coverage, increased confidence, reduced ambiguity and uncertainty, and improved resolution [47].

If the gyroscopes would provide perfect measurements of the IMUs turn motions, then simple integration of the gyroscope’s signal would give the attitude. But since IMUs gyroscopes suffer substantially from noise and drift, other sensors like accelerometers and magnetometers are needed to correct this imperfectness. So to get the best estimate of the IMU attitude, a sensor fusion algorithm is needed to combine the measurements from the different sensors [48] and to provide a more useful result which combines the strengths of each sensor.

2.5.3 Attitude Representation

The goal of an attitude determination algorithm is to determine the orientation of an object with respect to a reference frame. So two orthogonal coordinate frames are considered [48]:

- **Earth Reference Frame** – The earth frame E is represented by the orthogonal vector basis $\{x_0, y_0, z_0\}$ and is attached to the earth. Thereby x_0 points north, y_0 points east and z_0 points toward the center of earth as shown in Figure 2.14 [48]. This coordinate system is always static independently of the orientation of the body [44].

- **Sensor Reference Frame** – The sensor frame S is fixed to the object whose attitude we want to represent. This frame is fixed to the sensor, but varies relative to the Earth reference frame due to the sensor movement [44].

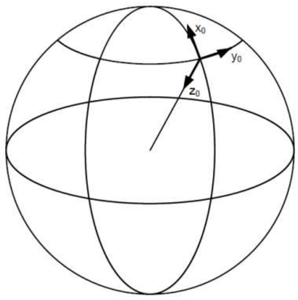


Figure 2.14: Earth Reference Frame [48].

In the literature there are different ways of representing the attitude between two coordinate frames and to transform vectors and coordinates from one coordinate frame to another one [48]. Euler angles, rotation matrixes and quaternions are three main mathematical constructs used to represent the attitude of a rigid body in 3D space [49].

Euler Angles

Euler angles are a set of three angles used to specify the orientation (or change in orientation) of an object in 3D spaces. Each of the three angles in an Euler angle triplet specifies an elemental rotation around one of the axes in a 3D Cartesian coordinate system (Figure 2.15) [50]. The rotations around the axes z, y and x are the rotation angles yaw, pitch and roll, respectively [51].

Euler angles are popular because they are easy to use and they provide a certain level of intuitive understanding. However, they also have some disadvantages [49]:

- Singularities: the singularities found in the various Euler angle representations are said to arise from gimbal lock. Intuitively, gimbal lock arises from the indistinguishability of changes in the first and third Euler angles when the second Euler angle is at some critical value. Take, for example, the (1,2,3) sequence. When the pitch angle is 90 degrees, the object is pointing straight up, and roll and yaw are indistinguishable [49].
- Ambiguity: for large angles, the rotation sequence becomes critical. For example, for a given set of three Euler angles, the result of a (1,2,3) sequence is very different from that of a (3,2,1) sequence [51].

- Euler angles are less accurate then unit quaternions when used to integrate incremental change in attitude over time [49].

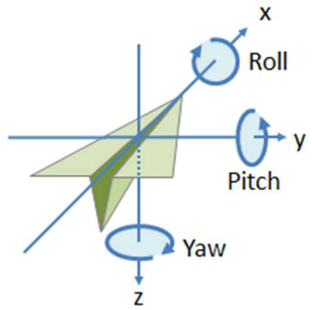


Figure 2.15: Euler angles axes [50].

Rotation Matrixes

A rotation matrix is composed of nine numbers arranged in a 3x3 matrix:

$$R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \quad (2.1)$$

Unlike Euler angles, rotation matrixes require no assumptions about the order of elemental rotations. A given rotation can be described by many different sets of Euler angles [50]. For each type of roll, there is a corresponding rotation matrix, i.e. a x rotation matrix, a y rotation matrix and a z rotation matrix. The matrixes rotate by multiplying them to the position vector for a point in space, and the result is the position vector for the rotated point [52]. The rotation depends on the order of elemental rotations. But for any given rigid body rotation, there is one and only one rotation matrix [50].

Rotation matrixes present a main disadvantage of being computationally expensive.

A common strategy for dealing with the main problems of Euler angles and rotation matrixes is the use of quaternions. Because of their simplicity, mathematical elegance and lack of singularities, quaternions are a very popular representation for encoding the attitude of a rigid body, however they also have disadvantages: the four quaternion parameters do not have intuitive physical meanings and a quaternion must have unit norm to be a pure rotation [49].

Summarizing, the description of an object orientation using inertial sensors needs an attitude estimation algorithm. Since quaternions do not present singularities and ambiguities of Euler angles and are more efficient than rotation matrixes, they signify a better option to attitude representation. The quaternions theoretical foundations are presented below.

2.5.3.1 Quaternions

This section was essentially taken from [45].

A quaternion is a four-dimensional complex number that can be used to represent the orientation of a rigid body or coordinate frame in 3D space. An arbitrary orientation of frame B relative to frame A can be achieved through a rotation of an angle θ around an axis ${}^{A}\hat{r}$ defined in frame A. This is represented graphically in Figure 2.16 where the mutually orthogonal unit vectors $\hat{x}_A$, $\hat{y}_A$ and $\hat{z}_A$, and $\hat{x}_B$, $\hat{y}_B$ and $\hat{z}_B$ define the principle axis of coordinate frames A and B, respectively. The quaternion describing this orientation, ${}^{A}_{B}\hat{q}$, is defined by equation (2.2), where r_x, r_y and r_z define the components of the unit vector ${}^{A}\hat{r}$ in the x, y and z axes of frame A respectively. A notation system of leading super-scripts and sub-scripts is used to denote relative frames of orientations and vectors. A leading sub-script denotes the frame being described and a leading super-script denotes the frame this is with reference to. For example, ${}^{A}_{B}\hat{q}$ describes the orientation of frame B relative to frame A and ${}^{A}\hat{r}$ is a vector described in frame A. Quaternion arithmetic often requires that a quaternion describing an orientation is first normalised. It is therefore conventional for all quaternions describing an orientation to be of unit length.

$$ {}^{A}_{B}\hat{q} = [q_1 \quad q_2 \quad q_3 \quad q_4] = \left[cos\frac{\theta}{2} \quad -r_x\,sin\frac{\theta}{2} \quad -r_y\,sin\frac{\theta}{2} \quad -r_z\,sin\frac{\theta}{2}\right] \tag{2.2} $$

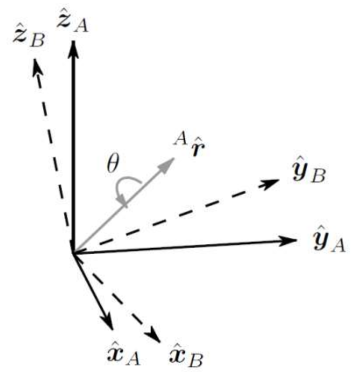


Figure 2.16: The orientation of frame B is achieved by a rotation, from alignment with frame A, of angle θ around the axis ${}^{A}\hat{r}$ [45].

The quaternion conjugate, denoted by *, can be used to swap the relative frames described by an orientation. For example, ${}^{A}_{B}\hat{q}$ is the conjugate of ${}^{B}_{A}\hat{q}$ and describes the orientation of frame A relative to frame B. The conjugate of ${}^{A}_{B}\hat{q}$ is defined by equation (2.3).

$$ {}^{A}_{B}\hat{q}^{*} = {}^{B}_{A}\hat{q} = [q_1 \quad -q_2 \quad -q_3 \quad -q_4] \tag{2.3} $$

The quaternion product, denoted by ⊗, can be used to define compound orientations. For example, for two orientations described by ${}^{A}_{B}\hat{q}$ and ${}^{B}_{C}\hat{q}$, the compounded orientation ${}^{A}_{C}\hat{q}$ can be defined by equation (2.4).

$$ {}^{A}_{C}\hat{q} = {}^{B}_{C}\hat{q} \otimes {}^{A}_{B}\hat{q} \tag{2.4} $$

For two quaternions, a and b, the quaternion product can be determined using the Hamilton rule, defined in equation (2.5). A quaternion product is not commutative; that is, $a \otimes b \neq b \otimes a$.

$$ a \otimes b = [a1 \quad a2 \quad a3 \quad a4] \otimes [b1 \quad b2 \quad b3 \quad b4] = \\ = \begin{bmatrix} a1b1 - a2b2 - a3b3 - a4b4 \\ a1b2 + a2b1 + a3b4 - a4b3 \\ a1b3 - a2b4 + a3b1 + a4b2 \\ a1b4 + a2b3 - a3b2 + a4b1 \end{bmatrix}^T \tag{2.5} $$

A 3D vector can be rotated by a quaternion using the relationship described in equation (2.6). ${}^{A}v$ and ${}^{B}v$ are the same vector described in frame A and frame B, respectively, where each vector contains a 0 inserted as the first element to make them 4 element row vectors.

$$ {}^{B}v = {}^{B}_{A}\hat{q} \otimes {}^{A}v \otimes {}^{A}_{B}\hat{q}^{*} \tag{2.6} $$

The orientation described by ${}^{B}_{A}\hat{q}$ can be represented as the rotation matrix ${}^{A}_{B}R$ defined by equation (2.7).

$$ {}^{A}_{B}R = \begin{bmatrix} 2q_1^2 - 1 + 2q_2^2 & 2(q_2q_3 + q_1q_4) & 2(q_2q_4 + q_1q_3) \\ 2(q_2q_3 + q_1q_4) & 2q_1^2 - 1 + 2q_3^2 & 2(q_3q_4 + q_1q_2) \\ 2(q_2q_4 + q_1q_3) & 2(q_3q_4 - q_1q_2) & 2q_1^2 - 1 + 2q_4^2 \end{bmatrix} \tag{2.7} $$

Therefore, by transposing this explanation to the orientation estimation of a sensor, with equation (2.6 a 3D vector that could be the IMU output, described in sensor frame, can be rotated by a quaternion, giving the same vector but described in the earth reference frame [44].

2.5.4 Parameters for Knee Kinematics Rehabilitation Exercises Evaluation

After understood what is behind the technology that will be used to collect data during rehabilitation exercises execution, now it is necessary determine what will be analyzed with this information.

To accomplish the first objective of this dissertation, evaluation of 3D knee kinematics, the definition of a set of relevant parameters able to characterize knee rehabilitation exercises and its evolution over time is required. Multiple reviews that have studied knee joint kinematics analysis using inertial sensors present common parameters that are described below [39] [53][54][55].

The assessments are mainly based on the measurement of the knee angle [54]. Estimation of 3D kinematics of intersegment joint is based on the modeling of the lower limb as a ball and socket joint permitting three ROM rotations: flexion/extension, abduction/adduction and internal/external rotation angles [53]. Understand the velocity during the exercise is also a parameter that should be observed in order to understand if the exercises are being performed as prescribed. Other evaluation parameters are related to compliance: number of rehabilitation sessions per day, duration of the exercises [54] and number of repetitions for each exercise. A summary of these relevant parameters is presented in Table 2.1: Summary of the relevant parameters for knee kinematics rehabilitation exercises evaluation used in the literature [39] [53] [54] [55].

Table 2.1: Summary of the relevant parameters for knee kinematics rehabilitation exercises evaluation used in the literature [39] [53] [54] [55].

Parameters for Knee Kinematics Evaluation
Max flexion knee angle
Max extension knee angle
Range of motion
Max abduction knee angle
Max adduction knee angle
Abduction/adduction ROM
Max internal rotation knee angle
Max external rotation knee angle
Internal/external rotation ROM
Rotational acceleration
Velocity
Number of repetitions for each exercise
Number of rehabilitation sessions per day
Duration of the exercises

The second objective of this dissertation intends to evaluate if the knee rehabilitation exercises are being performed correctly or not, by the patients, at home. With this in mind, for each exercise, some parameters will be defined, together with a physiotherapist.

Chapter 3

KneeRecovery System

This chapter describes the development of a knee rehabilitation exercises analysis system (KneeRecovery system), that is intended to be used during knee rehabilitation process, by the patient him/herself, at home, after being subjected to a TKR. This system can let users perform the rehabilitation program at home and provide a real-time biofeedback during the rehabilitation process, informing the patient about achieved results.

In this chapter, the knee rehabilitation program defined for this specific project, the methodology and processes for the implementation of the system will be presented, as well as the obtained results and the evaluation and discussion of its performance.

3.1 Knee Rehabilitation Program

In the beginning of this project, a knee rehabilitation program for patients who suffer from osteoarthritis and were subjected to TKR surgery was drawn in order to be applied in this study. For defining the tests that could be pertinent to be part of the program and to evaluate the patient's recovery, a program that includes a set of exercises to be performed at home were defined, together with a physiotherapist, Dra. Elisa Rodrigues, from Politécnico do Porto, Escola Superior de Saúde.

It includes three evaluation sets for the knee recovery. The first set is a treatment and exercise program, divided in three phases. The second set consists in evaluating the rehabilitation goals which must be achieved to enter into the next phase. The third set intends to be a report about the patient's evolution that will help the patient him/herself and his/her doctor to analyze the recovery progression.

This section is dedicated to present the knee rehabilitation program, with a short description of the exercises, since it is an important part of this study and provides a basis to the practical experiments.

Set I – Knee Rehabilitation Exercises

The first evaluation set of knee recovery program consists in seven knee rehabilitation exercises, divided in three different evolution phases, according to postoperative weeks and lasts six weeks.

The first phase (weeks 1-2) includes three exercises and the second (weeks 3-4) and third (weeks 5-6) phases include two exercises each. The patient should perform the exercises that were indicated for the phase he/she is, from twice until three times daily. It should be used as a guideline for rehabilitation progression, but may need to be altered pending the nature and extent of the surgical procedure, healing restraints or patient tolerance.

The importance of rehabilitation exercises lies in the benefits it presents to joint mobility and body metabolism. Some of the overall goals of the operation and rehabilitation are:

- Relax joint capsules and ligaments
- Prevent osteoporosis
- Strengthen muscles around the knee
- Increase active weight-bearing ability
- Control joint pain and swelling
- Regain normal knee flexion and extension
- Regain a normal gait pattern and neuromuscular stability for ambulation
- Regain normal quadriceps, hamstring lower extremity muscle strength
- Regain normal proprioception, balance and coordination for the desired activities
- Achieve optimal functional outcome based on orthopedic and patient goals [39] [56].

However, improper rehabilitation exercises not only put patients on risk of slower recovery, but also may cause more damage by adding stress to the injured parts of the knee. Therefore, developing a rehabilitation exercise assessment system that monitors patients' quality and accuracy of rehabilitation movements at home plays an important role in the success of the recovery process [39].

The rehabilitation exercise assessment system for knee OA can help patients self-manage their rehabilitation progress at home, and when the improper exercise posture is detected, a message is provided for the patients to verify their movements in real-time.

The seven knee rehabilitation exercises are described next. The subject should repeat ten times each exercise, two or three times per day, except the exercise 7, whose number of repetitions should be five.

Weeks 1 – 2

Exercise 1 – Quadriceps Setting

The subject lies on his/her back with the operative leg straight and tightens the quadriceps muscle on top of the thigh by pressing the knee straight down into the bed, holding for a count of six seconds.

This stretch is the most important following surgery, as it ensures a straight knee after surgery [57].

Exercise 2 – Straight Leg Raising

The subject lies on his/her back with the operative leg straight. The non-operative knee should be bent to reduce pressure on the low back. A quadriceps setting exercise should be performed to fully straighten the knee. The subject keeps the leg completely straight and bends the hip so the operative leg raises from the bed to reach the level of the opposite knee.

Exercise 3 – Seated Heel Slides

The subject sits towards the edge of a chair with the operative leg bending the knee, as much as possible without raising the hips off the chair. Then, he/she slides the foot outward until the knee is completely straight. The foot should always be kept on the floor during the exercise, so when the knee is in a straight position, the heels should be touching the ground. Then, he/she slides the foot back outward until the knee is again flexed.

This exercise strengthens the knee and increases the bending or flexion [57].

Weeks 3 – 4

Exercise 4 – Long Arc Knee Extension

The subject sits on a chair. With the knee bent at a right angle off the chair, he/she straightens the operative knee as fully as possible trying to achieve zero extension degrees.

This exercise strengthen the thigh or quadriceps muscles [57].

Exercise 5 – Hip Extension

The subject lies on his/her stomach in bed and raises the operative leg straight up towards the ceiling. The leg is lifted just to the point in which the kneecap leaves the bed and no higher.

Weeks 5 - 6

Exercise 6 – Prone Quadriceps Stretch

The subject lays with his/her stomach facing the bed. The subject tightens the stomach muscles and bends the knee until he/she feels a stretch in front of the thigh.

Exercise 7 – Single Leg Balancing

The subject stands with feet placed shoulder-width apart and bears full weight through the operative leg with the knee completely straight. Then, he/she brings the opposite knee upwards to the ceiling by bending at the hip to balance on the operative leg. The balancing is kept for 30 seconds.

Set II – Progression Criteria for the next phase

The knee rehabilitation program also includes two exercises and two questions about pain and swelling degree that will indicate if the patient is able to progress to the second and third evolution phases. The patient should perform these criteria exercises in the end of the second and third phases.

This second set of the program intends to evaluate specific variables with goals identified for each and makes a general observation of the patient’s condition.

One of the most important goals of TKR is to obtain postoperatively a maximized and function-regained ROM of the knee joint. However, during their recovery many TKR patients suffer from knee stiffness and reduced knee flexion of less than 90º. Indeed, restricted postoperative knee flexion is the most frequent complication after TKR procedures and it is also the main cause of patient dissatisfaction. The recommended knee ROM is at least 100º of knee flexion. Tasks such as walking upstairs require at least 83º of knee flexion, 90º to 100º are needed for walking down the stairs, 93º to 105º to arise from a chair, and more than 115º to squat or kneel.

Knee ROM shows to be a useful indicator to evaluate knee ROM restoration prognosis and it is a useful clinical indicator to evaluate knee ROM in the early stages and sub-acute stages after TKR procedures [10]. So, since the long arc knee extension exercise can analyze the knee ROM, it is one of the criteria for evaluating if the patient can advance to the next phase. The goal at the end of the first phase is to achieve 90º flexion and 100º at the end of the second phase.

One of the other main problems after TKR is a decreased knee extension. A healthy knee is able to perform a full extension, i.e., 0º. However, most of the subjects after the surgery are not able to achieve it. Obtaining full extension will reduce fatigue of the quadriceps muscles when standing for a long period of time. It also allows the knee to function more properly while walking. So, achieving 0º knee extension in the end of the second phase is also a goal for progression to the third phase.

Pain and swelling are the other two progression criteria.

Pain is commonly presumed to be a major source of inhibition in the ability to voluntarily activate muscle surrounding arthritic joints [58], so a reduced pain reveals to be an essential progression criteria. Pain was measured asking the patient to describe the pain feeling in a scale from zero to ten, with zero representing no pain and ten representing the worst pain imaginable. The patient must rate the pain level as five or less in order to be allowed to proceed to the second and third phases.

Swelling is a very common problem after TKR. It is a natural response to injury to any tissues of the body. A gradual decrease is expected and properly managed swelling makes the recovery process a lot better. The absence of swelling was defined as a criteria to progress to the second and third phases.

Summarizing the progression criteria:

Criteria for 2nd Phase

- Perform the long arc knee extension exercise, achieving 0º extension and 90º flexion.
- Pain less than 5 in a scale from 0 to 10.
- Absence of edema.

Criteria for 3rd Phase

- Perform the long arc knee extension exercise, achieving 0º extension and 100º flexion.
- Perform the straight leg raising exercise, with a fully straighten knee, which means, achieving 0º extension.
- Pain less than 5 in a scale from 0 to 10.
- Absence of edema.

Set III – Evolution Report

The third set of the knee rehabilitation program intends to be the patient's evolution report. During the follow-ups at outpatient clinics or medical departments, the physicians can assess the patients' progress and how effectively the rehabilitation activities were carried out through the recording of the system. The report includes a set of parameters that are the result of the progression criteria, and these parameters are:

At the end of the 1st phase:

- Achieved ROM.
- Reported pain.
- Presence/absence of edema.

At the end of the 2nd phase:

- Achieved ROM.
- Capability of performing the straight leg raise exercise correctly (knee completely straight: 0º).
- Reported pain.
- Presence/absence of edema.

3.2 System Overview

KneeRecovery system is a sequential algorithm that was thought to analyze the lower limb motion provided by the knee, through the use of inertial sensors. This analysis consists in obtaining and analyzing the information about knee angles achieved during the execution of a set of knee rehabilitation exercises defined in the previous section. This algorithm, composed by five different steps is represented in Figure 3.1.

Data Acquisition, described in section 3.3 is the first step of KneeRecovery system. Its aim is acquiring the sensor's signal. A brief explanation about the sensors and the used lower limb kinematic model is also presented in this section.

Orientation Estimation, described in section 3.4 presents the sensor fusion algorithm that was used to obtain the orientation of each lower limb segment (thigh and shank) relative to the Earth's reference frame. This algorithm fuses data from accelerometers and gyroscopes, computing the orientation that is represented by quaternions. Still in this section, the normalization processing applied to quaternions is explained.

Sensor local reference frame to Earth's reference frame, presented in section 3.5, explains how the limb vectors were determined. With this in mind, a known vector over time was defined and a rotation by a quaternion was applied in order to determine the shank and thigh vectors in Earth reference frame.

Angle Determination, described in section 3.6, gives an explanation about the two angle types for joint angles determination and describes the used method to calculate the knee joint angle achieved by the subject during knee rehabilitation exercises. After finding the knee angle signal, a low-pass filter was applied for smoothness.

The variables that will be defined in the following section will have a left superscript, a right superscript and a right subscript. The left superscript indicates the reference frame for which the variable is calculated. The right superscript indicates the body segment the variable related to. The right subscript usually represents the time variable. The most used left superscripts are *e* and *s*, which refers to Earth reference frame and sensor local reference frame, respectively. The right most used superscripts are *thigh* and *shank* which refers to thigh and shank segments of the lower limb, respectively. The most used right subscript is *t*, which refers to time variable

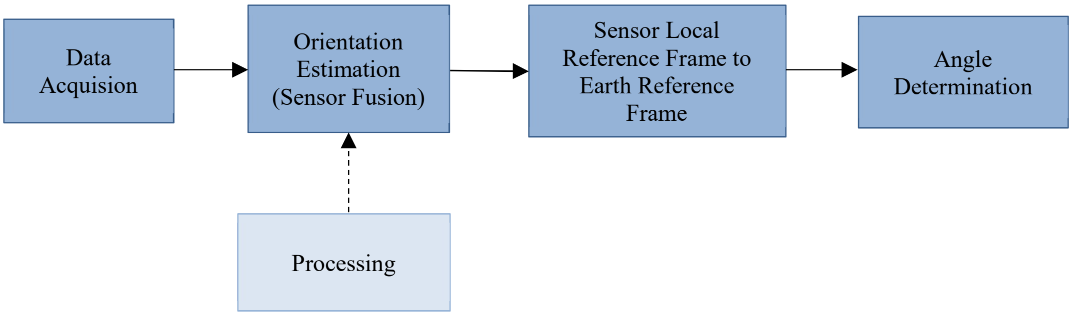


Figure 3.1: KneeRecovery system flowchart.

3.3 Data Acquisition

Data acquisition consists in obtaining a reliable signal able to analyze the knee rehabilitation exercises. The used sensors, coordinate frames and the way how the lower limb was modeled are described.

3.3.1 Inertial Sensors

As referred in section 2.5.1, inertial sensors are a group of sensors represented by accelerometers, gyroscopes and magnetometers. The accelerometer is used to detect inclinations, the gyroscope to detect fast changes and the magnetometer to measure a horizontal reference direction. The measurements of the magnetometer can be distorted in the proximity of ferromagnetic materials [59].

A set of 3D accelerometers attached on the human body can be used as an inclinometer to measure the orientation of sensors with respect to gravity. 3D gyroscopes can be incorporated to improve the accuracy. The angular rates measured by the gyroscopes are integrated to estimate the change of orientation. However, over time, large integration error can accumulate. The accelerometer in combination with the gyroscope can be used to compensate the drifts and to define an absolute orientation [59]. Data from magnetometer is used to measure a horizontal reference direction. As can be verified in the rehabilitation program, the angle of all the knee rehabilitation exercises only has variations relative to the vertical, which allow the exclusion of the magnetometer and the use of a combination between the accelerometer and the gyroscope. This way, with data from an IMU it is possible to estimate the 3D orientation or attitude of the device relative to a fixed Earth frame, and when attached to a body segment, they can be used to track angular movements of the segment [60]. Due to its properties, such as low cost, small size, light weight and limited power requirements, their usage is becoming increasingly popular. With the use of models, joint angles can be estimated.

In this work, the used IMU was the Pandlets developed by Fraunhofer AICOS, depicted in Figure 3.2. The device includes a MPU-9250 Nine-Axis unit and has a 3-axis accelerometer, a 3-axis gyroscope and a 3-axis magnetometer. It has a surface area with dimensions of 28 x 28 millimeters. Its height is 1,0 millimeter.

Figure 3.2: Pandlets developed at Fraunhofer AICOS.

For the data acquisition, each IMU is connected to a computer via Bluetooth and an application, developed by Fraunhofer AICOS, the PhysioModel allows to record data from Pandlets and store it in an csv file. The signals from accelerometers and gyroscopes are sampled at a 50 Hz frequency.

Two IMUs were placed on the two lower limb segments, one on the thigh lateral midsection and the other one on the shank lateral lower section.

3.3.2 Kinematic Model

Human body movement occurs when the muscles contract and pull on the bones they are attached to. Movement is possible due to the presence of joints, or articulations, in which adjacent bones come together and are allowed to move smoothly against each other [60]. The lower limb consists of the thigh and the shank. A simplified model for the shank-knee-thigh limbs, made by two bones (femur and tibia), linked by a spherical joint is assumed [54]. Its motion is approximated as an articulated motion of two rigid body parts, where each of the segments can only rotate about its preceding joints, the knee and the hip joints. The thigh connects with the shank at a point, and the thigh and the shank rotate in a rotation center. This point is the "center of the joint" and it is defined as the point in which the distance between the point and each sensor is fixed during knee joint rotation [55]. Thus, estimation of 3D kinematics of intersegment joint is based on the modeling of the lower limb joint as a ball and socket joint permitting three DOF rotations: flexion/extension, adduction/abduction and inversion/extension [53].

The two sensors were placed on the middle lateral section of the thigh and on the shank lateral lower section, the most possible aligned. The hip movements will influence the thigh position and the knee movements will influence the shank position.

3.4 Orientation Estimation

Orientation Estimation consists in obtaining the orientation or attitude of the two lower limb segments (thigh and shank), using data from inertial sensors that are combined through sensor fusion methods. Each segment's orientation is represented by quaternions.

Sensor fusion method as well as the processing applied to quaternions are explained in this section.

3.4.1 Sensor Fusion

Inertial sensors can be used to estimate 3D orientation/attitude relative to the Earth frame (defined by vertical-north-east direction) [60]. However, data provided by IMU is affected by high noise levels and time-varying biases. Therefore, a sensor fusion algorithm must be used to process the data to obtain a smooth and bias-free estimation of the orientation maintaining a low computational cost for running on the onboard processor [61]. This fusion method combines data from disparate sources of information in a way that should ideally give better performance than that achieved when each source of information is used alone. It requires the availability of complementary sensors in order that the disadvantages of each sensor are overcome by the advantages of the others [46].

In this work, the sensor fusion algorithm uses a second order complementary filter, bringing together the relevant information to compute the orientation of the device relative to the Earth frame with increased accuracy. The developed sensor fusion algorithm takes into account the long-term reference to the gravity direction (provided by the accelerometer), together with the short-term accuracy of the gyroscope in measuring the angular rotation of the device. Since the magnetometer can easily suffer interference from the environment, its information was not considered in this study. As there is no reference to magnetometer data (i.e., no reference about the North was available) the Earth frame consisted of a vertical axis and two perpendicular horizontal axes that could not necessarily point to the North and East directions. In practice, thought, the knowledge of the orientation of the sensor relative to the North is not required, as it is not relevant to each horizontal direction the user is facing at; in fact, only relative changes in orientation need to be considered [60].

The obtained orientation is represented in a quaternion form. Quaternions are a useful mathematical tool that require less computation time because of their minimal number of parameters. They are computationally effective and avoid problems with singularities such as gimbal lock. Furthermore, rotations of vectors are simply performed by quaternion multiplications [61], allowing data conversion to Earth frame.

Since the lower limb is represented by two segments linked by a spherical joint, each segment's orientation (thigh and shank) is represented by a quaternion. Thus, the output from the sensor fusion algorithm is the orientation of each sensor attached to the thigh and shank in the form of quaternions, relative to the Earth reference frame: q_t^{thigh} and q_t^{shank}, respectively.

3.4.2 Normalization

In order to avoid and decrease error accumulation, after obtaining quaternions through sensor fusion and after performing any operation with them, quaternions were normalized, i.e., they were processed in order to guarantee they have a unit length. In every quaternion operations, a small error is introduced, so over time the quaternion may no longer have a length close to one. So, in order to guarantee the quaternion is valid normalization is applied.

Taking the vector v as example, its components v_x, v_y and v_z were normalized to v_{xn}, v_{yn} and v_{zn} by:

$$\text{mag} = \sqrt{v_x^2 + v_y^2 + v_z^2} \tag{3.1}$$

$$\mathrm{v_{xn}} = \frac{v_x}{mag} \tag{3.2}$$

$$\mathrm{v_{yn}} = \frac{v_y}{mag} \tag{3.3}$$

$$\mathrm{v_{zn}} = \frac{v_z}{mag} \tag{3.4}$$

3.5 Sensor Local Reference Frame to Earth Reference Frame

After finding the sensor orientation through the sensor fusion algorithm, the vectors describing thigh and shank segments in Earth coordinate frames, ${}^{e}v_t^{thigh}$and ${}^{e}v_t^{shank}$, respectively, were defined.

In this process, two coordinate systems are involved: the sensor/device frame and the Earth frame. During data acquision, sensors are placed on the thigh and shank always in the same position (which is known), so the body frame is also involved in the process.

In order to know the sensor's coordinates, a subject was asked to perform a standing position, with the two sensors placed laterally on the thigh and on the shank. When the sensor's acceleration in each axis is plotted, we could understand that the gravity is represented in the x axis, since its value is approximately -9,8m/s^2 and 0 m/s^2 in y and z axis, as it is shown in Figure 3.3. So, it is possible to know that the sensor's vector has the form ${}^{s}_{t}\vec{v}^{sensor} = [-1, 0, 0]$. This vector aligns itself with the length of the body segments and since the sensor does not change its position during the movement (in relation to sensor local reference frame), the vector remains unchanged over the time.

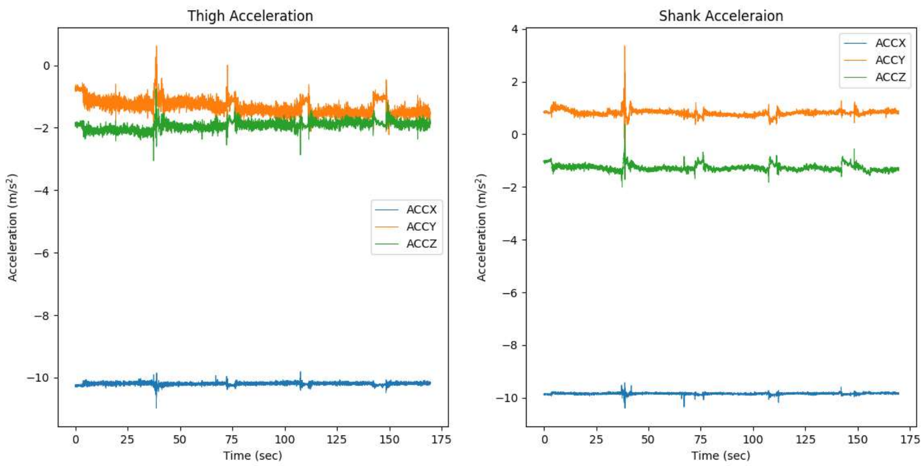


Figure 3.3: Components x, y and z of acceleration from thigh (left) and shank (right) sensors when a subject performs a standing position.

Knowing the sensor's vector, it is possible to convert this vector (in sensor local reference frame) to Earth reference frame, by rotating the sensor vector by a quaternion, as defined in equations 3.5 and 3.6.

$${}^{e}\vec{v}_t^{thigh} = q_t^{thigh} \text{ x } {}^{s}\vec{v}^{sensor} \text{ x } \left(q_t^{thigh}\right)^{-1} \tag{3.5}$$

$$ {}^{e}\vec{v}_t^{shank} = q_t^{shank} \text{ x } {}^{s}\vec{v}^{sensor} \text{ x } (q_t^{shank})^{-1} \tag{3.6} $$

where ${}^{e}\vec{v}_t^{thigh}$ and ${}^{e}\vec{v}_t^{shank}$ represents the thigh and shank vectors in Earth coordinates, respectively and $(q_t^{thigh})^{-1}$ and $(q_t^{shank})^{-1}$ represents the inverse of thigh and shank quaternions, respectively. So, ${}^{e}\vec{v}_t^{thigh}$ ${}^{s}\vec{v}^{sensor}$, as well as ${}^{e}\vec{v}_t^{shan}$ and ${}^{s}\vec{v}^{sensor}$ represent the same vector, but in different coordinate frames. In equations 3.5 and 3.6, the vector ${}^{s}\vec{v}^{sensor}$ contains a 0 inserted as the first element, i.e., it has the form [0, -1, 0, 0], to make it a four element row vector, allowing to perform a quaternion product using Hamilton's rule. A schematic figure of this vector coordinate frames transformation is presented in Figure 3.4: Scheme of the method used to convert the sensor vector in sensor local reference frame to Earth reference frame..

The correct position of the sensors and their alignment is required to allow the direct estimation of the limb vectors. As the bracelet was restricting the orientation of each limb axis relative to the sensor (at least to some extent), a reasonable approximation was used and this way the limb vectors were considered to be known [60].

After expressing the limb vectors in Earth coordinates, the horizontal component (x-y) of the vector was eliminated, so that only changes relative to the vertical component would be considered. Taking again the vector v as example and its components v_x, v_y and v_z, the vector v was expressed as: $[\sqrt{v_x^2 + v_y^2},\ 0,\ v_z^2]$.

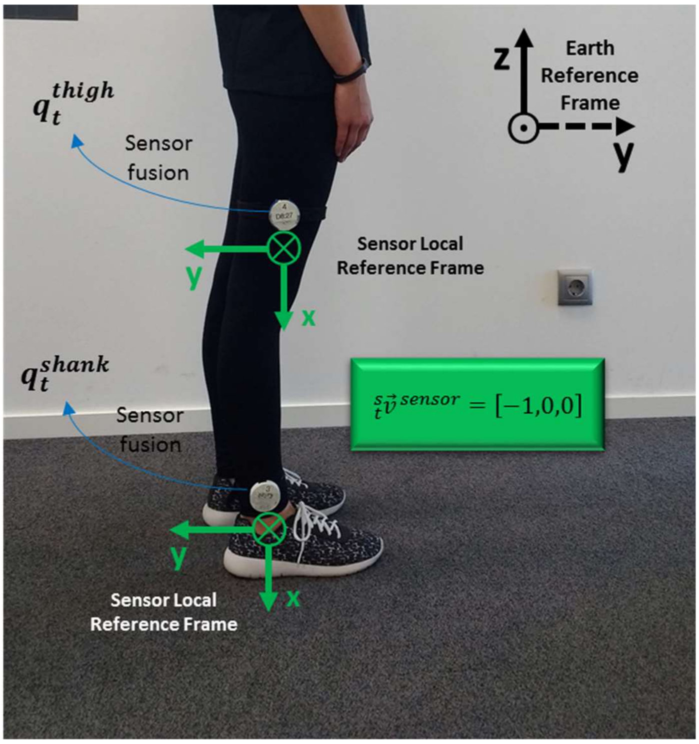


Figure 3.4: Scheme of the method used to convert the sensor vector in sensor local reference frame to Earth reference frame.

3.6 Angle Determination

After finding the vectors that characterize the orientation of the thigh and shank segments, the calculation of the knee angle was the next step. In the beginning of this section, a review of the different joint angles that can be estimated are presented: absolute and relative angles. Then, the method used to determine the knee angle achieved by the user is explained.

3.6.1 Absolute and Relative angles

An angle is composed of two lines, two planes, or a combination that intersects at a point called the vertex. In biomechanics, there are two different ways of describing joint angles: absolute angles and relative angles.

A relative angle measures the angle between two segments but cannot determine the orientation of the segments in space. When considering knee angle, if the longitudinal axis of the shank segment is one side of an angle and the longitudinal axis of the thigh segment is the other side, the vertex is the joint center of the knee. In this case, this angle describes a relative angle. The coordinate points describing the ankle and knee joint centers define the shank segment, while the coordinate points describing the hip and knee joint centers define the thigh segment. The vertex of the angle is the knee joint center [62]. The relative angles are useful for evaluating the angles during exercises in which the two segments are moving [60].

An absolute angle measures the orientation of a segment in space relative to a defined axis placed at the proximal end of the segment. This is the angle of inclination of a body segment to a fixed reference in the environment [62]. The absolute angles are useful when only one segment is moving [60].

A representative comparison of relative and absolute angles is shown in Figure 3.5.

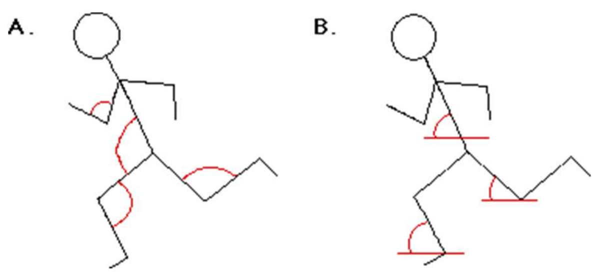


Figure 3.5: Comparison between relative (A) and absolute angles (B). In this specific case, the absolute angle is calculated with reference to an horizontal reference line [63].

3.6.2 Knee Angles Estimation

In this work, at first, the thigh and shank absolute angles relative to the vertical were defined. This fixed vertical line of reference is represented by the gravity vector ${}^{e}\vec{g}$ = [0, 0, -1].

The convention for absolute angles calculation involves the placement of a coordinate system at the proximal end point of the segment. The angle is then measured counterclockwise from the defined axis.

An illustration of the two thigh and shank absolute angles is depicted in Figure 3.6, which represents the long arc knee extension movement in the sagittal plane.

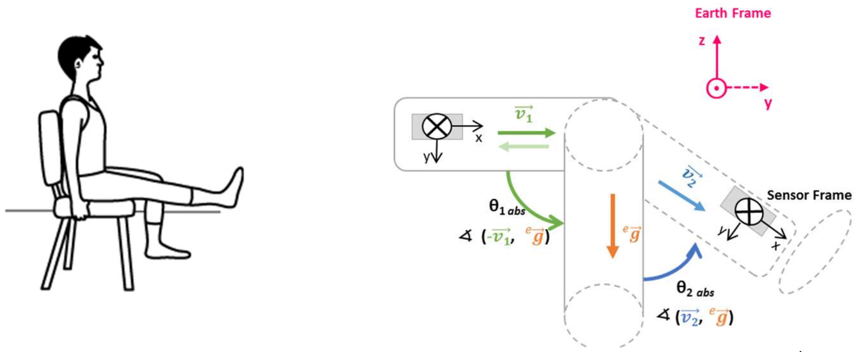


Figure 3.6: Knee extension/flexion and coordinate frames: Earth and sensor frames are illustrated. $\vec{v}_1$ represents the thigh, $\vec{v}_2$ represents the shank and ${}^{e}\vec{g}$ represents the vertical (adapted from [60]).

Absolute angles are calculated using trigonometric relationships of the cosine. The cosine is defined based on the sides of a right triangle. It is the ratio of the side adjacent to the angle in question and the hypotenuse. The angle in question is not the right angle in the triangle. If the shank and thigh segment coordinate positions are considered, the absolute angles of both the thigh and shank segments can be calculated [62].

For example, to calculate the absolute shank angle, the coordinate values of the segment end points of the shank are substituted into the equation 3.7 to define the cosine of the angle

$$\cos\theta_{shank} = \frac{{}^{e}\vec{g}}{\vec{v}_2} = \mathrm{w} \tag{3.7}$$

where $\vec{v}_2$ represents the shank vector.

Next, the angle whose cosine is the value determined through the equation 3.7 is again determined using trigonometric principles. This is called finding the inverse cosine and is written as follows:

$$\theta_{shank} = cos^{-1}\, w \tag{3.8}$$

As can be observed in Figure 3.6, the vector $\vec{v}_1$ was inverted so that the angle calculated has the same signal as the calculated in equation 3.8.

Using the absolute angle of the thigh and the shank, the knee joint angle is defined as:

$$\theta_{knee} = 180 - (\theta_{thigh\ absolute} - \theta_{shank\ absolute}) \tag{3.9}$$

In human locomotion, the knee angle is always positive, that is, in some degrees of flexion. If the knee angle gets progressively smaller, the knee is extending. A zero angle is a neutral position, while a negative angle would indicate a hyperextension of the knee [62].

After calculating the knee's angle, it was possible to obtain a signal over the time that describes the movement of the lower limb, while a subject is performing a certain knee exercise.

This approach has the practical advantage of not requiring any specific calibration procedure.

3.6.3 Low-pass filter

After obtaining the knee angle signal, a low-pass filter was applied in order to attenuate noise and smooth the signal. A first-order low-pass Butterworth filter was adapted to a sampling frequency of 50 Hz with a cutoff frequency of 0,4 Hz. Different cutoff frequencies were experimented, but the 0,4 Hz was the value that has resulted in a better outcome, smoothing the signal, but not altering its characteristics. This way, all the frequencies above the cutoff frequency were eliminated, while the ones below were left unchanged.

3.7 KneeRecovery System Evaluation

In order to demonstrate the performance of KneeRecovery system, an experimental work was developed. The knee angle obtained by KneeRecovery system was compared with two different validation methods.

This section presents the used validation methods, the experimental work, the data analysis, the experimental statistics used to evaluate the performance and the results achieved.

3.7.1 Validation Methods

In this work, two different validation methods were used.

The first validation method is the gold standard in motion analysis and consists in the usage of a camera motion tracking system, which tracks markers over time. Yellow markers are placed on key anatomical positions and video recordings of subjects executing the movements are collected. The markers should have a good contrast and definition, so when possible, dark clothes were used in order to achieve this requirement. Therefore, as reference to the inertial-based knee angle, a camera motion tracking system is used. Video recordings are analyzed with the video analysis Kinovea (Figure 3.7), a software whose targets are athletes and medical professionals. It has several tools, such as video observation, analysis, measurement and video comparison [64]. For the analysis in this study, after the yellow markers being identified in the video, an automatic tracking is performed. The information obtained is the position of each of the three markers and the correspondent instant of time. The obtained data is exported to a xml file for further processing.

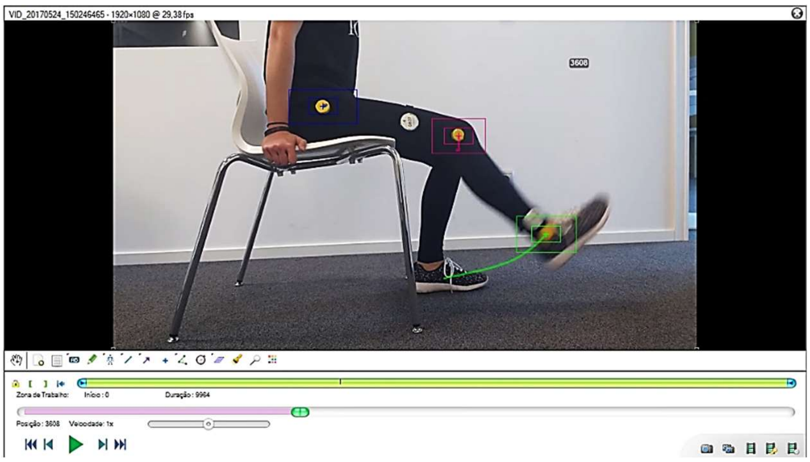


Figure 3.7: Lower limb tracking using Kinovea.

The second validation method is the goniometer (depicted in Figure 3.8), an instrument used in medicine to measure the range of motion of the knee's joint. It is a clinical tool that allows objective measurements in order to track progress in a rehabilitation program. Goniometric measurements are used by physical therapists to quantify baseline limitations of motion, decide on appropriate therapeutic interventions, and document the effectiveness of these interventions. Probably, goniometer is the most widely used evaluation procedure and can be considered a fundamental part of the "basic science" of physical therapy.

The two most important factors affecting objective goniometric measurements are reliability and accuracy. Reliability in goniometry means the consistency or the repeatability of the ROM measurements, that is, whether the application of the instrument and the procedures produce the same measurements consistently under the same conditions [65]. A study about goniometry [65] referred the next example: studies in which repeated tests are separated by short time intervals (i.e., one hour) may yield very different results than studies in which repeated tests are separated by longer time intervals (i.e., days or weeks). The reliability of the measurements expresses their reproducibility or stability only in relation to the time intervals reported. The most accurate evaluation of the reliability of the instrument and procedures is determined when short time intervals separate tests. These results probably will be more reliable than the results of studies with long time intervals between tests because the accuracy of the measurements is increased with few uncontrolled variables.

The other problem with goniometer is the reading accuracy, that is not always the greatest. Issues between measures and between clinician's reliability seem to increase as the experience of the examiner decreases. Some studies suggest that these errors can be anywhere between 5 and 10 degrees when completing repeated measures [66].

The main advantages of this method include the low cost of the instrument and the ease of measurement by the clinicians. On the other hand, its utility requires a professional's prior experience. Another important consideration is the fact that, unlike the camera motion tracking system, the used manual goniometer does not allow a continuous measurement, so when this method was used (it will be explained in 3.7.2.2), only some measurements in certain instants of time were considered for validation. This method was considered in this study, since it is widely used and accessible in physiotherapy clinics, representing an important method to be studied.

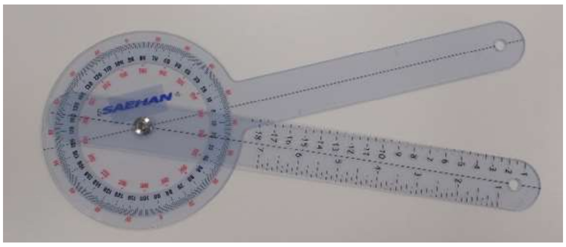


Figure 3.8: Goniometer.

As will be explained in 3.7.2.2, the experimental protocol consists in seven knee rehabilitation exercises plus two progression criteria exercises. The camera motion tracking system was used for evaluating the first seven exercises and the goniometer was used to validate the last two exercises (progression criteria tests).

3.7.2 Experimental Work

The experimental work is presented next. In this section, the experimental setup, protocol and dataset will be presented.

3.7.2.1 Experimental Setup

Before the evaluation begins, the experimental environment requires definition. A schema of the test environmental, described next is shown in Figure 3.9.

Two wearable sensors, the Pandlets developed by Fraunhofer AICOS were used to monitor movements and were placed on the lower limb. Sensors communicated wirelessly with a laptop via Bluetooth low energy, and data from each individual sensor (i.e., accelerometer and gyroscope) were collected at 50 Hz. The application Physiomodel installed in the laptop records the data read by the sensors, which are exported to a csv file and afterwards analyzed using Python 3.6.0 with software PyCharm.

For the first validation method, the camera motion tracking system, yellow markers were placed on key anatomical positions and video recordings of subjects executing the movements were collected with a camera with a frame rate of 25 frames per second. The camera used is a Canon Legria HF G10 and it was placed in order to film the sagittal plane of the subject. Video recording were analyzed with the video analysis Kinovea v 0.8.25.

For the validation method that uses the goniometer, only the instrument is required.

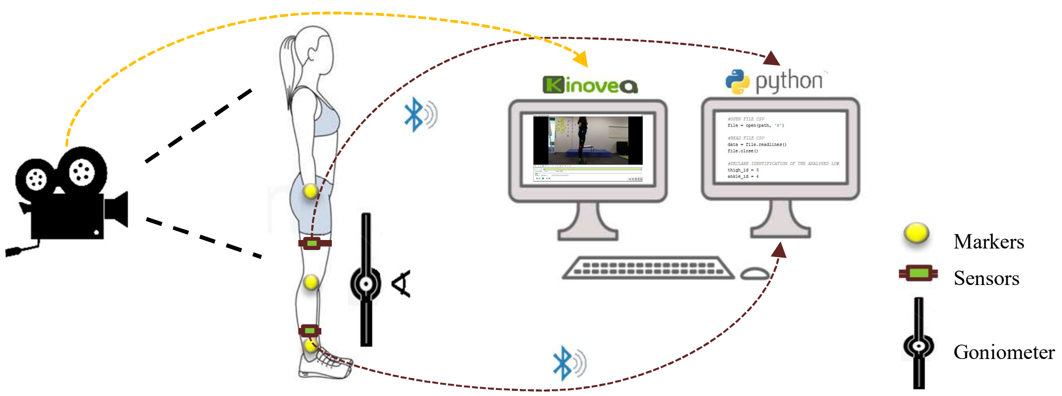


Figure 3.9: Experimental setup (adapted from [60]).

3.7.2.2 Experimental Protocol

The two Pandlets were placed on the lower limb, one on the middle lateral section of the thigh and the other one on the shank lateral lower section, aligned with each other.

Both the validation methods involve some knowledge about the anatomy of the body, particularly body landmarks.

For the validation with the camera motion tracking system, three yellow markers were placed on the subject, following the standard convention: greater trochanter, lateral epicondyle and lateral malleolus [67].

About the second validation method, the knee angle measurement using the goniometer also involves the knowledge of body landmarks. In the knee joint, the axis (point of rotation) is placed on the lateral epicondyle of the femur, while the stationary arm is lined up with the greater trochanter of the femur. Finally, the moveable arm of the goniometer is lined up with the lateral malleolus of the fibula and a measurement is taken using the degree scale on the circular portion of the tool [66]. As goniometer does not allow continuous measurements, it was defined that for each exercise repetition, two angles are measured, one in the initial position and the other one in the opposite position. The measurements were performed and noted for future analysis.

The positions of the sensors, markers and goniometer are depicted in Figure 3.10.

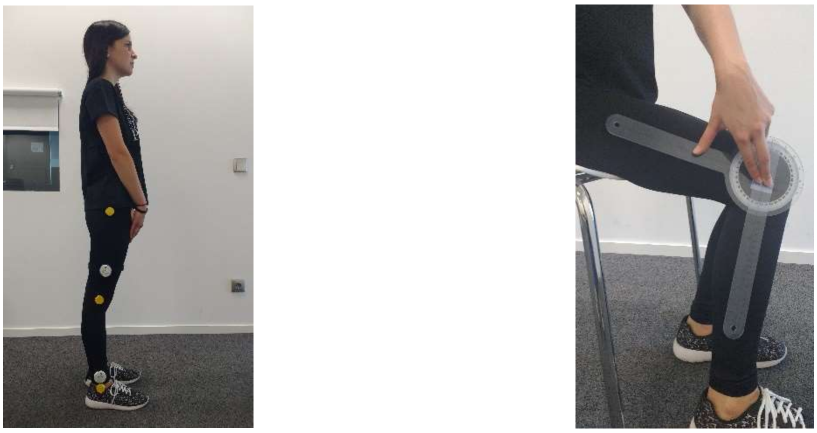


Figure 3.10: Placement of sensors and yellow markers (left) and placement of goniometer (right).

The experiments are indicated below and illustrated in Figure 3.11.

- Test 1: Quadriceps Setting
- Test 2: Straight Leg Raising
- Test 3: Seated Heel Slides
- Test 4: Long Arc Knee Extension
- Test 5: Hip Extension
- Test 6: Prone Quadriceps Stretch
- Test 7: Single Leg Balancing
- Progression Criteria Test I: Straight Leg Raising
- Progression Criteria Test II: Long Arc Knee Extension

Each subject repeated each test ten times, except test 7, which was repeated five times.

Tests 1, 2, 3, 4, 5, 6 and 7 were validated using the camera validation system and the progression criteria tests I and II were validated using the goniometer. As can be understood, progression criteria test I and test 2 are the same exercise as well as progression criteria test II and test 4.

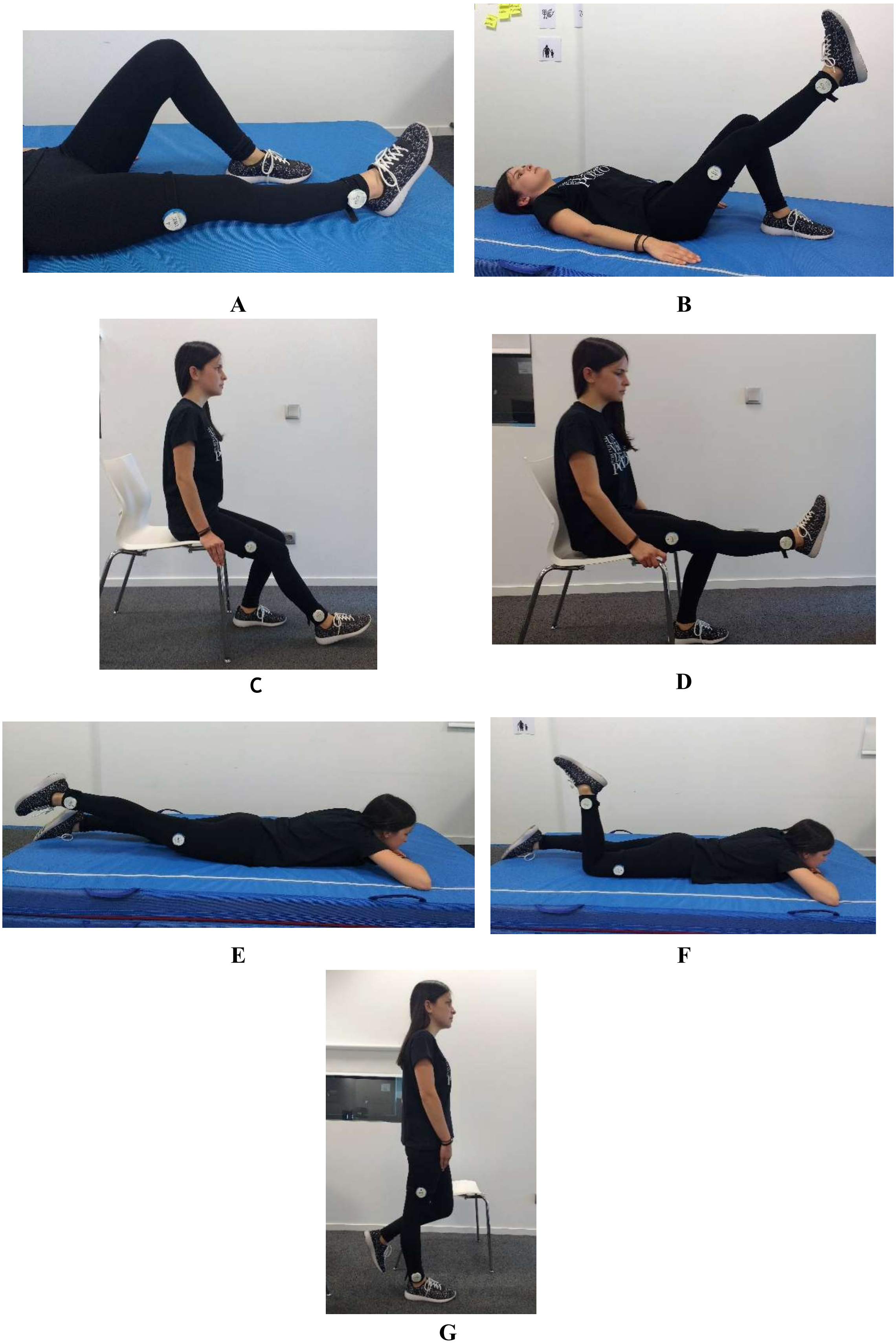


Figure 3.11: A - Test 1: Quadriceps Setting; B – Test 2: Straight Leg Raising/Progression Criteria Test II, C – Test 3: Seated Heel Slides; D – Test 4: Long Arc Knee Extension/Progression Criteria Test I; E - Test 5: Hip Extension; F - Test 6: Prone Quadriceps Stretch; G - Test 7: Single Leg Balancing.

3.7.2.3 Dataset

In the present study, a dataset was collected with 5 healthy volunteers (36,2 $\pm$ 16,16 years old) and 1 osteoarthritic volunteer (74 years old) who suffered knee osteoarthritis and was subjected to TKR. The data from the patient was collected in hospital environment. The data acquision from the unhealthy subject has also intended to analyze the evolution of the exercises performance. So, four sessions were defined: beginning of the 1st phase, end of the 1st phase/beginning of the 2nd phase, end of the 2st phase/beginning of the 3nd phase and end of the 3rd phase. Because the patient dropped the rehabilitation in the beginning of the second phase, only the first two sessions were accomplished.

The collected dataset resulted in a total of 43 signals.

3.7.3 Data analysis

With the method and process presented in sections 3.3, 3.4, 3.5 and 3.6, knee joint angles were calculated from the inertial sensors data, using Python.

In relation to the first validation method, the camera motion tracking system, video recordings were analyzed using Kinovea software. Yellow markers were manually annotated and automatically tracked using the object tracking functionality. However, most of the times, object point location was manually adjusted. The use of yellow markers intended to cause good contrasts, however reflective markers could be a better choice as they could facilitate the automatic tracking. Markers locations in the video timeframes of interest were exported to an excel file, where position coordinates (abscissa and ordinates) of the three markers (greater trochanter, lateral epicondyle and lateral malleolus) were defined. Through this information, thigh and shank vectors were calculated as demonstrated in equations 3.10, 3.11, 3.12 and 3.13:

$$x_{thigh} = x_{epicondyle} - x_{trochanter} \tag{3.10}$$

$$y_{thigh} = y_{epicondyle} - y_{trochanter} \tag{3.11}$$

$$x_{shank} = x_{malleolus} - x_{epicondyle} \tag{3.12}$$

$$y_{shank} = y_{malleolus} - y_{epicondyle} \tag{3.13}$$

where $x_{trochanter}$, $x_{epicondyle}$ and $x_{malleolus}$ represents the abscissa of the markers placed on the greater trochanter, epicondyle and lateral malleolus, respectively and $y_{trochante}$, $y_{epicondyle}$ and $y_{malleolus}$ the respective ordinate. x_{thigh} and y_{thigh} represents the coordinates of the thigh vector and x_{shank} and y_{shank} represents the shank vector coordinates.

The knee angles for all time instants were calculated using equation 3.14:

$$\theta_{knee} = \cos^{-1} \frac{x_{thigh} \times x_{sha} \quad + y_{thigh} \times y_{shank}}{\sqrt{x_{thigh}^2 + y_{thigh}^2} \times \sqrt{x_{shank}^2 + y_{shank}^2}} \tag{3.14}$$

where θ_{knee} represents the knee angle.

The knee angle signal was saved in a csv file and afterwards analyzed using Python. In order to eliminate some rapid oscillations in markers locations and to smooth the signal, a first order low-pass Butterworth filter with a cutoff of 0,4 Hz and sampling frequency of 50 Hz was applied to the obtained signals. Thus, knee angle obtained from the markers' locations were used as a ground-truth.

As referred in section 3.7.1, the first validation method was used to validate the seven knee rehabilitation exercises that make part of the group I of the knee rehabilitation program. Calculated angles were compared with the ground-truth after a temporal alignment of the two signals, as will be explained in 3.7.3.1.

In relation to the second validation method (goniometer), as referred before, it does not allow continuous measurements, so for each exercise repetition, two angles were measured and noted manually. These angles correspond to the maximum and minimum values, so the maximum and minimum values of the sensor signal were calculated and compared with the goniometer ground truth.

3.7.3.1 Signals Alignment

To align the two signals (sensor signal and ground truth camera signal), cross-correlations between the two pairs of signals were computed and the locations of the maximum values of the cross-correlation indicated time leads or lags.

In mathematics, the convolution theorem states that under suitable conditions the Fourier transform of a convolution is the pointwise product of Fourier transforms. In other words, convolution in one domain (e.g., time domain) equals point-wise multiplication in the other domain (e.g., frequency domain). Let f and g be two functions with convolution $f * g$. Let $\mathcal{F}$ denote the Fourier transform operator, so $\mathcal{F}\{f\}$ and $\mathcal{F}\{g\}$ are the Fourier transforms of f and g, respectively [68]. Then,

$$\mathcal{F}(f * g) = \mathcal{F}(f) \cdot \mathcal{F}(g) \tag{3.15}$$

where $\cdot$ denotes point-wise multiplication.

By applying the inverse Fourier transform $\mathcal{F}^{-1}$, we have:

$$f * g = \mathcal{F}^{-1}\{\mathcal{F}\{f\} \cdot \mathcal{F}\{g\}\} \tag{3.16}$$

Similar logic allows computing the cross correlation in the same way. Being now f the knee angle signal obtained by the sensors and g the knee angle signal obtained by the first validation method, the following operation was applied:

$$f \star g = \mathcal{F}^{-1}(\overline{\mathcal{F}(f)} \cdot \mathcal{F}(g)) \tag{3.17}$$

where $\overline{\mathcal{F}(f)}$ is the complex conjugate of $\mathcal{F}(f)$.

The location of the maximum value of the operation defined in equation 3.17 was computed and subtracted to each value of the ground truth signal, since this last one is always delayed in relation to the sensor signal, because during signal acquisition video recordings started earlier than sensor acquisition.

3.7.3.2 Calibration

As will be explained and discussed in section 3.7.5, a calibration method was necessary in order to decrease significant errors on the knee angle estimation, since the presence of an offset was detected. So, a method that uses the camera motion tracking system or the goniometer to perform calibration of inertial sensors was implemented.

When the camera is used as validation method, the two obtained signals (signal from the sensors and signal from the camera) are continuous. However, when the goniometer is used as validation method, the sensor's signal is continuous and the goniometer's signal is discrete. It implies that calibration cannot be applied in the same way.

With this on mind, when the camera was the used validation method, the average value of the calibration signal and the sensor signal were calculated and the offset was defined. Then, the offset was subtracted to the sensor signal, since the obtained error was always negative, i.e., the sensor signals always had highest values in relation to the calibration signals.

Being f the sensor signal and g the calibration signal, both continuous signals, the mean value of $f(x)$ and $g(x)$ over the interval (a,b) was defined by:

$$\bar{f} = \frac{1}{b-a}\int_a^b f(i)\, di \quad (3.18)$$

$$\bar{g} = \frac{1}{b-a}\int_a^b g(i)\, di \quad (3.19)$$

The offset between the two signals is:

$$Offset = \bar{f} - \bar{g} \quad (3.20)$$

Then, a subtraction operation to the sensor signal was applied, obtaining so the calibrated sensor signal, $f_{calibrated}$:

$$f_{calibrated}(i) = f(i) - Offset \quad (3.21)$$

The same idea was applied when the goniometer was the validation method. In this case, since the goniometer signal is discrete, there was the need of obtain the correspondent values of the sensors' signal. The values obtained by the goniometer correspond to the maximum and minimum of each repetition. So, the maximum and minimum values of the sensors' signal were determined, obtaining a discrete signal. Then, the same method presented in equations 3.18, 3.19, 3.20 and 3.21 was applied, but taking into account that two discrete signals are being analyzed. In addition, since the goniometer's values were obtained manually, the time variable is not significant in the future analysis.

3.7.4 Experimental Statistics

In order to compare angle estimation between KneeRecovery system and the two used validation methods, a statistical analysis was performed.

For each validation method, mean absolute deviation, maximum absolute errors and standard deviation were calculated for each exercise. Box plots were created in order to compare the distribution of errors associated to each exercise. Moreover, only for the camera validation method, Pearson correlation coefficients were also determined to assess whether the correlation was statistically significant or not. This last statistical variable was not applied to goniometer validation method, because as explained previously, a discrete signal was acquired with this method. So, it would not show significant statistical results.

3.7.5 Results and Discussion

This section describes the results obtained with the proposed methods for KneeRecovery implementation. These results are relative to the experimental work described in 3.7.2 and will provide the necessary information to evaluate the algorithm performance. This section also enables the identification of gaps that need improvements. A simultaneous discussion of results is also done. Considering the overview block diagram depicted in Figure 3.1, after data acquisition, signal was processed in order to obtain the orientation of the thigh and shank segments, transforming the data from the sensor to the Earth reference frame. Then, knee angles were estimated.

The proposed experimental work was defined in order to compare the knee angle obtained using KneeRecovery system with two validation methods: camera motion tracking and goniometer. The camera validation system will have a great focus, since the goniometer was only included in the project, because of its wide use in clinics and for this reason it was considered to be an important inclusion.

Five healthy subjects and one unhealthy performed the seven described tests plus the two tests that make part of the criteria tests. Unfortunately, the unhealthy patient dropped the rehabilitation program, so it was not possible to perform all the tests that were expected.

The defined rehabilitation tests intend to analyze if the subject is able to perform a straight knee or to evaluate the achieved range of motion. At a clinical level, the angle representative of a straight knee is 0º, however in this project, this position is referred as 180º. The right knee is represented by 90º.

First, the obtained results relative to camera validation system are presented. The relevant results and the main problems will be identified and discussed.

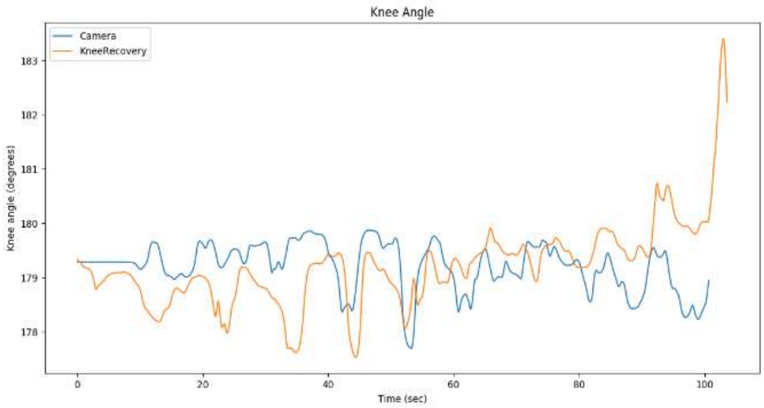
Secondly, a small section is dedicated to the results obtained when the goniometer was used as validation method.

A section about a case study relative to the patient who participated in this project is presented, discussed and the results are compared with the healthy ones.

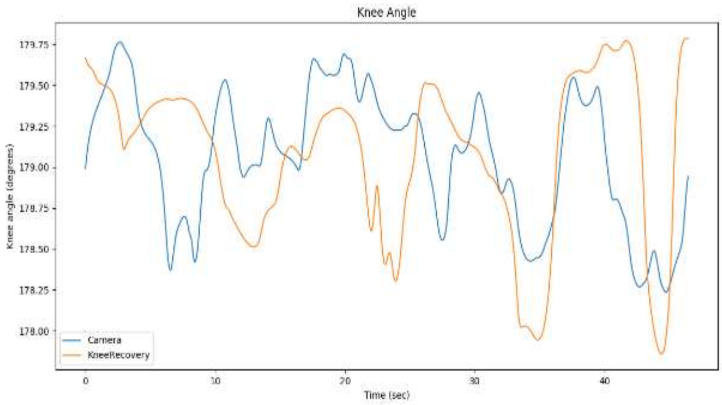
Lastly, an analysis about the ROM obtained by the different validation methods is presented.

3.7.5.1 Camera Motion Tracking Validation System

In order to compare the angles of the two systems (KneeRecovery and camera), some procedures were necessary in order to synchronize the signals. The cross-correlation between the two signals was computed and the locations of maximum values of the cross-correlation indicated lags. This identified lag was subtracted to each time value of the ground truth signal, since this last one is always delayed in relation to the sensor signal. This method had revealed to obtain good results, aligning the signals as expected. However, due the characteristic of oscillation and noise presented in the test 1 and mainly test 7, some of these had problems with alignment and the method showed failures in its execution. An example of this failure is shown in Figure 3.12. When this problem occurred, a visual identification of the lag had to be identified in order to synchronize the signals.



(a) Test 1 before synchronization



(b) Test 1 after synchronization failure

Figure 3.12: Synchronization failure.

As referred previously, a calibration method was necessary to be implemented, since an offset was observed in all the tests. A summary of the offset between the signal obtained from KneeRecovery system and from the camera validation method is presented in Table 3.1.

Table 3.1: Summary of the offset mean values between the KneeRecovery and camera signals for the 7 tests in all the dataset. The grey cells correspond to the tests that were not accomplished due to the patient's dropout. The results are presented in the form mean ± standard deviation.

	Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Test 6**	**Test 7**
Subject 1	22,2 ± 0,5	21,1 ± 1,0	33,2 ± 2,7	29,7 ± 2,5	20,4 ± 1,1	31,5 ± 5,0	19,2 ± 1,3
Subject 2	13,9 ± 0,5	13,9 ± 0,8	19,5 ± 1,0	21,3 ± 2,5	9,9 ± 1,1	14,2 ± 6,7	1,6 ± 1,4
Subject 3	17,1 ± 0,9	15,6 ± 0,9	14,3 ± 2,8	12,7 ± 2,6	13,7 ± 1,4	24,2 ± 7,5	15,0 ± 1,1
Subject 4	13,1 ± 0,6	7,6 ± 1,3	8,6 ± 4,1	12,2 ± 4,7	20,4 ± 3,2	7,8 ± 2,9	5,1 ± 1,4
Subject 5	18,1 ± 2,9	13,5 ± 2,2	2,4 ± 2,6	2,7 ± 3,1	23,2 ± 0,9	28,4 ± 3,2	0,4 ± 0,8
Subject 6, session 1	19,7 ± 1,2	14,9 ± 0,9	17,4 ± 8,2	3,2 ± 6,2	52,9 ± 0,7		
Subject 6, session 2	2,7 ± 0,4	4,2 ± 0,7	12,8 ±8,9				

The offset between the signal obtained by KneeRecovery system and the camera validation method (the ground truth) was presented in all the analyzed signals, being that the KneeRecovery signal showed superior values relative to the ground truth.

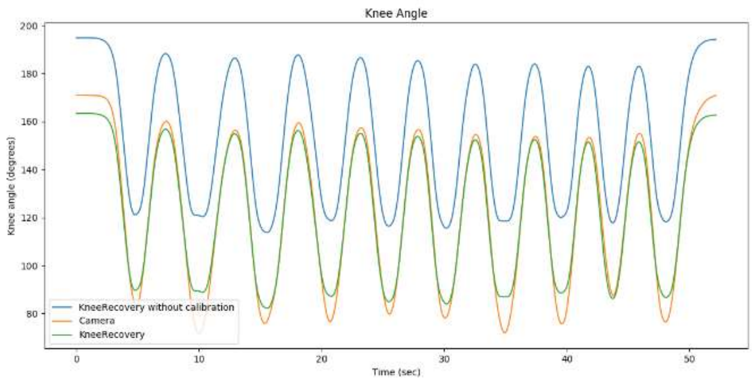
Although the results obtained without calibration indicate that the used algorithm may provide acceptable performance, significant errors on the knee angle computed may still occur. So, in order to obtain such satisfactory response when large errors are presented, suitable calibration is required.

As can be concluded from Table 3.1, the presence of an offset is common for all the tests and this one vary from patient to patient and from exercise to exercise. This means that the offset can be derived from different sources.

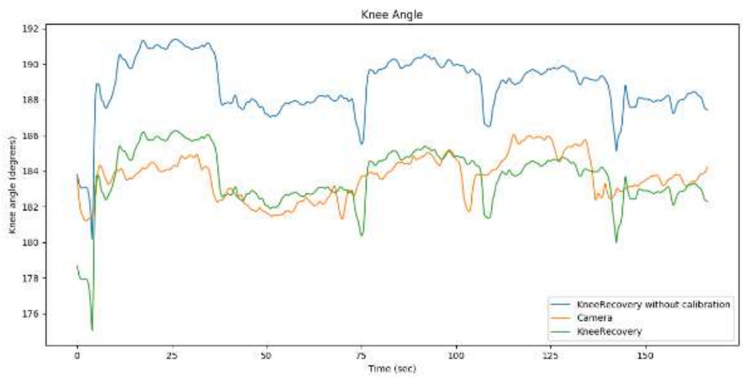
Firstly, one of the big problems of data acquisition relates to the sensors' and markers' placement. In fact, analyzing the offsets obtained for the same test, but for different subjects, it can be observed that the offset varies from subject to subject. Obviously, the sensor's and marker's placement varies between subjects, which means that this placement influences the offset. During data acquisition, sensors' bracelets and markers' placement was always done by the same person in order to eliminate one of the possible error varieties if the different users have to do the placement to him/herself. So, subjects were not charged with this task. However, due to the non-planar and complex surface of the leg structure, a perfect alignment hardly is achieved, even when anatomical positions were defined and a very carefully placement is performed. This condition means that it was difficult to ensure the axes of the two sensors on the thigh and shank were in the same direction. In fact, it reveals to be an issue when considering a home-based rehabilitation scenario. Calibration procedures based on calibration movements or postures and complex mathematical models have been proposed to correct sensor misalignment, however, the most advanced and accurate methodologies require the execution of complex movements which are unsuitable to inexpert users and increase user burden, making them unsuitable to interactive applications [60] [69] [70].

In fact, during the first data acquisition of this project, the sensors' and markers' placement was not strictly carried out, since anatomical positions had not yet been defined. These first results had shown a large offset and they were essential to consider the need to improve and place the sensors and markers with much more accuracy, defining and searching in the bibliography the anatomical positions in which the material should be placed. It is worth mentioning that this data collection was not considered in the final results.

Comparing the offsets obtained for the same subject, but for different tests, from Table 3.1 it can be observed that in general the offset in tests 5 and 6 have a tendency for presenting greater errors when compared with tests 1, 2, 3 and 4, and test 7 has a tendency for presenting the smallest offset. An illustrative example of this condition is shown in Figure 3.13. It can be explained by the different velocities associated with each exercise. In fact, in test 7 (single leg balancing) there is almost no movement. The subject stands, balancing the leg that is being studied for 30 seconds. About the tests 5 and 6, hip extension and prone quadriceps stretch, respectively, they may propitiate faster movements in relation to tests 1, 2, 3 and 4. It is worth mentioning that in this analysis the sensors' placement did not have influence, since the placement did not change between the tests of the same subject. A study investigated the estimation of knee joint flexion/extension angles from acceleration and angular velocity data in different speeds [67]. The results showed that the accuracy decreased as the speed increases, which meets the obtained results in this project.



(a) Test 6



(b) Test 7

Figure 3.13: Comparison between knee angles obtained with KneeRecovery system (with and without calibration) and the camera validation method for the (a) test 6 and (b) test 7 of the experimental work. Test 6 represents the group of tests that present a large offset and test 7 represents the group with smaller offsets. The green and blue lines represent the knee angle signal obtained by KneeRecovery system with and without calibration, respectively, and the orange line represents the knee angle signal obtained by camera validation method.

One of the disadvantages of application of wearable sensors in human motion analysis is that noise in data collection is usually severe. So, another possible source of error is related with the resulting noise inherent to the motion performed during the exercises. Since the sensors were fixed on the thigh and shank with a bracelet, which allows a small amount of motion between the sensors and the body, skin motion artifact due to impact loading and muscle activities would contaminate the measured accelerations and angular velocities of the thigh and shank with noise, and then bring errors to the calculated knee angles [53]. Therefore, knee angle signal had to be filtered. Two different filters were experimented. Initially, the Savitzky-Golay filter was implemented, since several bibliographic referenced had mentioned it as a low-pass filter, well adapted for data smoothing [71] [72] [73]. However, the final implemented filter was a first-order low-pass Butterworth filter [74] [75], since this one had shown small better results than the Savitzky-Golay. As expected, after the filter application, it was inevitable that the signal was distorted. When data which had a peak was smoothed, the peak height was more reduced with the Savitsky-Golay filter in comparison with the Butterwoth filter, so this last one had been chosen to be applied.

Besides the benefits of inertial systems as low cost, small dimensions, portability, high compactness and efficient computation, they also present some disadvantages. Accurate estimates of body orientation in the 3D space can be produced using quite complex filter algorithms [46], as the sensor fusion algorithm implemented. An essential prerequisite for multi-sensor data fusion is transforming all sensor readings into a common coordinate system. This is referred as sensor registration. However, registration errors usually exist and deteriorate the fusion performance seriously. Such errors may come from the azimuth biases caused by axis misalignments, the offset biases of range measurements, and probably the location biases of moving sensor platforms. This constant offset produced by the sensors is one of the major disadvantage of inertial sensors, together with the reduced performance in terms of accuracy [76]. It is also known that the use of numerical integration of acceleration/angular velocity information from inertial sensors (accelerometers/gyroscopes) to obtain orientation information inherently causes orientation errors to grow with time, which is commonly known as "integration drift" [77]. It is inevitable the existence of an error associated due to these mentioned inertial sensors conditions, which will affect the knee angles estimation.

As knee angles require the use of two sensors simultaneously, it means the possibility of error accumulation from both sensors.

Another source of errors may come from the used validation method, the camera motion tracking system. A perfect and perpendicular alignment of the camera with the plane of movement is difficult to guarantee. The coordinates of the markers on the video may also have some problems, not only due to tracking errors (since most of the times object point location was manually adjusted), but also due to the distortions that are introduced on the image while capturing the video [60]. As previously mentioning, the use of reflective markers instead of the used yellow markers could be a better choice to cause good contrast and facilitate the automatic tracking. When relative fast movements were performed, a blurriness and pixilation were presented during video analysis, which may have influenced the results. However, the reliability of Kinovea in measuring joint angles had been previously demonstrated, therefore, it was considered as an acceptable source of information that could be used as reference in the evaluation of the results [60] [78].

It is worth mentioning that the need to implement a calibration method was also referred in [79]. This study proposed the inclusion of Kinect as an additional correction, in order to minimize some of the undesirable effects of the used system. Problems related with sensor readings and the initial states related to each sensor are referred.

In summary, the presence of an offset is present in all the tests, however it is not a systematic error, since it is dependent from different factors. The existence of this error caused the need of a calibration method, which is dependent from the validation method. It means that future work can still be defined to improve KneeRecovery system.

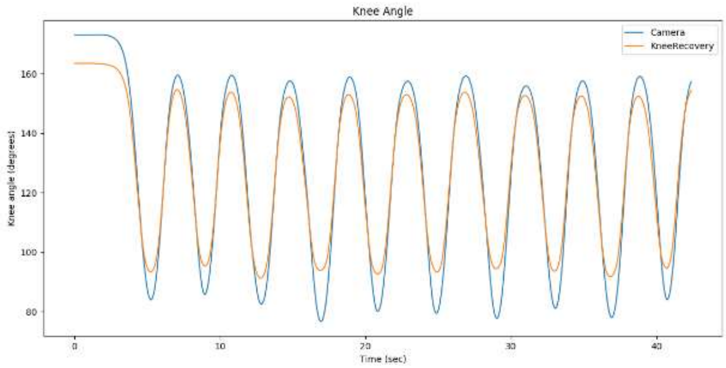
From now on, in this section, the graphics and the results about the knee angle obtained by KneeRecovery system include always the calibration, using the camera validation method. So, the angles are always relative and the errors are relative to a signal that is compensated by the offset.

The statistics based on the experiments are now introduced in order to compare the KneeRecovery system and camera validation system. To obtain a quantitative analysis, the mean absolute deviation between them was calculated for all the tests performed for the different subjects. The absolute error was also defined in terms of maximum and standard deviation and Pearson correlation coefficients were calculated. A mean value is presented for the four parameters. Camera motion tracking system validated the seven defined tests in the experimental protocol. The results of this statistic analysis are presented in Table 3.2 and the discussion of the obtained results is described next.

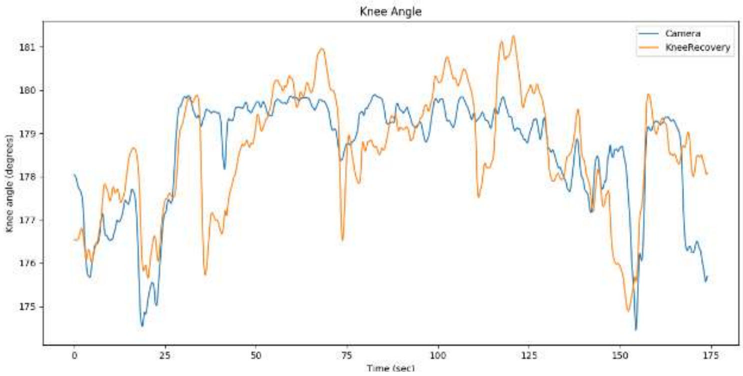
Table 3.2: Absolute errors (in degrees) of knee angles estimation for each test and respective correlations with angles extracted from the camera motion tracking validation system. The presented values are the mean of all the subjects.

Test	Mean Absolute Deviation	Maximum Error	Standard Deviation	Pearson Correlation Coefficient
Test 1	0,85 ± 0,78	2,58 ± 1,58	0,51 ± 0,31	0,60 ± 0,35
Test 2	0,89 ± 0,31	3,03 ± 1,67	0,69 ± 0,36	0,91 ± 0,08
Test 3	3,49 ± 2,29	11,85 ± 7,62	2,55 ± 1,69	0,96 ± 0,05
Test 4	3,00 ± 1,29	9,17 ± 2,89	1,98 ± 0,55	0,99 ± 0,00
Test 5	1,12 ± 0,70	3,60 ± 1,93	0,85 ± 0,48	0,87 ± 0,11
Test 6	4,02 ± 1,78	15,65 ± 3,65	3,05 ± 0,74	0,99 ± 0,00
Test 7	0,74 ± 0,40	3,79 ± 1,50	0,70 ± 0,18	0,31 ± 0,29

Considering Table 3.2, it is possible to observe that the tests 3,4 and 6 are the ones which present higher errors in terms of mean absolute deviation, maximum absolute error and standard deviation when compared with the other tests. This can be explained because, in fact tests 3, 4 and 6 are the ones which propitiate faster movements. They evaluate the knee ROM and the exercises involve a greater amplitude of motion, while the others evaluate if the subject is able to have the knee completely straighten and the exercises involve a small amount of movement, resulting less velocity. For example, test 7 (single leg balancing) is an exercise in which the subject has to balance the leg in analysis for 30 seconds, which means that most of the time he/she is practically stopped. On the other hand, in test 6 it is expected that the subject will reach 90 degrees of flexion, at least. This comparison between these two exercises is shown in Figure 3.14. As referred previously, a study investigated the estimation of knee joint angles from inertial sensors data in different velocities and the results had revealed that the accuracy decreased as the speed increases [67]. This conclusion can also be taken from the results obtained in this project.



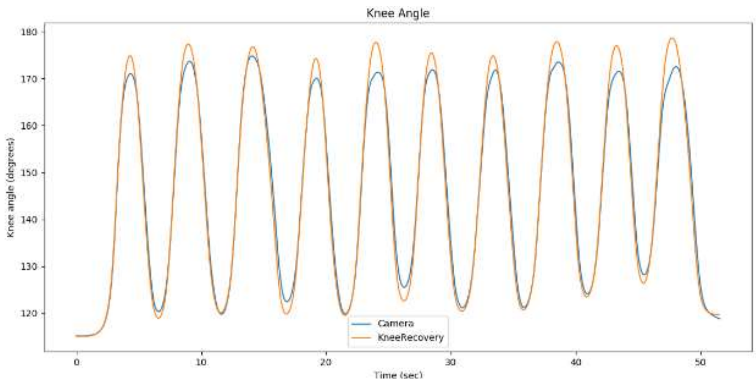
(a) Test 6



(b) Test 7

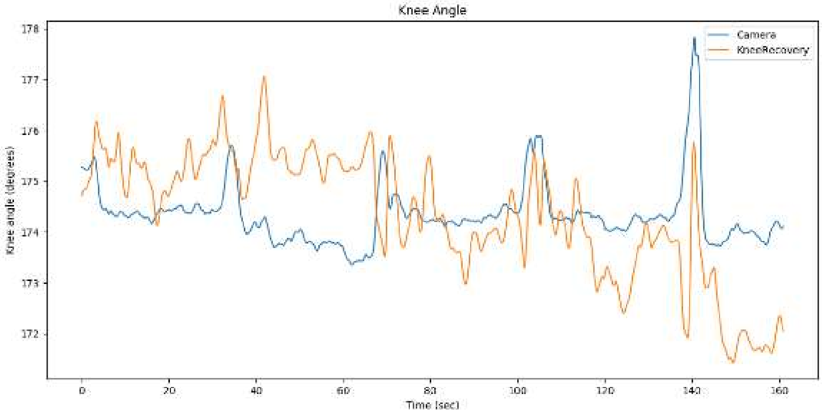
Figure 3.14: Knee angle estimation by KneeRecovery system and camera validation system for (a) test 6 and (b) test 7. Test 6 is a representative exercise of the group that involves faster movements. Test 7 is a representative exercise of the group that involve slower movements and consequently lower errors. The orange line represents the KneeRecovery results and the blue line the camera results.

From Table 3.2, it is also possible to observe that a strong correlation exists between angles extracted using KneeRecovery system and angles extracted from video recordings, with Pearson correlation coefficients greater than 0,96. This result is not verified in tests 1 and 7, since they are not periodic signals and present noise and oscillations inside a small amplitude. To illustrate this condition, the results obtained from tests 4 and 7 are presented in Figure 3.15.



(a) Test 4

Figure 3.15: Knee angle estimation by KneeRecovery system and camera validation system for (a) test 4 and (b) test 7. Test 4 is a representative exercise of the group that presents strong values of correlation and test 7 is a representative exercise of the group, which due to be a non-periodic signal, the correlation values were low. The orange line represents the KneeRecovery results and the blue line the camera results.



(b) Test 7

Figure 3.15 *(continued)*: Knee angle estimation by KneeRecovery system and camera validation system for (a) test 4 and (b) test 7. Test 4 is a representative exercise of the group that presents strong values of correlation and test 7 is a representative exercise of the group, which due to be a non-periodic signal, the correlation values were low. The orange line represents the KneeRecovery results and the blue line the camera results.

Besides the referred differences between the set of exercises (faster and slower exercises), all of them revealed an acceptable accuracy with mean absolute deviation below 4,02 degrees. The maximum errors are not significant, except for the tests 3, 4 and 6 that had a maximum error of 11,85; 9,17 and 15,65 degrees, respectively. The magnitude of these errors may be a significant limitation, since it can mislead the analysis of the clinician or the patient's perception of his/her evolution. Non-objective measurements and incorrect interpretation of the its results can have a substantial impact on the development of the scientific basis of therapeutic interventions [65]. So, in order to decrease this type of errors, future improvements constitute a need of the KneeRecovery system. Except for tests 1 and 7, the correlation's results demonstrate the existence of a strong dependence and relationship between the knee angle signals obtained by KneeRecovery system and the camera validation method, which means that both signals share a very similar shape.

Box and Whisker charts were created in order to compare and graphically visualize the errors distribution associated to each test. According to Figure 3.16 , errors in estimate knee joint angles are generally low, with mean values below 4 degrees for all the tests. As explained, due to greater velocities, tests 3, 4 and 6 present greater errors and spread in the obtained results.

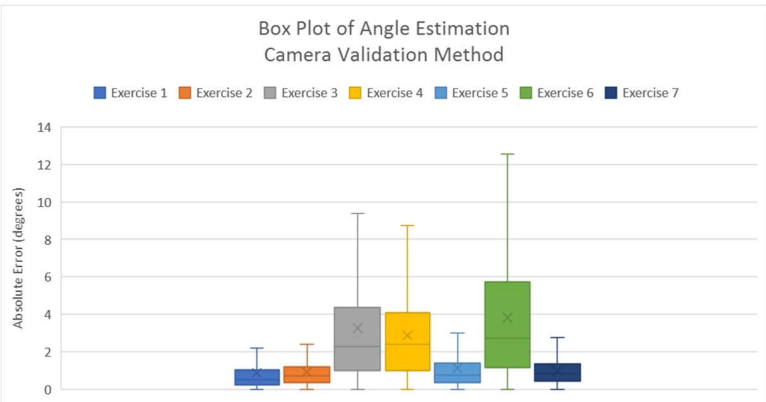


Figure 3.16: Absolute errors of knee angles for each the 7 tests, when the camera validation system was used. × marks represent average values.

The results which illustrate the typical knee angle obtained for a healthy subject for each test are now presented.

It is worth mentioning that the results that will be presented are representative of the common healthy patterns, however, variations in the amplitudes of values of the knee angles in different subjects were verified. These differences can be explained as the result of different subjects had performed the exercises.

The main aim of tests 1, 2, 5 and 7 is to induce and evaluate if the subject is able to perform a straight knee, since it is an important achievement after TKR. Usually, after the surgery, patients have a big difficulty in achieving a completely straight the knee. The angle that symbolizes a straight knee is an angle close to 180º. The main aim of test 3, 4 and 6 is to evaluate the ROM, whose usually values go from 90º/100º to 180º.

The test 1, quadriceps setting exercise is illustrated in Figure 3.17. It is visible that when the subject goes from rest position to the knee straight position, the angle value increases slightly and becomes close to 180º, during approximately 6 seconds, decreasing the small flexion that had existed before, as was expected.

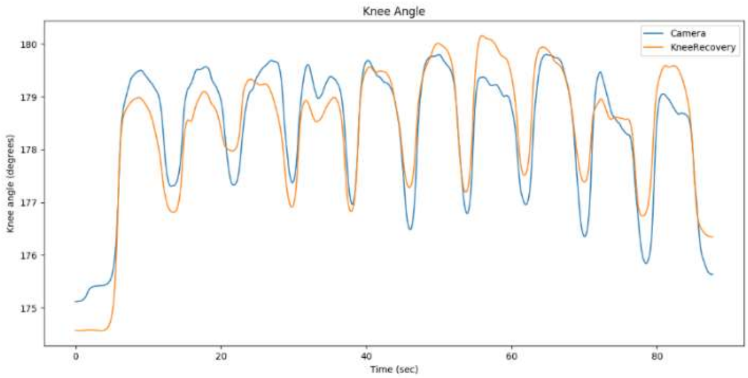


Figure 3.17: Knee angle obtained in test 1. The orange line represents the KneeRecovery results and the blue line the camera results.

The test 2, straight leg raising exercise is illustrated in Figure 3.18. Initially, the subject is in a lying and relaxed position and the knee angle is lower than 180º. When the movement starts, i.e., when the subject starts to raise the leg from the bed, the lower limb should be kept completely straight, so an approximation to 180º is verified. When the subject returns to the resting position, the knee angle returns to be closed to the starting position.

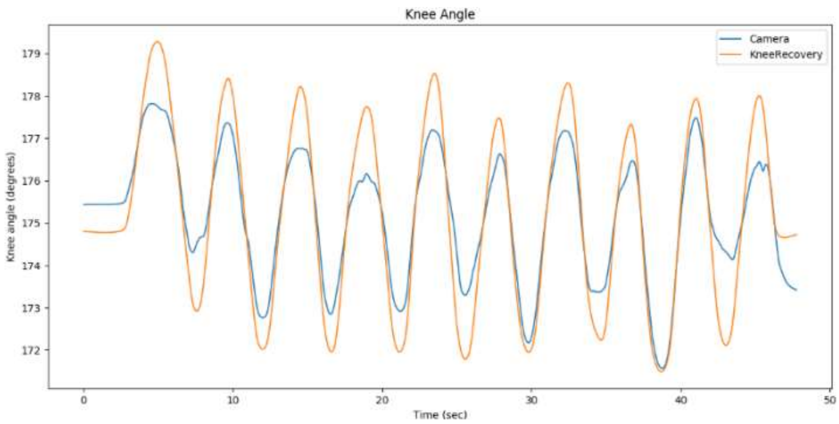


Figure 3.18: Knee angle obtained in test 2. The orange line represents the KneeRecovery results and the blue line the camera results.

In test 3, the seated heel slides exercise, the subject starts with the bent knee, which means that an angle close to 90º should be verified. In the case of Figure 3.19, the knee presented approximately 110º of flexion. It can be explained, since the high of the chair in which the subject was seated did not induced a position in which the knee had a completely right angle. When the subject starts to slide the foot outward, an increase of the knee angle is verified, since the knee approximates to the straight position and a value close to 170º is verified. Summarizing, the subject performed a ROM of 60º, approximately.

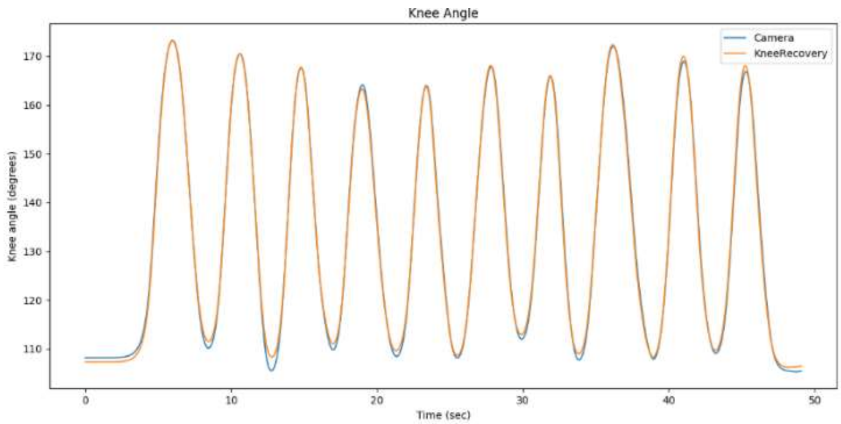


Figure 3.19: Knee angle obtained in test 3. The orange line represents the KneeRecovery results and the blue line the camera results.

Test 4, long arc knee extension exercise has a behavior similar to test 3 and it is illustrated in Figure 3.20. The subject starts with the knee bent, so an angle close to 90º should be verified. Then, he/she straightens the knee and an angle close to 180º should be achieved. In the case of **Erro! A origem da referência não foi encontrada.**, a ROM of 65º, proximately, was verified.

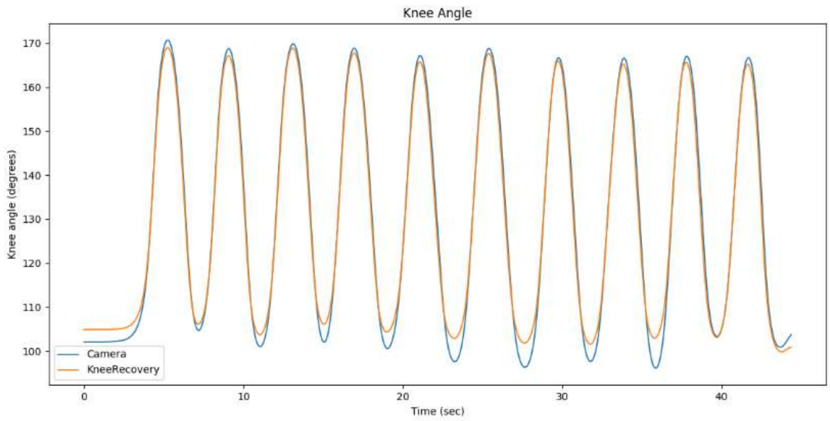


Figure 3.20: Knee angle obtained in test 4. The orange line represents the KneeRecovery results and the blue line the camera results.

Test 5, hip extension exercise is in somehow an exercise opposite to test 2, since the execution is the same, but in this case the subject lies on his/her stomach in bed. So, initially an angle close to 180º is verified (in the case illustrated in Figure 3.21, 172º) and when the leg starts to raise straight up towards the ceiling, a decrease of the angle is verified, since this movement induces the subject to have the knee slightly bent.

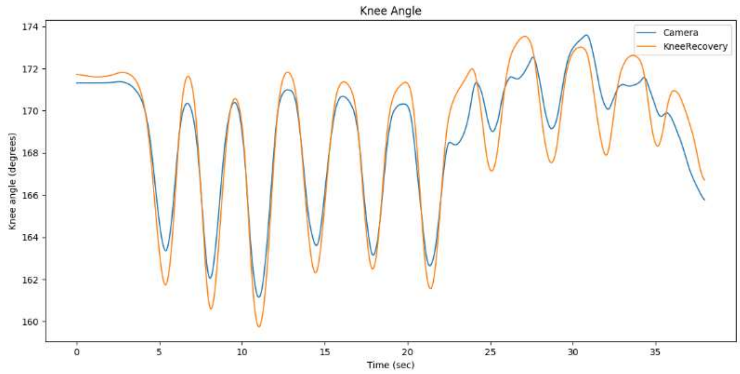


Figure 3.21: Knee angle obtained in test 5. The orange line represents the KneeRecovery results and the blue line the camera results.

Test 6, prone quadriceps stretch exercise is in somehow an exercise opposite to test 4, since the execution is the same, but in this case the subject lies on his/her stomach in bed. Initially, the subject is in a resting position and with the leg straight, so an angle close to 180º should be verified. Then, the subject bends the knee and the angle decreases, becoming close to 90º. In the case illustrated in Figure 3.22, a ROM of 70º was achieved.

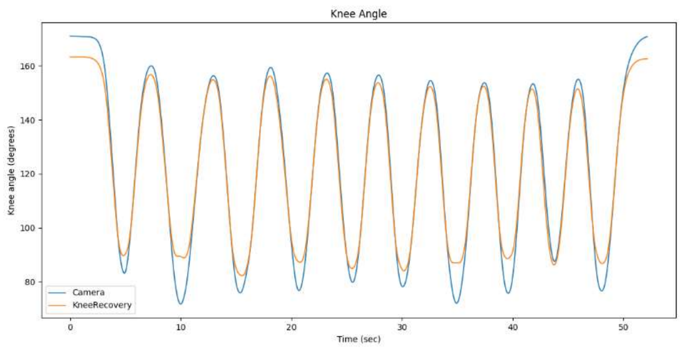


Figure 3.22: Knee angle obtained in test 6. The orange line represents the KneeRecovery results and the blue line the camera results.

Test 7, single leg balancing intends to evaluate if the patient is able to balance the leg with the knee completely straight for 30 seconds. From Figure 3.23 it is observable that during all the test the angle maintains between 177º and 179º. Besides the verified oscillations, since the knee angle is always close to a certain value, it means that the balance was achieved.

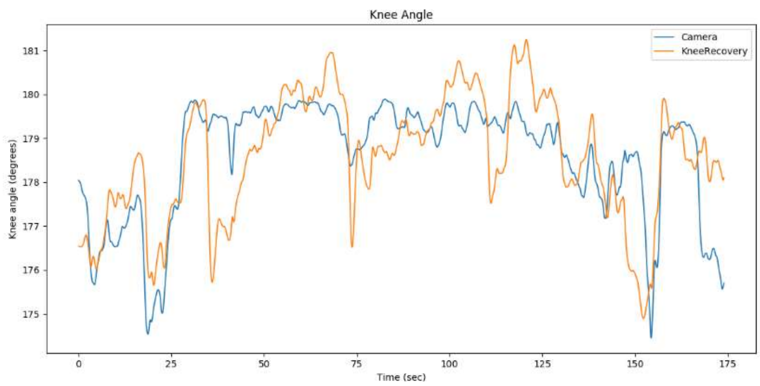


Figure 3.23: Knee angle obtained in test 7. The orange line represents the KneeRecovery results and the blue line the camera results.

3.7.5.2 Goniometer Validation System

As discussed in section 3.7.1, goniometry is a method widely used in clinics and for this reason, it was also target of study in this project. The goniometer method was used as a validation method for the criteria progression tests. An offset was also verified, so, in this section, the graphics and the results about the knee angle obtained by KneeRecovery system include always the calibration, but this time using the goniometer validation method. The angles are always relative and the errors are relative to a signal that is compensated by the offset.

A summary of the offset between the signal obtained from KneeRecovery system and from the goniometer validation method is presented in Table 3.3.

Table 3.3: Resume of the offset mean values between the KneeRecovery and goniometer for criteria test I and criteria test II in all the dataset.

	Criteria I	**Criteria II**
Subject 1	31, 1 ± 6,5	1,4 ± 2,4
Subject 2	26,4 ± 6,6	4,0 ± 4,5
Subject 3	21,1 ± 2,0	15,0 ± 3,7
Subject 4	15,9 ± 2,7	8,2 ± 4,9
Subject 5	19,4 ± 6,4	8,4 ± 3,9
Subject 6	6,2 ± 8,6	

As can be understood from Table 3.3, such as with the camera validation system, the offset problem was also verified with the goniometer and similar conclusions can be taken. As referred previously, factors like sensors' placement, noise resulting from the application of wearable sensors in human motion, the simultaneous use of two sensors, the offset biases and drift sensors problems can justify the obtained offset error. Problems of accuracy and reliability of the goniometer can be added in this analysis.

Table 3.4 presents the statistical analysis results in order to compare the KneeRecovery system and the goniometer validation method. Criteria test I is equal to test 2 and criteria test II is equal to test 4. So, a comparison between the two validation systems is possible to be done.

Table 3.4: Absolute errors (in degrees) of knee angles estimation for each test when the goniometer was used as validation method. The presented values are the mean of all the subjects.

Test	**Mean Absolute Deviation**	**Maximum Error**	**Standard Deviation**
Criteria I	4,61 ± 2,11	11,04 ± 4,43	2,85 ± 1,21
Criteria II	4,22 ± 2,08	9,05 ± 2,71	9,06 ± 12,09

The three parameters evaluated, mean absolute deviation, maximum error and standard deviation revealed to be slightly higher than the results obtained with the camera. This can be explained by the lower precision of the goniometer, mainly when static situations are not being evaluated, as referred in [80].

Box and Whisker charts were created in order to compare and graphically visualize the errors distribution associated to each criteria test and they are presented in Figure 3.24.

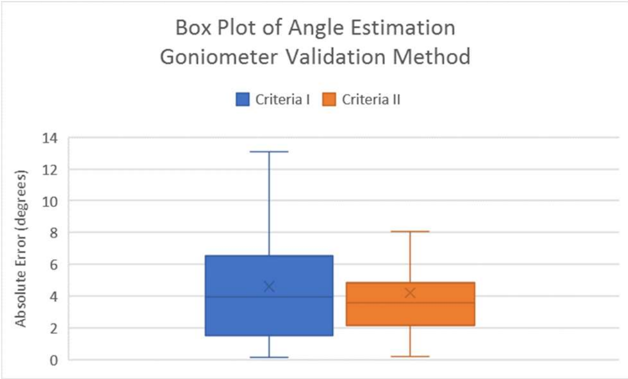


Figure 3.24: Absolute errors of knee angles for each the two criteria progression tests, when the goniometer validation system was used.

According to Figure 3.24, errors in estimate knee joint angles present mean values below 7 degrees for the two tests. It is visible that once again, since criteria test I implies a greater movement and can induce higher velocity than criteria II, the first presented greater errors and spread in the obtained results.

3.7.5.3 Case of study

A 74 years old patient who suffered knee osteoarthritis and was subjected to TKR was target of study in this project. The aim was to follow the recovery and progress of the patient, so four sessions were defined. However, the patient dropped the rehabilitation sessions and only the next ones were made:

- Session 1: test 1 and 2.
- Session 2: test 1, 2, 3, 4, 5 and criteria test I.

The sessions had a time interval of two weeks.

According to the three sets of the rehabilitation program presented in section 3.1, an analysis of each one will be presented. The results have as point of comparison the camera validation method.

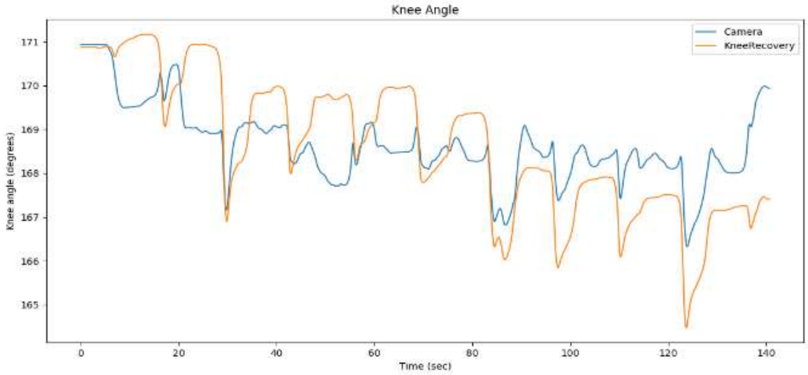
For this analysis, the camera validation method was used and for that reason the graphics and the results about the knee angle obtained by KneeRecovery system include always the calibration, using the camera validation method.

Set I – Knee Rehabilitation Exercises

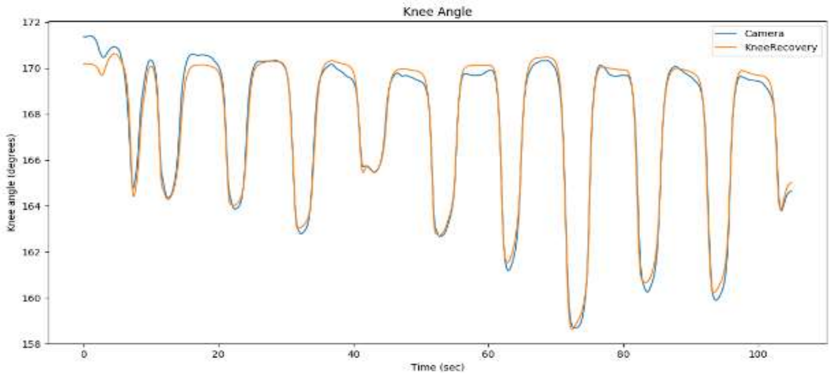
The first set corresponds to the knee rehabilitation exercises performed by the patient. An analysis of the patient's evolution and a comparison with the healthy subjects will be performed.

Erro! A origem da referência não foi encontrada. presents a comparison between the knee angle obtained in test 1 for the unhealthy subject in different moments of his/her recovery and the healthy subject. The aim of test 1 is to achieve a straight knee, which is represented by 180 degrees.

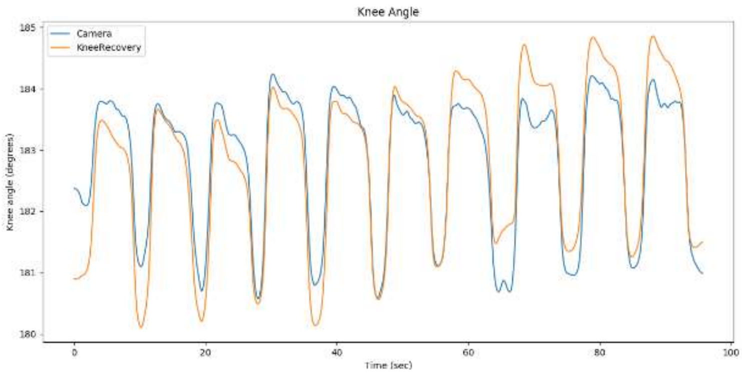
From the first (Figure 3.25 (a)) to the second session, (Figure 3.25 (b)), an improvement is visible. In fact, in the first session, the patient was not able to perform a constant angle and it was decreasing to values lower than 170 degrees, while in the second session, the patient maintained a constant angle of 170 degrees (when the straight position was performed). When a comparison with the healthy subject is done (Figure 3.25 (c)), it is visible that this one was able to achieve better results, since an angle close to 180 degrees was achieved, while the unhealthy only achieved 170 degrees.



(a) Knee angle performed by the unhealthy subject in the first session.



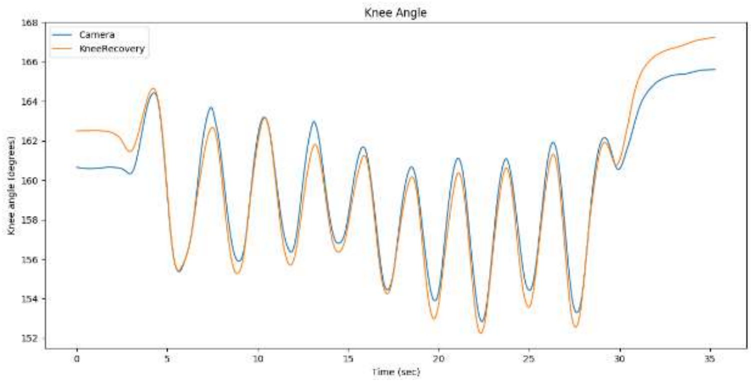
(b) Knee angle performed by the unhealthy subject in the second session.



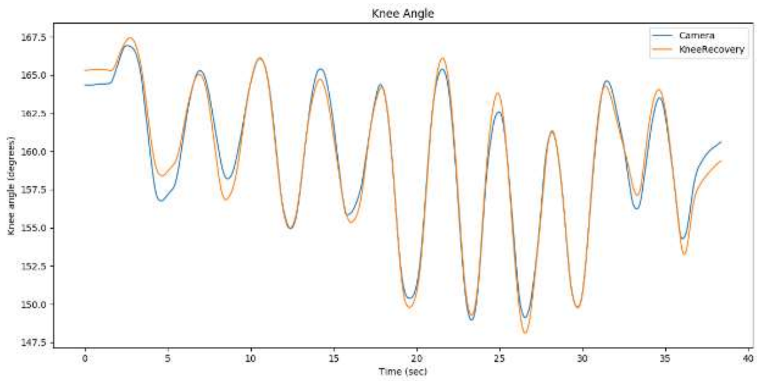
(c) Knee angle performed by a healthy patient.

Figure 3.25: Comparison of the knee angle achieved by the unhealthy subject in different recovery phases and the healthy subject in test 1. The orange line represents the KneeRecovery results and the blue line the camera results.

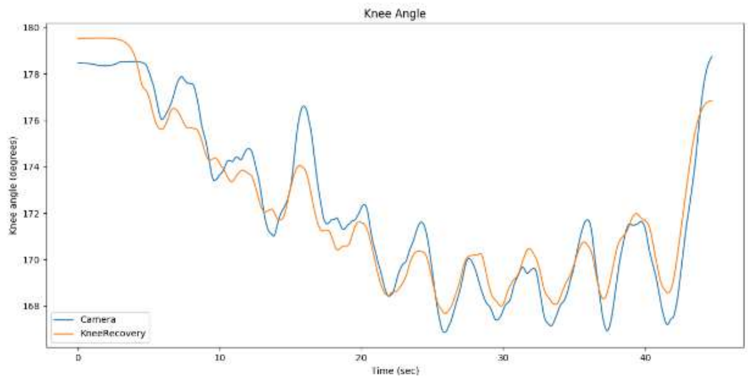
Figure 3.26 presents the same previous comparison, but this time for test 2. Analyzing the two different moments, it is observable that in the second session, the unhealthy subject achieved a slightly better result than in the first session, as was expected. The healthy subject performed a straight knee close to 180º, while the unhealthy only achieved 167º in the second session.



(a) Knee angle performed by the unhealthy subject in the first session.



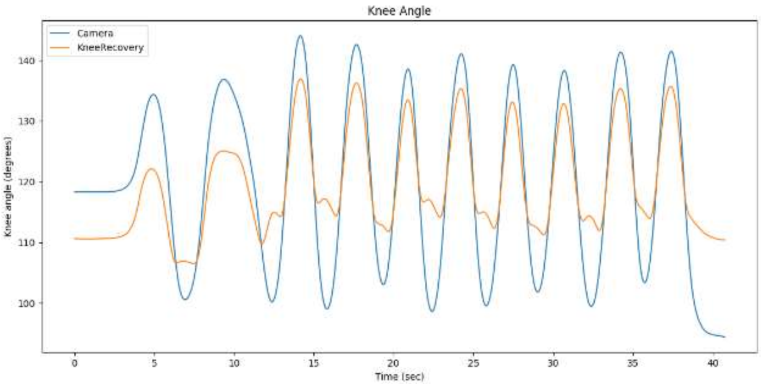
(b) Knee angle performed by the unhealthy subject in the second session.



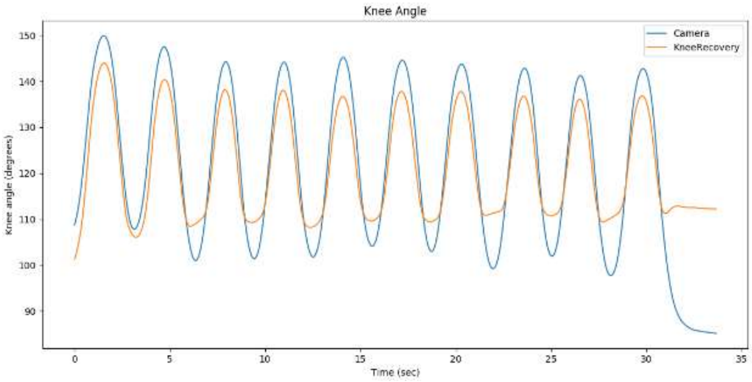
(c) Knee angle performed by a healthy patient.

Figure 3.26: Comparison of the knee angle achieved by the unhealthy subject in different recovery phases and the healthy subject in test 2. The orange line represents the KneeRecovery results and the blue line the camera results.

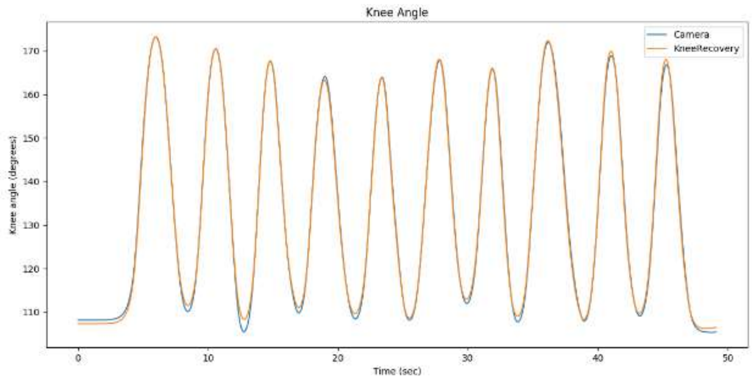
Figure 3.27 illustrates again the same comparisons as the previous ones, but this time for test 3. An evolution from the first session to the second session is verified, since in the first one the patient achieved a ROM of 30º (between 105º and 135º) and in the second session 40º (between 100º and 140º). Comparing with the healthy patient, this last one performed better results, obtaining a ROM of 60º (between 110º and 170º), as was expected.



(a) Knee angle performed by the unhealthy subject in the first session.



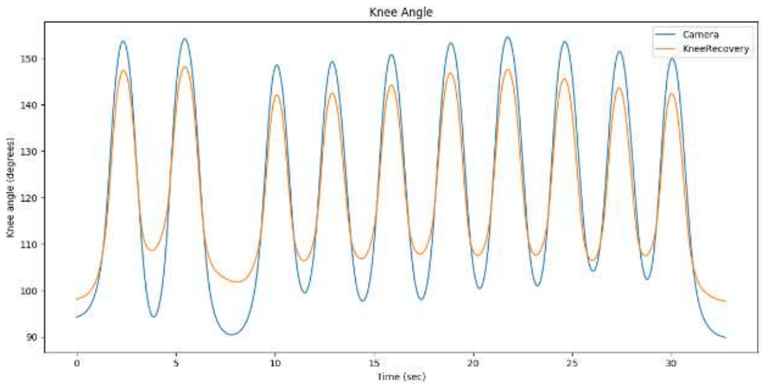
(b) Knee angle performed by the unhealthy subject in the second session.



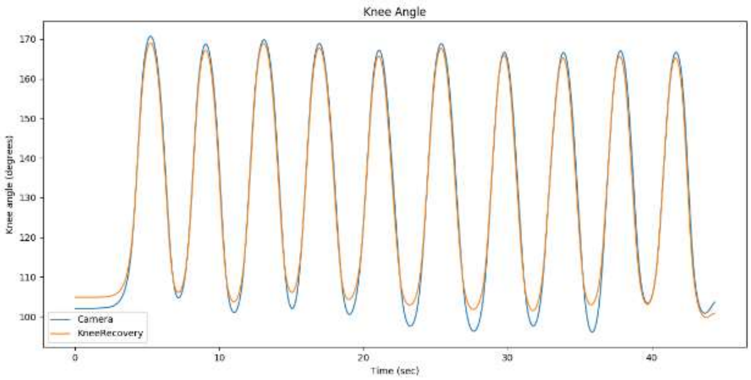
(c) Knee angle performed by a healthy patient.

Figure 3.27: Comparison of the knee angle achieved by the unhealthy subject in different recovery phases and the healthy subject in test 3. The orange line represents the KneeRecovery results and the blue line the camera results.

In Figure 3.28, a comparison between the unhealthy and healthy subjects for the test 4 is illustrated. Better results were clearly obtained by the healthy one, with a ROM of 70º (between 100º and 170º), while the unhealthy subject achieved a ROM of 50º (between 100º and 150º).



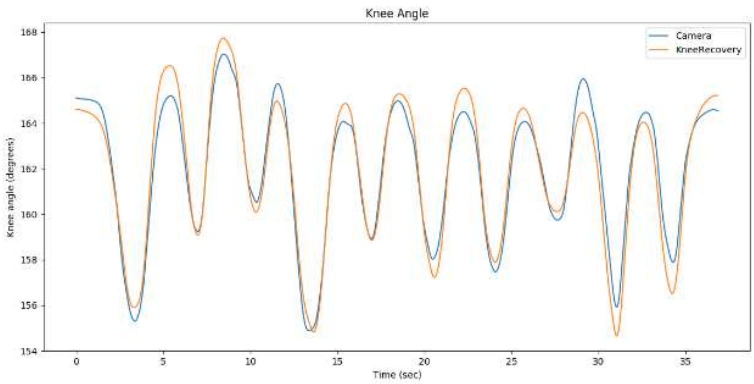
(a) Knee angle performed by the unhealthy subject.



(b) Knee angle performed by the healthy subject.

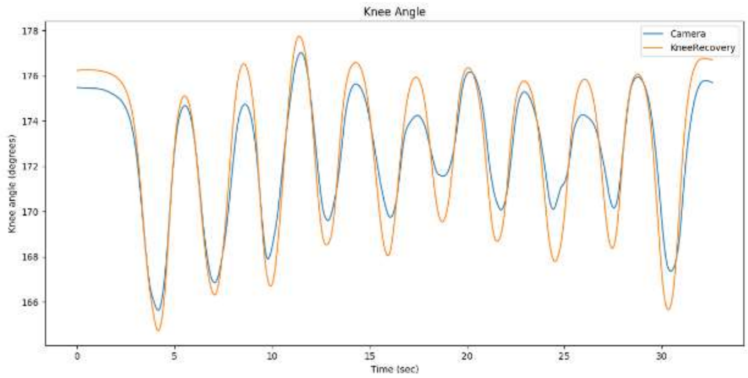
Figure 3.28: Comparison of the knee angle achieved by the unhealthy and healthy subjects in test 4. The orange line represents the KneeRecovery results and the blue line the camera results.

In Figure 3.29, a comparison between the unhealthy and healthy subjects for test 5 is illustrated. A difference is verified, since the healthy one achieved a straighter knee than the unhealthy subject.



(a) Knee angle performed by the unhealthy subject.

Figure 3.29: Comparison of the knee angle achieved by the unhealthy and healthy subjects in test 5. The orange line represents the KneeRecovery results and the blue line the camera results.



(b) Knee angle performed by the healthy subject.

Figure 3.29 (continued): Comparison of the knee angle achieved by the unhealthy and healthy subjects in test 5. The orange line represents the KneeRecovery results and the blue line the camera results.

Set II – Progression Criteria for the next phases

The second set of the knee rehabilitation program is about the criteria that evaluate if the patient is able to progress to the second and third phases of the program.

Due to the patient's dropout, only the criteria to advance to the second phase was possible to analyze. As defined before, the patient had to be able to perform the long arc knee extension exercise, achieving 0º extension and 90º flexion; had to feel a level pain less than 5 in a scale from 0 to 10 and the edema had to be not present. Figure 3.30 presents the knee angles obtained when the patient was asked to perform the long arc knee extension exercise. As explained previously, the validation was performed with the goniometer, so discrete signals were analyzed. As can be observed, he/she only achieved flexion and extension angles of 95º and 160º, respectively, i.e., 95º and 20º, respectively, in clinical terms, which means that the criteria were not achieved in this point. About the pain level and edema, the criteria were fulfilled, since the patient reported a pain of level 4 and the edema was almost insignificant. Summarizing, according to the defined criteria to progress to the second phase of the program, the patient did not fulfill the requisites.

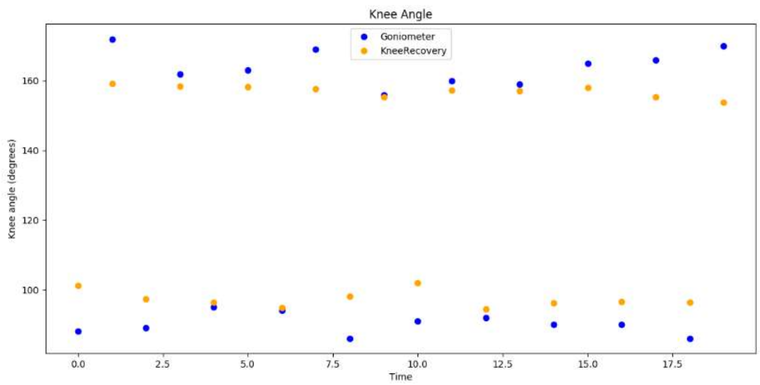


Figure 3.30: Knee angle performed by the patient in the long arc knee extension exercise (Progression Criteria Test I), one of the criteria to progress to the second phase of the knee rehabilitation protocol.

Set III – Evolution Report

The third set of the knee rehabilitation program intends to be the patient's evolution report. Once again, due to the patient's dropout it was incomplete.

According to parameters established in the program, the next conclusions can be taken.

- At the end of the first phase, the patient achieved a ROM of 75º (between 20º and 95º).
- The patient reported a pain of 4.
- The edema was almost insignificant.

3.7.5.4 ROM analysis

As already understood, the KneeRecovery system is dependent of a calibration method, since there is an offset between the signal obtained by the sensors and the signal obtained by the validation methods. In order to give an analysis more focused in the results obtained directly by KneeRecovery system, i.e., the absolute angles, a statistical analysis of the ROM was performed. ROM describes the amount of mobility that can be demonstrated in a given joint, in this case, the knee joint.

The ROM values obtained by sensors' signal and the camera's signal were calculated and a statistical analysis was performed. Only the tests 3, 5 and 7 evaluate the ROM, so only the ROM of these three tests were evaluated. The results are shown in Table 3.5.

Table 3.5: Absolute errors (in degrees) of the ROM obtained for tests 3, 5 and 7, comparing the results obtained by KneeRecovery system without calibration and the camera validation method.

Test	Mean Absolute Deviation	Maximum Error	Standard Deviation
Test 3	8,40 ± 3,36	26,90 ± 3,36	8,89 ± 3,36
Test 5	8,10 ± 2,34	17,78 ± 2,34	5,72 ± 2,34
Test 7	17,83 ± 2,47	24,11 ± 2,47	5,52 ± 2,47

As can be observed from Table 3.5, an acceptable mean absolute deviation for test 3 and 5 was verified, however, for test 7, this parameter was significantly higher: 17,83 degrees. In fact, the amplitude of this mean absolute deviation, as well as the maximum errors may mislead the therapists.

In this chapter, the development and implementation of KneeRecovery system was described. The obtained results allowed to conclude that the main aim of this project, i.e., the development of an inertial system able to analyze the knee angle performed by patients during the knee rehabilitation program at home, and consequently giving him/her feedback was fulfilled. However, future work is needed to potentially enhance its performance, since some errors were identified, namely the presence of an offset. In fact, an accurate analysis is fundamental in the results obtained by KneeRecovery system. Besides the acceptable results obtained, improvements are still needed in order to get better performance.

Chapter 4

Conclusions and Future Work

Knee osteoarthritis is one of highest contributor to global disability, with sufferers reporting diminished health-related quality of life. When the disease is already in an advanced state, surgical intervention, called total knee replacement, is the common indicated procedure. Exercise rehabilitation after the surgical procedure is accepted as standard and essential treatment. Traditionally, rehabilitation exercise is delivered in a hospital or clinic environment, however, recent years have witnessed an increasing demand for more efficient health care delivery, which has resulted in an increase in home based rehabilitation. Performing home rehabilitation exercises can be compromised by the lack of real time feedback and adherence. There are already several solutions to enhance home exercise by providing essentially feedback to patients, however they still have some limitations. Thus, the development of an inertial system able to analyses the knee angle was proposed since it can be a fundamental tool to perform the knee rehabilitation at home.

In this project, a study has done been regarding knee rehabilitation, aiming at improving the current inertial system developed.

Based on current research, the KneeRecovery system consists in two IMU that are placed on the lower limb, one on the middle lateral section of the thigh and the other one on the shank lateral lower section, aligned with each other in order to determine its orientation through a sensor fusion method. After finding the sensor orientation, the vectors that describe thigh and shank segments in Earth coordinate frames were calculated, which enabled the knee angle estimation.

The KneeRecovery system was evaluated comparing its performance with two different methods: the camera motion tracking validation system and the goniometer validation method. The presence of an offset was verified for all the tests, which led to the need to implement a calibration method. After the calibration, a maximum mean absolute deviation of 4,02 degrees and 4,61 degrees was found for the camera and goniometer validation methods, respectively. These errors can be derived from different sources, such as sensors' alignment, intrinsic sensors' characteristics or the influence of faster movements. A ROM analysis, independent of the calibration implemented, showed a 17,83 degrees maximum absolute mean deviation of the absolute error.

Despite the errors presented and the dependency of a calibration method, the results obtained for the KneeRecovery system suggest that it can be used to knee angle estimation, and can be a low-cost suitable system for the implementation of knee rehabilitation at home. Therefore, further development of the project would be of great value.

4.1 Future Work

Considering the results obtained in this dissertation, some future work was identified to potentially improve the knee angle estimation. The following list details some of future tasks:

- The current knee angle estimation system presents an offset, what makes it dependent on a calibration method. This offset is derived from different factors. Therefore, future work could be developed in order to identify the offset, but without the need of a validation method, as currently is being done.

- One of the main problems of the experimental work is the placement of the two sensors, aligned to each other. To avoid the burden of manually aligning the sensors to each other, a more efficient method to guarantee this condition could be studied. A method that did not imply the need of aligning the sensors could even be investigated. This possibility could substantially improve the accuracy of the KneeRecovery system, since sensor alignment is a very difficult task.

- Since the implemented algorithm allowed the determination of the angle between each segment and the vertical, a comparison with the camera validation system could also be done in order to understand better the origin of the obtained errors.

- System evaluation based on longer tests could also be studied in order to evaluate the reliability of the proposed algorithm and evaluate drift progression over time.

- Accuracy could be investigated by comparing KneeRecovery system with more reliable systems than Kinovea or goniometer. For instance, KneeRecovery system could be compared to a commercially available motion tracking system such as the Microsoft Kinect.

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