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Computer-Assisted Surgery System for Trochleoplasty

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ABSTRACT

Throchleoplasty is an orthopaedic surgical intervention that aims to correct the trochlear dysplasia, the main predisposing factor of patellar instability. Due to the complexity of this surgery and the lack of solutions to improve this surgical procedure, orthopaedic surgeons from Hospital of Braga have proposed this work. A solution to overcome the limitations and complications that this surgery involves should be addressed.

Traditional procedures performed during this surgical intervention have demonstrated some limitations that were considered in the developed implementation. A state of the art regarding the computer-assisted surgery systems in the orthopaedics field has shown that there are no references of computer-assisted surgery systems addressing the trochleoplasty intervention.

A design and planning of a computer-assisted surgery system for trochleoplasty was performed aiming to overcome the main limitations of the trochleoplasty surgical procedures. The main modules addressed during this thesis were the planning of the robotic system to implement in this application and its simulation and an implementation of a surgical navigation module. A robotic arm that fulfills the requirements of this application was selected to assist the surgeon.

A hands-on robotic system was planned in order to provide surgical procedures assistance. A robotic simulation was developed with an operating room environment composed by the main components of a computer-assisted surgery system. The manipulation of the robotic arm during the simulation was implemented resorting to a PS3 controller, a Wii remote plus and a joystick.

Surgical navigation module is one of the main components of this system. This module was developed in order to provide the required guidance to the surgeon during the trochleoplasty using the proposed robotic system. The point-to-point and surface registrations were implemented in this module in order to achieve the navigated surgery.

The connection between the robotic system and the surgical navigation module was implemented allowing to perform a simulated computer-assisted trochleoplasty. The surgical navigation module was validated with orthopaedic surgeons and these results show a great acceptance by the surgeons.

Keywords: patellar instability; trochleoplasty; computer-assisted surgery; preoperative plan; registration; robotic system; surgical navigation; orthopaedic surgery.

RESUMO

Trocleoplastia é uma intervenção cirúrgica ortopédica que tem como objetivo corrigir a displasia troclear. Esta é considerada como o principal fator de predisposição para a instabilidade patelar. Devido à complexidade desta cirurgia e à carência de soluções para a aperfeiçoar, cirurgiões ortopédicos do Hospital de Braga propuseram a realização deste trabalho. Este deve endereçar uma solução para combater as limitações e complicações que esta cirurgia contempla.

Os procedimentos tradicionais que são usados nesta intervenção demonstram algumas limitações que foram consideradas na implementação da solução. O estado de arte sobre os sistemas de cirurgia assistida por computador aplicados à ortopedia mostrou que não existe nenhuma referência de um sistema destes que seja aplicado à trocleoplastia.

A conceção e o planeamento de um sistema de cirurgia assistida por computador para a trocleoplastia foram realizados com o objetivo de implementar soluções às limitações dos procedimentos cirúrgicos realizados. Os principais blocos endereçados durante esta tese correspondem à implementação de uma simulação do sistema robótico planeado e de um módulo de navegação cirúrgica. Um braço robótico que atende aos requisitos desta aplicação foi selecionado para assistir o cirurgião.

Foi planeado um sistema robótico controlado pelo cirurgião de maneira a fornecer-lhe assistência durante a cirurgia. A simulação robótica foi criada com a representação de um bloco operatório composto pelos principais componentes de uma cirurgia assistida por computador. A manipulação do braço robótico foi conseguida com a utilização de um comando de PS3 e da Wii e um *joystick*.

O módulo de navegação cirúrgica é muito importante nos sistemas de cirurgia assistida. Foi desenvolvido um módulo que pretende guiar o cirurgião durante a trocleoplastia com o recurso ao sistema robótico planeado. O registo baseado em pontos de referência e em superfície foram implementados neste módulo no sentido de obter a cirurgia navegada.

A conexão entre o sistema robótico e o módulo de navegação foi estabelecida permitindo realizar a simulação da trocleoplastia assistida por computador. O módulo desenvolvido foi validado com cirurgiões ortopédicos e os resultados mostram uma grande recetibilidade por parte dos cirurgiões.

Palavras-chave: instabilidade patelar; trocleoplastia; cirurgia assistida por computador; plano pré-operatório; registo; sistema robótico; navegação cirúrgica; cirurgia ortopédica.

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ACRONYMS

CMEMS	Center for Microelectromechanical Systems
MRSLab	NearLab Medical Robotics
RQ	Research questions
MPFL	Medial patellofemoral ligament
ACL	Anterior cruciate ligament
PCL	Posterior cruciate ligament
LCL	Lateral collateral ligament
MCL	Medial collateral ligament
TKR	Total knee replacement
TT-TG	Tibial tubercle-trochlear groove
CAS	Computer-assisted surgery
CAOS	Computer-assisted orthopaedic surgery
CT	Computed tomography
MRI	Magnetic resonance imaging
3D	Three-dimensional
RIO	Robotic Arm Interactive Orthopaedic System
ROS	Robot Operating System
DOF	Degrees of freedom
DH	Denavit-Hartenberg
GUI	Graphical User Interface
PS	Playstation
ICP	Iterative closest point
CPD	Coherent point drift

1. INTRODUCTION

This dissertation presents the work developed in the scope of the fifth year of the Integrated Master in Biomedical Engineering. The present work was developed in the Center for Microelectromechanical Systems (CMEMS) group from University of Minho. This work has started in NearLab Medical Robotics (MRSLab) group from Politecnico Milano with the design and planning of the problem solution and all background regarding the required tools to implement the solution in Portugal, as it is addressed during this document.

The proposed work addresses the field of surgical robotics to orthopaedic interventions. More specifically, the trochleoplasty intervention has led to the implementation of this work. This project arose from the necessity of Dr. Vieira da Silva and Dr. Bruno Santos, orthopaedic surgeons from Hospital of Braga, to look for strategies in order to improve the procedures of trochleoplasty. Trochleoplasty is an orthopaedic intervention that is complex to the surgeon and involves a significant risk to the patient.

Therefore, in order to overcome this lack in the orthopaedic field, this work presents the design and planning of a computer-assisted surgery system for trochleoplasty. The main components of these systems have to be identified in order to address the modules that must be implemented.

In this context, the implementation of a robotic system simulation and a surgical navigation module was planned aiming to provide a computer-assisted surgery simulation. The underlying idea is that the implementation of a robotic system in this computer-assisted system would provide the improvement of the traditional procedures and it would induce consequently less risks to the patient during the intervention. The planning of this robotic system has to consider the entire intervention and its technical procedures.

The surgical navigation modules have led to more precise surgical interventions and the implementation of this module in the addressed scope would provide a great tool for the surgeon.

All the procedures and achieved outcomes are fully detailed in this dissertation.

1.1 Motivation

Patellar instability is one of the problems that affects the knee. This is a complication that leads to patellar subluxations and dislocations that reduce the quality of life of the patients. The pain and the problems during the locomotion lead the affected people with patellar instability to look for a surgical solution. The overall incidence of this knee problem is around 50 in 100 000 young people [1], [2]. The young people have the higher incidence of this morphological abnormality [3].

The main predisposing factor of patellar instability is the trochlear dysplasia that is present in 85% of patients with recurrent patellar instability [3]–[5].

This work addresses the intervention that aims to correct this deformity. The trochleoplasty aims to correct the trochlear groove in order to provide the ideal shape to keep the patellar stability.

This is an intervention that does not provide the precision and the reproducibility desired by the surgeons. This is a complex surgery that involves risks for the patient. One of them is the cartilage damaging. The field of view of the surgeon to perform this surgery is very limited due to the cartilage. These are some of the factors that difficult the surgeon actions during this intervention. After intervention, just a functional evaluation is performed to the patient and there are no fixed metrics to evaluate the final outcome of the surgery.

Due to this complexity, in some cases, the trochleoplasty is not performed to avoid other possible problems even if the patient has trochlear dysplasia and the trochleoplasty improves his quality of life. Also, it is presented in some literature some reports of patients submitted to a trochleolplasty whose pain is still present and the outcomes of the intervention do not improve their physical condition [6]. Note that the trochlear dysplasia is responsible for 85% of the recurrent patellar instability.

After a thorough literature and state of the art review regarding the Computer-Assisted Surgery (CAS) systems addressed to the knee, it was possible to verify that there are no systems addressing the trochleoplasty intervention. With a system that ensures the reproducibility and security of the procedures all of these limitations can be overcome.

One of the main aspects of this work is the real necessity that brought the creation of this project. As referred above, this work was developed with the support and advise of Dr. Vieira da Silva and Dr. Bruno Santos. These are two orthopaedic surgeons from Hospital of Braga that have the necessity of more accurate and precise procedures during this intervention to overcome their limitations. This is a concrete case and with their knowledge it is possible to transform that into the strengths of the planned system. One great motivation is to plan the best solution to overcome the real limitations of this medical team that supported this work.

1.2 Problem statement and scope

To overcome the aforementioned limitations regarding the trochleoplasty intervention it is necessary to plan a system that tackles the main complications that the medical team reports. In this context, first of all it is important to collect all limitations, requirements and complications that the trochleoplasty involves.

Since there are no references to a CAS system addressed to trochleoplasty, a well-defined planning of a CAS system to overcome these limitations can be an innovative implementation that presents the relevance of the present work and its contribution to the scientific community.

Robotic systems can be addressed to CAS systems. Robotic assisted surgery research has known an outstanding growth in the scientific community in the last few years. Regarding the present work, the planning of the robotic system to surgical procedure assistance is the key to the implementation of a CAS system. Firstly, the main modules that compose a CAS system have to be identified in order to perform a robust integration of the system. The main modules addressed in these systems consist of a tracking system, a preoperative module, a robotic system and the surgical navigation module. This work will address the robotic system and the surgical navigation module. The preoperative module is part of a work carried out at University of Minho that will be integrated in this thesis. Also, the tracking system is also being developed in a master thesis at University of Minho. Further work addresses the connection of the surgical navigation module with this tracking system.

In this thesis, the main aim is to implement the simulation of the computer-assisted trochleoplasty resorting to the developed robotic system simulation, the surgical navigation module and the integration of the preoperative module.

1.3 Goals and Research questions

As aforementioned, the ultimate goal of this thesis is the planning and simulation implementation of a CAS system for trochleoplasty intervention. To achieve this ultimate goal, firstly it is required the knowledge of several multidisciplinary fields such as surgical navigation, tracking systems and robotic systems addressed to orthopaedic surgeries.

Also, the knowledge of the surgical procedures of this intervention is important to have enough background to plan a robust and viable system for this application.

Therefore, the main goals to achieve with this thesis are enunciated next.

Goal 1: The first goal to achieve is relative to the surgical intervention. It consists in analyzing the traditional procedures that are performed during the intervention in order to understand the main complications and difficulties that the implemented system should overcome.

Goal 2: In order to be able to present a system planning for CAS, it is required to know the state of the art and the evolution of the CAS systems addressed to knee interventions. Thus, the second goal is to identify the main modules that compose the CAS systems that are being applied in the operating room to assist the surgeon.

Goal 3: The third goal is regarding the planning of the robotic system to be address to this work. The goal is to plan a robotic system to surgical procedure assistance that overcome the presented requirements of this work. A robotic simulation must be implemented with the operating room environment and a robotic arm to assist the surgeon. Also, the simulation should provide a kind of manipulation of the robotic arm to simulate the surgeon hands-on procedures.

Goal 4: The fourth goal aims to implement a surgical navigation module to be applied to the operating room providing the required guidance to the surgeon during the computer-assisted surgery. The module should contain the integration with the preoperative plan and provide the necessary feedback such that the surgeons perform the surgical intervention with accuracy.

Goal 5: Resorting to the robotic system simulation and the surgical navigation module, the computer-assisted trochleoplasty can be simulated. To reach that, the connection between both modules is required. This goal aims to establish the connection between both environments to exchange the required data between them in order to achieve the navigated surgery.

Goal 6: The last goal corresponds to the validation of the implemented module. After concluding goal 5, the validation in a medical context of the surgical navigation module is very important. To achieve that, the module should be used by orthopaedic surgeons and some parameters of the implemented module should be evaluated.

In the present work, the following research questions (RQ) are expected to be answered.

RQ1: Which are the limitations of the trochleoplasty intervention that the CAS system should overcome? This RQ will be addressed in chapter 3.

RQ2: Which are the main advantages of a CAS system for trochleoplasty? This RQ will be addressed in chapter 3.

RQ3: In a CAS system addressed to trochleoplasty, should a robotic system be addressed? Will the robotic system provide an added value to the CAS system? This RQ will be addressed in chapter 3.

RQ4: Which are the required parameters that the robotic arm should fulfill? This RQ will be addressed in chapter 4.

RQ5: How to implement an intuitive manipulation of the robotic arm in the simulation? This RQ will be addressed in chapter 4.

RQ6: Which are the required procedures to perform in order to achieve a navigated surgery based on a CT exam? This RQ will be addressed in chapter 5.

RQ7: Is it beneficial to provide feedback to the surgeon during the intervention according to his actions? How can this feedback be provided? This RQ will be addressed in chapter 5.

1.4 Contribution to knowledge

This thesis provides a simulation of a computer-assisted trochleoplasty resorting to a robotic system simulation and a surgical navigation module. The main contributions of this work are:

- The main limitations, requirements and complications of the trochleoplasty intervention are raised and addressed in order to propose an innovative approach to a CAS system addressed for trochleoplasty;
- Implementation of a robotic system simulation with the planned CAS system for trochleoplasty. It provides the simulation of the computer-assisted trochleoplasty and it is a great tool to conclude about the viability of a CAS system for these interventions;
- Creation of a surgical navigation module for trochleoplasty intervention.

1.5 Publications

The developed work during the past year allowed the publication of three conference papers:

- Luís Serrador, Roberto M. Barbosa, Bruno Santos, M. V. Silva, Elena De Momi and Cristina Santos, *Patellar Instability: Traditional Surgical Interventions and a Robotic Approach*, 2017 IEEE 5th Portuguese Meeting on Bioengineering (ENBENG), Porto, Portugal, 16th - 18th February 2017

- Roberto M. Barbosa, Luís Serrador, Bruno Santos, M. V. Silva, Elena De Momi and Cristina Santos, *Intraoperative Bone Registration: An Implementation In Orthopaedic Surgery Using Polaris Vicra System*, 2017 IEEE 5th Portuguese Meeting on Bioengineering (ENBENG), Porto, Portugal, 16th - 18th February 2017

- Roberto M. Barbosa, Luís Serrador, Bruno Santos, M. V. Silva, Elena De Momi and Cristina Santos, *3DSlicer Module To Perform Registration: An Intraoperative Situation*, IEEE 17th International Conference on Autonomous Robot Systems and Competitions (ICARSC), Coimbra, 26th - 28th April 2017

1.6 Thesis outline

In order to provide to the reader a general overview of this thesis, here it is described the organization of this document.

In chapter 2 is presented the literature review about the knee. A brief description of its anatomy and their associated problems are described. Also, the patellar instability and its associated causes are detailed. The trochleoplasty, one intervention that aims to correct one of the patellar instability causes, is addressed and the traditional procedures are described. Lastly, it is presented an introduction to Computer-Assisted Surgery systems and a state of the art of CAS systems addressed to knee interventions.

Chapter 3 contains the solution description for the stated problem. The main modules are identified detailing the structure of the following chapters.

In chapter 4 it is presented the implementation of the robotic system simulation where it is described the creation of the operating room environment and the robotic arm manipulation.

Chapter 5 presents the surgical navigation module implemented to guide the surgeon during the computer-assisted trochleoplasty. Here, it is presented the workflow of the implemented module.

The connection between both components of this work, the robotic simulation and the surgical navigation module, is described in chapter 6.

In chapter 7 it is presented the validation of the surgical navigation module and its results.

Finally, the conclusions and the proposals to continue this work in future are presented in Chapter 8.

2. LITERATURE REVIEW - ORTHOPAEDICS

Orthopaedics is the medicine field which ensures the treatment of musculoskeletal tissues. The bones, the cartilages and the ligaments are part of this group and ensure the human body posture and movements, allowing its integrity and structure [7]. According to this, the joints have a huge role in the integrity of the structures of the body. One example of these joints is the knee. The knee is one of the most complex joints in the human body. With an enormous impact in the locomotion, the knee has many structures that ensure the necessary stability and functionality to the daily activity and it is subject of a huge number of associated problems [8], [9].

2.1 Knee Anatomy

Due to the complexity of the knee anatomy, it is important to clarify some terms in order to obtain a better background of this subject during this document. The knee structures will be deeply addressed throughout this work. To understand the complexity of some knee interventions it is important to have knowledge of its complex anatomy and biomechanical function [10].

The following knee anatomy description takes into account the most important structures of the knee that will be addressed throughout this work. A general approach of the knee constitution will be performed in order to realize the performance of this complex joint.

With a perfect architecture, this important structure of the human body consists of 2 joints that provide the stability associated to its mobility: **femorotibial** and **patellofemoral** joints.

The **femorotibial** joint consists of the articulation between the **medial and lateral femoral condyles** and the corresponding **tibial plateaus**. In figure 1C it is possible to see both femoral condyles and the tibial plateaus on the top of the tibia. As shown, these structures are coated with **cartilage** that is represented by white color in the figure 1C. This tissue allows the bones to slide freely on each other. Below the cartilage, it is present a thin thickness of **cortical bone** and the **subchondral bone**. The latter is more flexible. Even deeper, the **cancellous bone** is less dense and softer. To provide more stability during the rotations and to absorb the impact between the bones, this gap is composed by the **medial and lateral meniscus**, figure 1A [9]–[14].

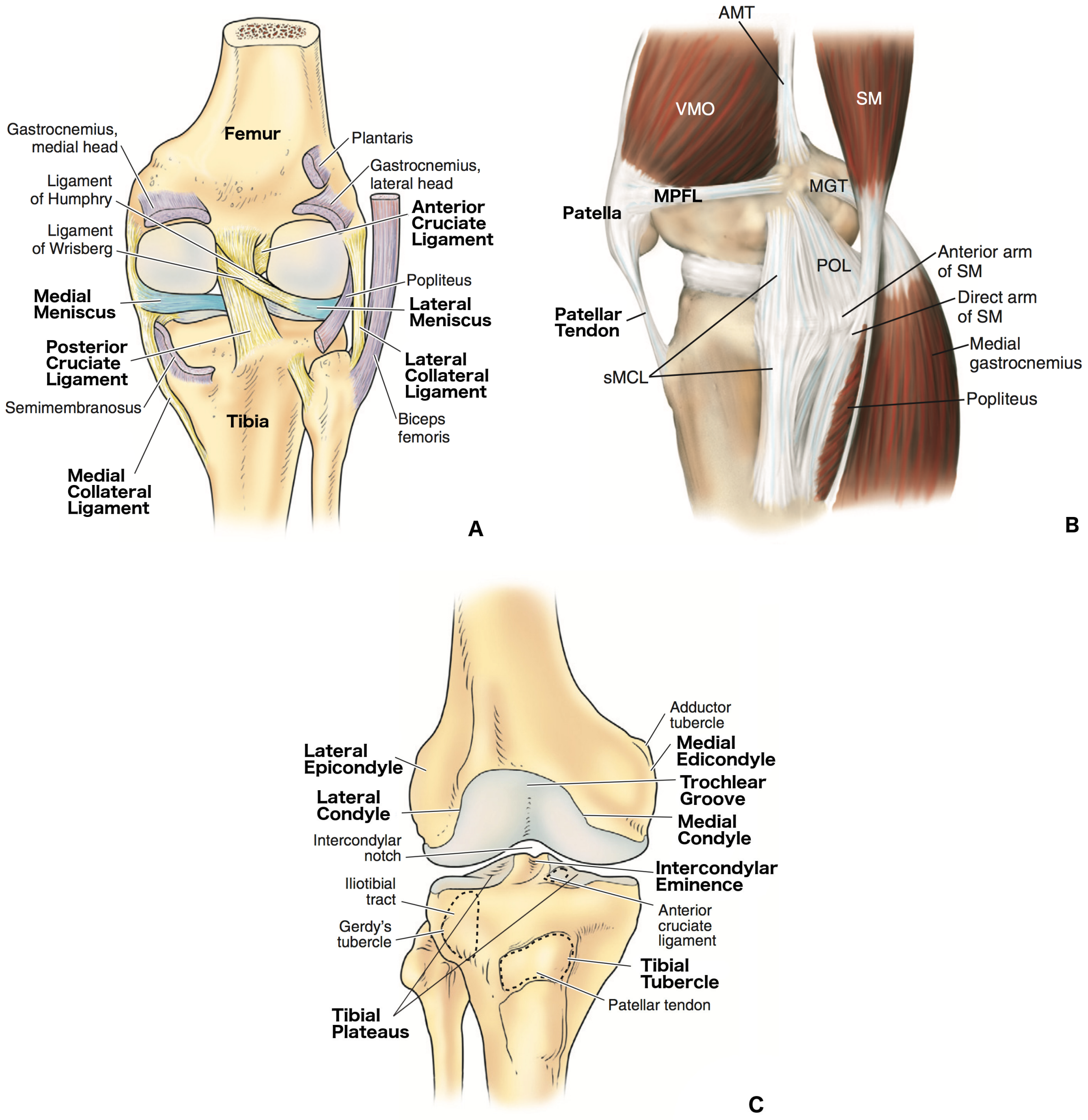


Figure 1 - Different views of the knee: anterior view (A); right view (C) and posterior view (C) [11].

The **patellofemoral joint** is responsible for the sliding between the **patella** and the **trochlear groove** pointed in figure 1C. As the medial and lateral femoral condyles and the tibial plateaus, the surface of the patella which is in contact with the trochlear groove is coated by **cartilage**, as well as the trochlear groove. The medial patellofemoral ligament (**MPFL**) allows to keep the patella centered along the front of the knee, so that it tracks well during knee flexion and extension. It has an important role in the **patellar stability** as will be detailed below.

The anterior cruciate ligament (**ACL**) and the posterior cruciate ligament (**PCL**) are two of the major ligaments of the knee and they are the key to provide the stability to the knee. As illustrated in figure 1A, the PCL connects the posterior intercondylar area of the tibia to the medial condyle of the femur. It allows to resist to the forces that push the tibia to a posterior zone in relation to the femur. The ACL is attached to the posterior part of the medial surface of the lateral femoral condyle regarding the femur and in front of the **intercondylar eminence** of the tibia. This is a strong ligament that resists to anterior translation and medial rotation of the tibia, in relation to the femur [15].

Lateral collateral ligament (**LCL**) and medial collateral ligament (**MCL**) are the other two major ligaments of the knee. They provide enough strength to keep the stability of the knee against forces from medial and lateral sides. Their insertions can be seen in figure 1A, where it is shown the place of fixation of these ligaments in the femur and in the tibia.

It is relevant to mention some landmarks of the knee that will be addressed during this work. **Lateral and medial epicondyle** (figure 1C) are two landmarks well defined in the femur surface. They correspond to a bony protrusion located on the medial and lateral side of the bone, respectively. The **tibial tubercle** is a large elevation of the tibia where the patellar tendon is held, figure 1C [10], [11], [16]–[18].

2.2 Knee associated problems

There are several problems that are associated to the knee. Due to the huge complexity of this human body part, the knee entails some complications that are addressed to its structures. **Osteoarthritis** and **rheumatoid arthritis** are two of the major factors that lead to the total knee replacement (**TKR**) intervention. This is one of the most commonly performed orthopaedic procedures in the world. This surgery intends to replace the joint surfaces that are damaged with metal or plastic components in order to relieve the pain and improve the motion of the knee [19], [20].

Usually associated to athletes, the **ACL reconstruction** is one common surgical intervention that is indicated to treat the ACL rupture. A portion of semitendinosus and patellofemoral tendons are used to replace the damaged ligament. This intervention has a significant recovery time of eight months and it ensures the enough strength and elasticity to the replaced ACL [21], [22].

Another knee surgery performed to oppose some complications in the knee is the **high tibial osteotomy**. This is an intervention to correct the angle between the tibia and the femur. The procedure consists on removing a wedge from the tibia or the femur, it depends on the surgeon methodology, with an angle that will originate the desired alignment [11], [23], [24]. In figure 2 is shown one example of varus deformity and its correction. Conversely, the valgus correction is represented in the figure 3.

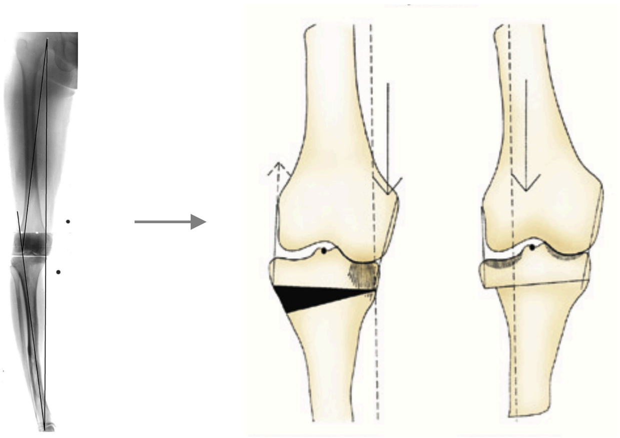


Figure 2 - Example of a high tibial osteotomy to correct the varus deformity [11].

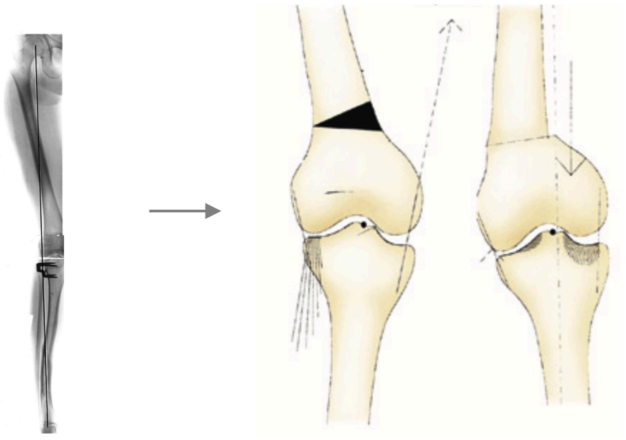


Figure 3 - Example of a high tibial osteotomy to correct the valgus deformity [11].

2.3 Patellar Instability

Patellar instability is a morphological abnormality in patellofemoral joint that occurs principally in young and active individuals, especially in young females [3]. This disability leads to recurrent patellar dislocations inducing some pain in the knee and complications on locomotion. The overall incidence is around 50 in 100 000 young people and this has led to an added preoccupation to provide the best solutions to these patients [1], [2]. This is the knee complication that this work aims for. The intervention that will be described aims to correct one of the causes of patellar instability. All the information regarding the intervention will be detailed below. At this moment, it is necessary to understand the patellar instability and its causes.

A healthy patellofemoral joint has two kinds of **stabilizers**. The active stabilizers correspond to extensor muscles, and passive stabilizers correspond to the bones and ligaments. Together, they are responsible to ensure the patella fixation. A modification on the anatomy of the patellofemoral joint can lead to patellar instability [3], [25].

Associated to patellar instability, subluxation and dislocation are two events that characterize this knee problem. Subluxation corresponds to an excessive lateral deviation of the patella without moving out totally from the trochlear groove. Dislocation means that the patella jumps out of the groove and it can lead to the MPFL rupture. Recurrent subluxations may be treated with less complicated surgeries and sometimes a conservative treatment is applied in order to solve the problem. The consequences of this kind of events are not so harmful as the patellar dislocations [26], [27].

The most cited factors in the literature that lead to patellar instability are the **trochlear dysplasia**, **patella alta** and an excessive tibial tubercle-trochlear groove (**TT-TG**) distance [4], [11], [28], [29]. The **MPFL rupture** can be cited as a cause or a consequence, it depends if the dislocation occurs before or after the rupture but, normally, its reconstruction is associated to these factors. In most cases, MPFL reconstruction is performed simultaneously to the other interventions to treat the patellar instability.

To diagnose these predisposing factors to patellofemoral instability a computed tomography (**CT**) scan is required to visualize the patient's anatomy and evaluate some important bone structures that indicate which factor is responsible for patellar instability [11], [30].

It is important to refer that the patella only contacts the trochlear groove from 30 to 90 degrees of knee flexion as shown in figure 4. Thus, when performing the CT scan, the patient's knee should be flexed about 30 degrees to be sure that the patella is contacting with trochlear groove [11].

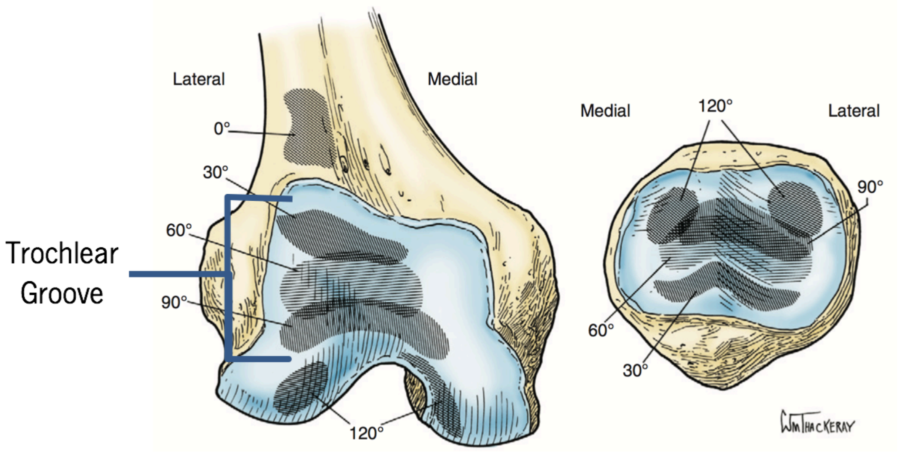


Figure 4 - Patellofemoral joint contact areas according to the knee flexion angle [11].

In order to achieve a better comprehension about the patellar instability causes, next will be explained the main causes that lead to this problem. The respective abnormality and the associated intervention to correct it will be described.

2.3.1 Patella Alta

Patella alta, also known as high-riding patella, is caused by a too long patellar tendon that induces a bad position of the patella during the flexion of the knee. The patella is too high above the trochlear groove during the knee flexion. This results in less osseous stability because the degree of flexion at which the patella engages in the trochlea is higher than in a normal knee. Furthermore, this abnormality reduces the patellar contact areas when compared with knees with normal patellar height.

In order to evaluate this problem, the following **indexes** are used to measure the parameters resorting to a lateral view of the knee, in a sagittal view:

- Caton-Deschamps index: ratio between the distance from the lower edge of the patellar articular surface to the anterosuperior angle of the tibia outline (AT) and the length of the articular surface of the patella alta (AP). When this ratio is greater than 1.2 indicates patella alta.

- Insall-Salvati index: ratio between the length of the patellar tendon (LT) and the longest sagittal diameter of the patella (LP). It was determined that a ratio greater than 1.2 indicates patella alta.
- Blackburne-Peel index: ratio between the length of the perpendicular line drawn from the tangent to the tibial plateau to the inferior pole of the articular surface of the patella (A) and the length of the articular surface of the patella (B). A ratio of 0.8 is a normal value and a value greater than 1 indicates patella alta.

Figure 5 illustrates these indexes.

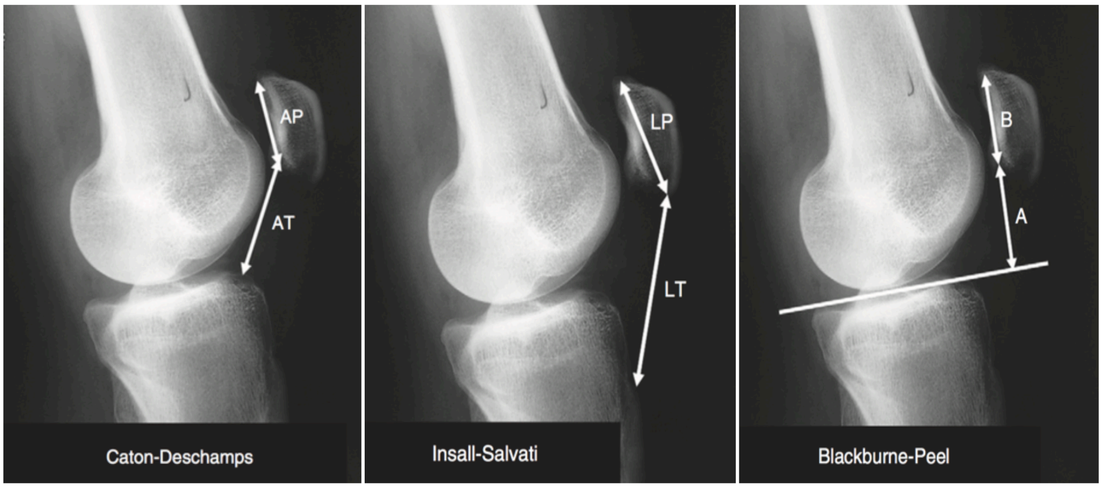


Figure 5 - Patella alta indexes [11].

To choose the best index many factors must be taken into account. However, the **Caton-Deschamps index** is indicated as the easiest to use and is advisable for surgical planning [1], [3], [11].

In order to correct this disorder, a surgical intervention that aims to fix the patella position could be performed. **Distal tibial tubercle transfer osteotomy** is indicated in this case. In figure 6 is illustrated the final result of this intervention. The procedure starts when the proximal portion of the tibial tubercle is pried off. While the distal portion is being cutted, this portion is grasped with bone-helding forceps. The distal portion must stay as smooth as possible because any prominence would interfere with knee movement. The block is then transferred to distal position and the fixation starts at the lower screw site. It is important to insert the screws perpendicular to the tibia in order to avoid any movement from the tibial tubercle. The second screw is inserted when the desired amount of medialization is obtained [11], [31].

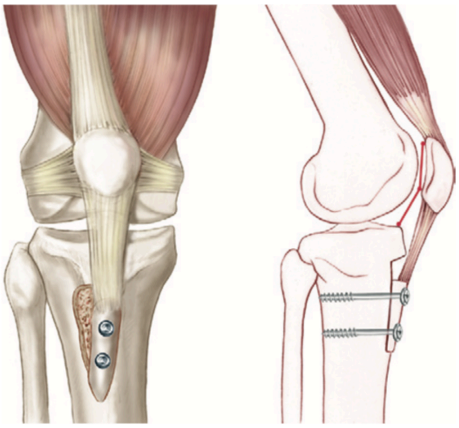


Figure 6 - Distal tibial tubercle transfer osteotomy [11].

2.3.2 TT-TG distance

An excessive **TT-TG distance** is another of the major causes of patellar instability.

The angle between the quadriceps insertion and the patellar tendon insertion causes a laterally directed force vector. This angle is called the **Q angle** and it can be measured by tracing two lines that intersect the center of the patella: one is traced from the anterior iliac spine, representing the quadriceps tension line and the other is traced from the tibial tubercle and represents the patellar tendon force line. This measure is represented in figure 7. Healthy subjects have an expected Q angle up to 15 or 20 degrees and it was concluded that women have the greatest values [3], [11], [32].

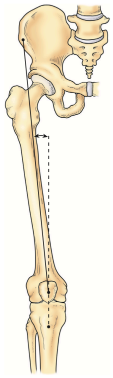


Figure 7 - Representation of Q angle [11].

TT-TG distance is a parameter that measures this alignment directly. This is achieved overlapping two slices from a CT scan as shown in figure 8. One of the slices has the bottom of the trochlear groove and the other has the most proximal part of the tibial tubercle. Two perpendicular lines to the bicondylar line, that intersect the middle of the trochlear groove and the tibial tubercle respectively, are drawn and the distance between these two projections corresponds to TT-TG value. It is referenced that a TT-TG distance superior to around 20mm is considered abnormal and a surgical intervention should be performed [3], [4], [11], [32].

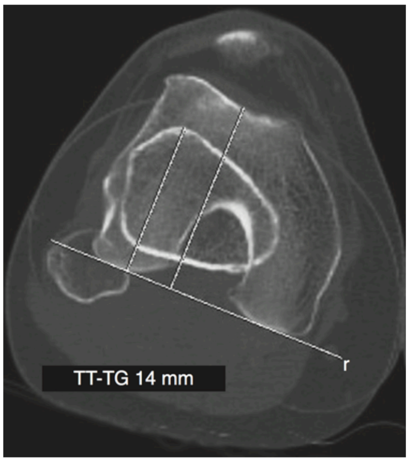


Figure 8 - TT-TG measurement [11].

In contrast to the distal tibial tubercle transfer osteotomy mentioned above, in the **medial tibial tubercle transfer osteotomy,** the tibial tubercle is fully detached on three sides only, leaving a distal bony hinge. Therefore, one single screw is enough to ensure the tubercle fixation. The pilot hole for the screw is made prior to the osteotomy with a 3.2mm drill bit and it is overdrilled with a 4.5mm drill bit. As a last step, the tubercle is attached with a 4.5mm screw originating a final result like shown in figure 9 [11].

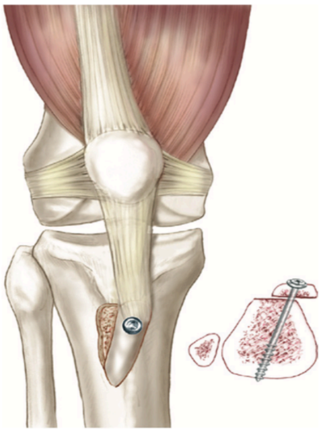


Figure 9 - Medial tibial tubercle transfer osteotomy [11].

2.3.3 Trochlear Dysplasia

Lastly, the **trochlear dysplasia** is the most important predisposing factor of patellar instability once it is present in 85% of patients with recurrent patellar instability [3]–[5].

Trochlear dysplasia consists of abnormal values of a set of parameters with regards to malformation of trochlea. **Trochlear depth**, **sulcus angle**, **lateral trochlear inclination**, **trochlear facet asymmetry** and the **lateralization of the patella** are examples of these parameters that provide the severity of the deformity. Next, each one of them will be described and the healthy values of these parameters will be presented.

Dysplastic trochlea is shallow, flat or even convex. In 1987, Henri Dejour described for the first time one way to characterize trochlear dysplasia on the sagittal view, the crossing sign. A representation of a healthy trochlea can be seen in figure 10. It is possible to see that the trochlear groove is posterior to the facets and there is no crossing sign. To understand this characterization, in figure 10 on the right, three lines are presented. The line below is drawn in the trochlear groove. The other two are drawn in the facet of medial and lateral condyles in a parallel way. When the lines do not overlapping, there is no crossing over, as it is presented here.

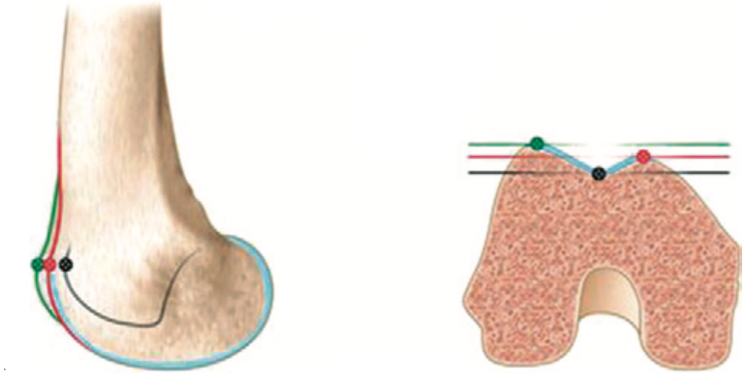


Figure 10 - Normal trochlea illustration [11].

In 1996, Dejour and Le Coultre improved the classifier system and classified trochlear dysplasia in four grades based on the crossing sign and two more signs found during the study they performed. This classification system is based mainly on the lateral view, although CT may assist in differentiation between types. This classification resulted in four types of trochlear dysplasia (see figure 11) [2]–[4], [11], [29], [33]:

- **Type A**: The trochlea has a normal shape but it is shallower than normal. It is still symmetrical and concave. There is presence of crossing sign in the lateral view.
- **Type B**: The trochlea is flat in axial images and all of the trochlea is prominent. Presence of crossing sign and trochlear spur.
- **Type C**: Trochlear facet asymmetry, with too high lateral facet, and hipoplastic medial facet. Presence of crossing sign and the double-contour sign on the lateral view.
- **Type D**: This type combines all previously mentioned signs. In the axial view, it is presented a clear asymmetry of the height of the facets, also referred to as cliff pattern.

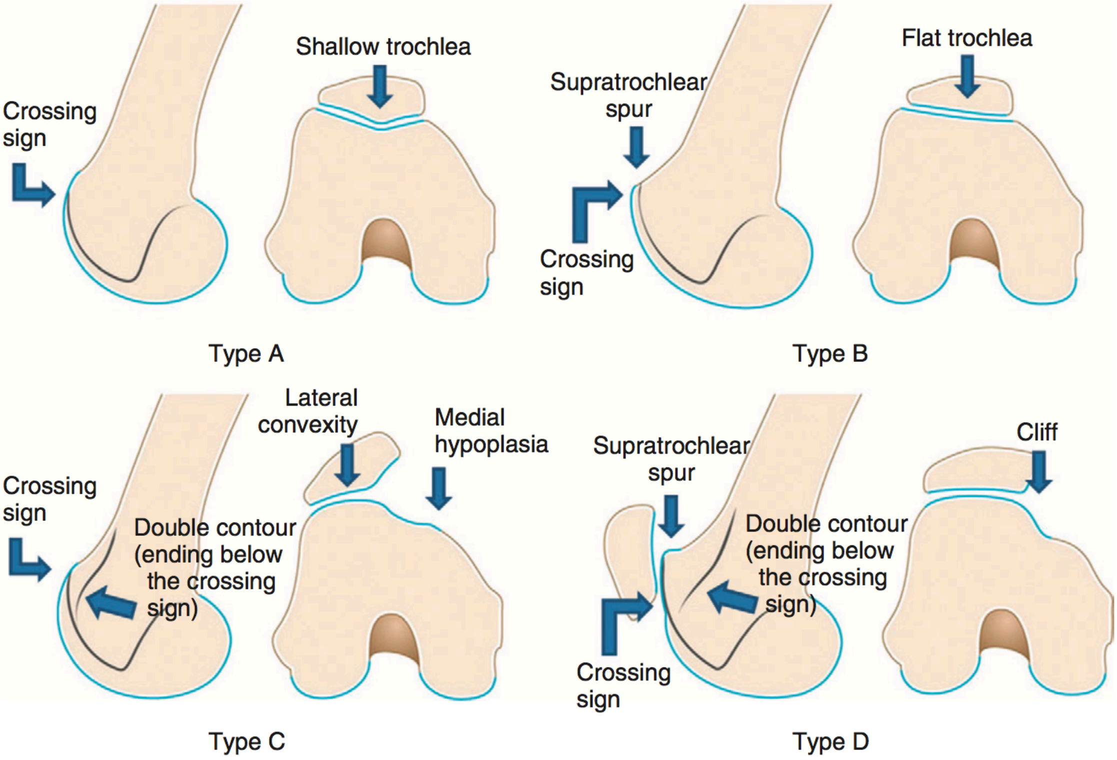


Figure 11 - Classification system of trochlear dysplasia according to Dejour [11].

As mentioned, there are five parameters that are used to detect trochlear dysplasia. To perform these measures a CT scan is required. Note that the CT scan is performed when the knee flexion is reaching 30 degrees in order to provide the contact of the patellofemoral joint, as described previously. The evaluated patellofemoral parameters and its values of a dysplastic trochlea are presented below:

- The **sulcus angle** normally averages 138 degrees. A sulcus angle greater than 145 degrees it is indicative of trochlear dysplasia (Figure 12A).

- The **trochlear facet asymmetry** is defined by a ratio of the medial to the lateral trochlear width. One value less than 0.4 indicates trochlear dysplasia (Figure 12B).
- The **lateral trochlear inclination** corresponds to the angle between the posterior condylar axis and lateral trochlear facet. An angle less than 11 degrees is considered abnormal (Figure 12C).
- The minimum limit for the **trochlear depth** is 3 mm. This measurement is calculated as the mean of the perpendicular distance between the medial and lateral margins of the trochlea to the posterior condylar axis minus the sulcus height measured in the same way (Figure 12D).
- Axial scan shows one way to assess **lateral patellar subluxation**, with a distance between the lateral margin of the trochlea and the lateral margin of the patella greater than 6mm considered abnormal (Figure 12E).

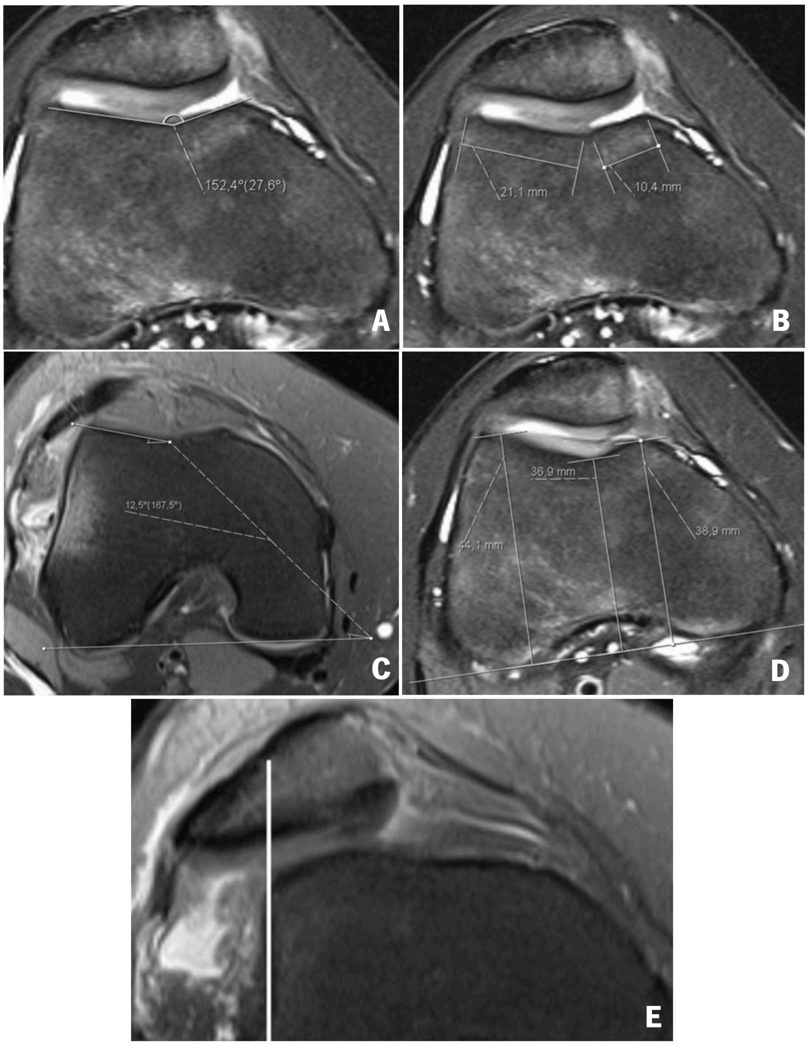


Figure 12 - Sulcus Angle (A); Trochlear facet asymmetry (B); Lateral trochlear inclination (C); Trochlear depth (D); lateral patellar subluxation (E) [3].

After all considerations regarding the trochlear dysplasia are analyzed, the surgeon is able to decide if the surgical intervention is needed to treat the patient. Trochleoplasty is addressed to these cases. This intervention is in the origin of this work. The complex procedures involved in this kind of surgery will be detailed below. It is important to refer that this intervention is performed only by traditional procedures so far and the surgeon's experience has a crucial role in the success of this surgical intervention as it will be described in the following.

2.4 Traditional Trochleoplasty

Trochleoplasty is an intervention that aims to correct the trochlear dysplasia. The following procedures to fix the **trochlear groove** are addressed to interventions that aim to correct the trochlear dysplasia type B and C, according to the classification system of trochlear dysplasia of Dejour. Trochlear dysplasia type D can be also addressed to this intervention but once it is a more complex deformity, the outcome from this intervention is more dependent of the surgeon experience. This is the surgical intervention most frequently performed for trochlear dysplasia disease [33]. The surgeon has to redefine the trochlear groove in order to perform a new groove to stabilize the patella in the sulcus.

The first step is to perform a 4cm incision using a scalpel with the knee flexed 90 degrees. This provides all the required space for the surgeon to perform the intervention.

The leg is then positioned in extension and a medial full-thickness skin flap is developed. After that, the trochlea is exposed as figure 13A shows. By changing the knee degree of flexion, it allows a better view of the complete operative field and it avoids extending the incision.

While performing the surgery, the surgeon must have an increased careful with the cartilage and the depth of bone that he will resect. The cartilage is the structure that turns this surgery more complex. During all steps, the surgeon has to ensure that the cartilage is not damaged. A damaged cartilage will cause other knee problems to the patient. The new trochlear groove must be planned to be between the articular cartilage and the deep cancellous bone. Thus, this volume is chosen preoperatively and before resecting the bone, the cartilage has to be elevated like in figure 13B.

After, a drill with a depth guide set at 5mm is used to remove the cancellous bone, figure 13C. The 5mm correspond to normal thickness of cartilage in the knee. This drill ensures the uniform thickness of the osteochondral flap and it avoids injuring the cartilage. Also, it keeps enough flexibility of the produced shell so that it could be modelled by the surgeon without being fractured. Once the articular cartilage is elevated from the femur, a straight osteotome is used to carefully create a V shape in the subchondral bone, as shown in figure 13D.

At the end, the cartilage has to be modelled and attached to the new sulcus using some strips, figure 13E. These strips are attached using the distal part of the new trochlea as a starting point to the first lock and the surgeon has to be sure that this point does not contact with the patella during the knee motion. This kind of disposition of the strips ensures that the cartilage goes deep into the new trochlear groove. The outcome of the intervention is shown in figure 13F.

This is a surgery with some special cares. The surgeon has to reach the bone under the cartilage and the procedures to elevate and hold the cartilage could damage it. Another complication in this intervention is the reduced field of view of bone that is being resected due to the small incision to provide a minimal invasive surgery and due to the cartilage. Nowadays, the surgeon must check the bone removal flexing the leg to verify if the trochlea is stabilized. If the trochlea is not stabilized, the surgeon should continue the intervention [4], [11], [33].

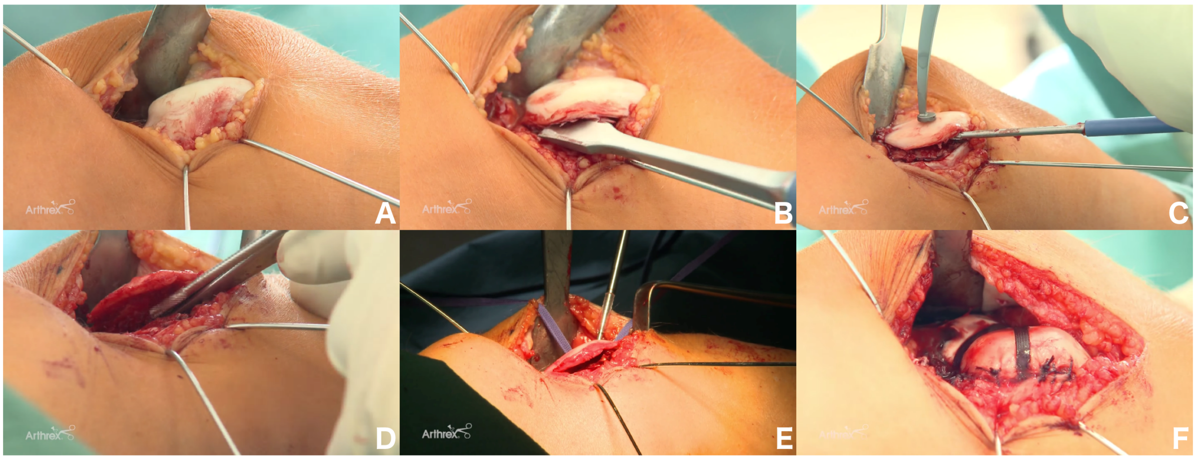


Figure 13 - Steps of the trochleoplasty intervention.

2.5 Computer-Assisted Orthopaedic Surgery

The concept of CAS is very present in the medical field. Since the past decades, this technology has provided less invasive, more accurate and reproducible and safer surgical procedures and it is a great help for the surgeon. Also known as surgical navigation, CAS has been widely integrated in the different areas of medicine such as neurosurgery, orthopaedics, craniomaxillofacial, trauma and many other surgical applications [34]–[37]. During this work, it will be addressed the CAS oriented to orthopaedics, named computer-assisted orthopaedic surgery (**CAOS**). Once a bone is a rigid structure that does not deform when drilled, it is easier to apply preoperative imaging and planning information to surgery during the intervention. So, orthopaedics is a field where CAS has an increased value.

A CAOS module improves the surgical interventions quality thanks to the accurate **guidance** of surgical instruments. It allows the surgeon to get real-time feedback about the performed surgical actions. Even during a situation with a limited surgical field of view, the surgeon can get the exact location of surgical instruments by resorting to a virtual view of the instruments on a screen in the operating room.

Surgical navigation is able to combine medical images from medical exams with tracking systems. The set of required procedures in a CAOS workflow is very similar in all kind of implementations. There are a set of basic elements that characterizes the CAOS such as the **virtual object**, the **surgical object**, the **registration**, the **tracking system** and the **referencing**.

Normally, the **virtual object** corresponds to a medical exam, more often a CT or a magnetic resonance imaging (MRI) three-dimensional (3D) reconstruction of the **surgical object**. The surgical object corresponds to the musculoskeletal structure of the patient that is the target of the treatment. In order to simplify and standardize the document, the virtual object and surgical object terms will be applied whenever it is necessary to refer to the 3D reconstruction of the medical exam of the anatomical structure of the patient and the musculoskeletal structure of the patient that is the target of the treatment intraoperatively, respectively.

To address a spatial position, it is necessary to resort to a reference frame. The spatial position is relative to a specific reference frame and it corresponds to different coordinate systems. Each coordinate system is characterized by its reference frame.

The **tracking system** is the main component of CAOS. It is composed by a **navigator** that establishes a global 3D coordinate system in which the target is to be treated in the operating room and the current position and orientation of the end effector of surgical instruments are mathematically described.

The **registration** procedure is necessary to ensure the uniformity of the setup. Usually, the coordinate system of navigator that is operating intra-operatively differs from the coordinate system of virtual object on the software. The mathematical relationships between both coordinate spaces are determined by the registration procedure as will be detailed in the next sections.

Lastly, in order to have into account the motions between the navigator and the surgical object during the surgical procedures, normally small devices are mounted onto the bone, **referencing** always the surgical object in relation to the navigator global coordinate system [7], [38], [39]. A general system setup of CAS system, using a CT exam to perform the 3D reconstruction to obtain the virtual object, is represented in figure 14.

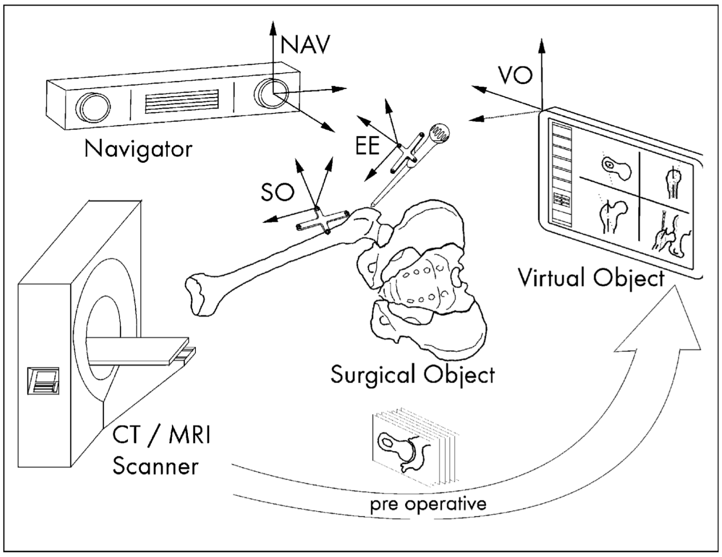


Figure 14 - General system setup for a CT-based navigation system [39].

The surgical navigation allows the visualization of surgical the plan and the positions of the surgical tools during the intervention. To follow the preoperative plan as precisely as possible, the robotic systems have been applied in the CAOS to complement the capabilities of the orthopaedic surgeon. Their precision and their resistance against tremor and fatigue are important factors to improve the outcome of the bone as described above.

2.5.1 Robotic systems in orthopaedic surgery

Robots have become a strong part of our lives, during the last years. Actually, all areas have the necessity to have mechanisms to improve the accuracy and the efficiency of processes. We are surrounded of mechanisms that tend to overcome possible mistakes of human hand and provide uniformity on the performance.

The first relevant historic fact in the robotic area appears in the middle of the year 1958, with the creation of Unimate produced by General Motors® which aims to assist in automobile production. Since then, robots had an exponential growing and extended to many areas [40].

Medicine, was not an exception and in fact, during last decades, the robots started to emerge in the operating room. The prototype for Neuromate (Integrated Surgical Systems, Sacramento, CA, USA) was the first surgical application of industrial robotic technology, in 1985. It was obtained by modification of an industrial robotic arm to accomplish a stereotactic brain biopsy [40].

Surgical interventions are medical procedures that require accurate and precise movements. The reproducibility and the precision inherent to robots make them the ideal tools for these applications. It has been evident that the alliance of this equipment with the surgeon has presented great results.

In table 1, are presented the main differences in the behavior and characteristics between surgeon and robot to understand which advantages the robot can carry out to the operating room.

Table 1 - Strengths and limitations of robots and humans, adapted from [41]

HUMANS	**ROBOTS**
Strengths	
Strong hand-eye coordination	Stability and good geometric accuracy
Dexterous (at human scale)	No fatigue or inattention
Flexible and adaptable	Can be designed for a wide range of scales
Can integrate diverse information	May be sterilized
Able to use qualitative information	Resistant to radiation and infection
Good judgment	Can use diverse sensors in control
Easy to instruct and debrief	Repeatability
Limitations	
Limited dexterity outside natural scale	No autonomous judgment
Prone to inattention and fatigue	Limited dexterity and hand-eye coordination
Limited geometric accuracy	Limited to relatively simple procedures
Fine motion tremor	Expensive
Limited sterility	Difficult to construct and debug
Susceptible to radiation and infection	Low adaptability

As analyzed, medical robots have potential to improve the quality of assistance during surgical procedures. The fast growth of robot industry has provided to robotic systems appealing features from a surgeon point of view.

As the name suggests, the main goal of robotic-assisted orthopaedic surgery is not to replace the surgeon, but to provide an important assistance during the procedures so the surgeon can complement his capabilities in order to obtaining better results and improve the patient quality of life.

Literature refers different classifications of robots. Thus, robotic surgery systems can be characterized as **autonomous**, **hands-on** and **telerobotic** devices and also as **active**, **semi-active**, or **passive**.

Active devices, where autonomous robots are included, are totally programmable and carry out tasks independently. They are programmed to perform some automated actions according to the preoperative plan and the surgeon must supervise the entire process.

Semi-active and **passive** robotic devices translate movements from surgeon's hands into powered or unpowered movements of the robotic arms. **Hands-on** systems are robotic systems that allow the surgeon to guide the robotic arm to perform the operation. They are classified as semi-active system since they can provide some haptic force feedback to the surgeon. This technology requires constant input by the surgeon during the intervention and for this reason they are named by **surgeon-controlled** robotic arms, also.

Teleoperated robots, known as **telerobotic** robots, are controlled remotely by a human. The remote control signals can be sent through a wire, through a local wireless system over the Internet or by satellite [42]–[46].

2.6 State of the Arte of CAOS systems

A brief overview of CAOS systems addressing knee interventions and which are being used in the operating room is presented below to realize its usability and the application of these systems.

2.6.1 ROBODOC

ROBODOC® is cited as the first surgical robot to perform a task automatically. The system was designed to help surgeons to reduce errors when performing cementless total hip replacement. The system consists of a preoperative preparation performed in a computer workstation, ORTHODOC®, and in ROBODOC®, a robotic arm with five degrees of freedom, a mobile base, a 6-axis load cell and a rotary cutting head.

The lack of accuracy created gaps at the implant to bone interface and it leads to instability and the decrease of bone ingrowth. Based on these problems, ROBODOC® improves the implant selection, sizing and positioning within the bone and it improves the accuracy of preparation of the bone cavity to accept the implant. The software ORTHODOC® provide the preoperative plan of the surgery based on CT scan and a robotic arm from ROBODOC® with an end effector mills the femoral canal to attach the implant according to the planned position in the preoperative workstation.

The first ROBODOC® system in Europe was installed in 1994. The robotic system is large, heavy, not easy to handle and it is difficult to clean and sterilize its surface. These are the main disadvantages of this CAOS system [46]–[49].

The ROBODOC® and ORTHODOC® are shown in figures 15 and 16, respectively.

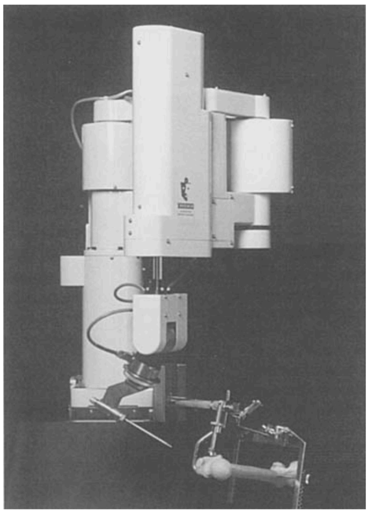
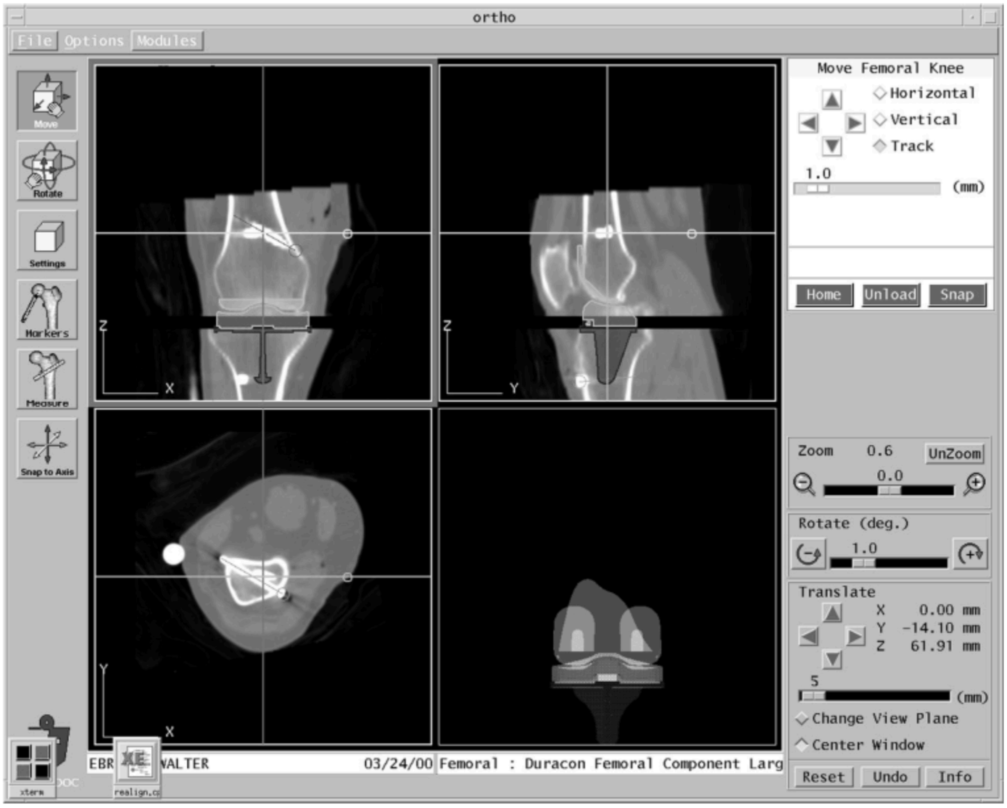


Figure 15 - ROBODOC® robotic system [47].



1.0 (mm)

Zoom 0.6

0.0

1.0

X 0.00 mm
Y -14.10 mm
Z 61.91 mm

5 (mm)

EBR WALTER 03/24/00 Femoral : Duracon Femoral Component Larg

Figure 16 - ORTHODOC® planning workstation [49].

2.6.2 ACROBOT

Acrobot® is a surgical robot designed to help surgeons during total knee replacement. Typically, this surgery consists of three components, one for each bone of the knee: tibia, femur and patella. To fit the prosthesis, each specific bone is resected according to the size and shape of the implant. To avoid pain and other complications the implant must be accurately placed. A bad placement of the implant compromises the normal functionality of the knee and provides pain to the patient.

Unlike ROBODOC®, Acrobot® is directly guided, hands-on by a surgeon. It was developed by Imperial College London and it is constituted by a preoperative planning workstation and an intraoperative robotic system, similar to ROBODOC®. Figure 17A shows the planning software of prosthesis placement.

Acrobot® is a small and low-powered robot designed to use in a sterile operating room environment. This robot has a spherical manipulator with three orthogonal axes of motion. It has a relatively small workspace, 30cm to 50cm, and a range of angles between -30 to 30 degrees. The mechanical impedance of the axes is low allowing the surgeon moving the robot with low force. The surgeon moves the robot by pushing the handle near the tip of the robot. The handle comprises a six axes force sensor, which measures the forces and the torques. The end effector has a motor where the tools are mounted. Due to its small workspace, the robot is placed on a gross positioning device which moves the Acrobot® to optimal cutting locations around the knee. The system is mounted in a trolley to be easy to move, figure 17B.

To avoid bones movements relatively to Acrobat®, two bones clamps are rigidly clamped to the exposed areas of the tibia and femur. A revolutionary method of this robotic system was an active constraint control. Gradually, the robotic arm increases the stiffness according to the distance to predefined boundaries. A safe region is defined where the robot can move freely. Thus, the surgeon can feel the forces on the robot tip and can adjust his movement [43], [45], [46].

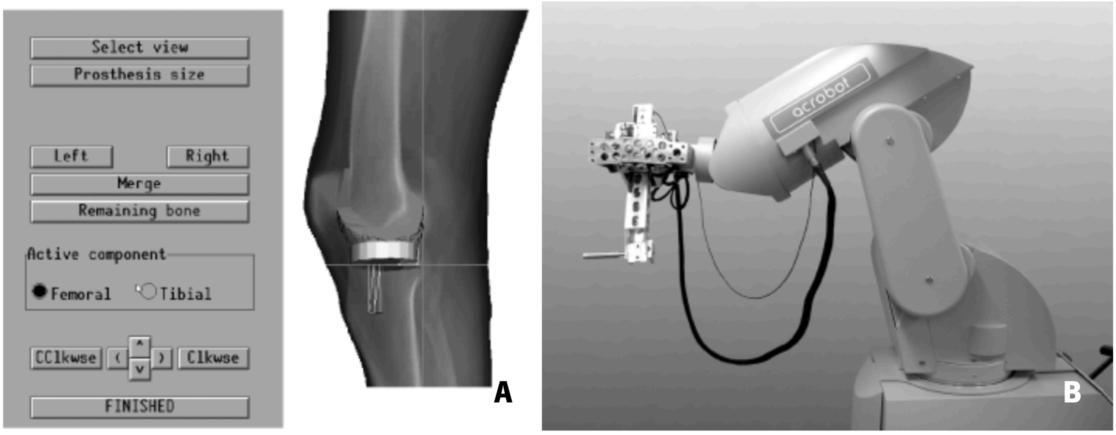
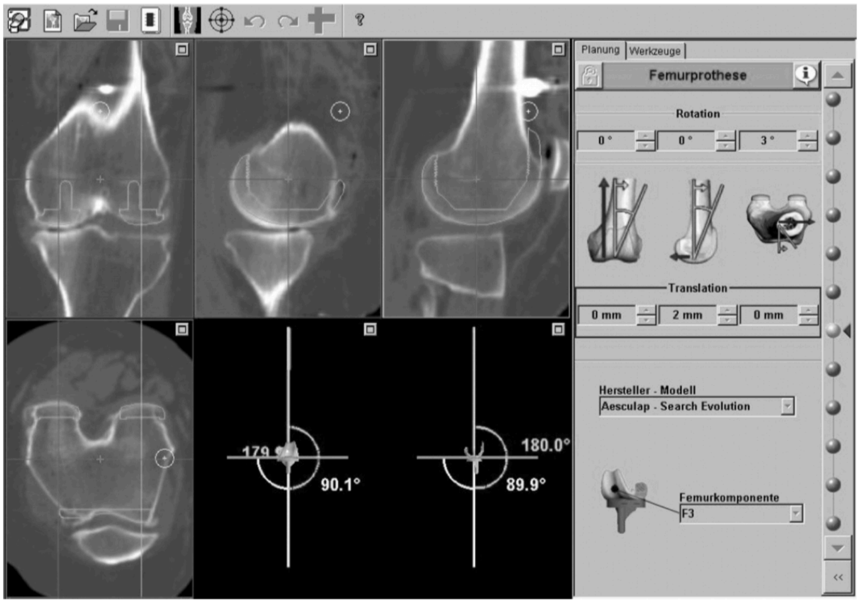


Figure 17 - Planning software of prosthesis placement (A); Acrobot® mounted on the positioner and trolley (B) [43].

2.6.3 CASPAR

CASPAR® is a commercial CAOS system that is able to assist orthopaedic surgeons in ACL reconstruction and TKR interventions. CASPAR® is classified as an active robotic system since it functions autonomously. Therefore, this system uses infrared cameras and reflective trackers to track the knee motion. A rigid body is fixed to the knee holder frame, like shown in figure 18. However, the surgeon can stop the action of the robot. An interactive PC planning station based on CT images constitutes the system, figure 19. CASPAR® uses a robot based on an industrial clean-room robot, which has been modified for orthopaedic surgery [50].

Figure 18 - CASPAR system setup [50].



Rotation: 0 ° 0 ° 3 °

Translation: 0 mm 2 mm 0 mm

Hersteller - Modell: Aesculap - Search Evolution

Femurkomponente: F3

Figure 19 - Planning station of CASPAR system [50].

2.6.4 MAKO Robotic Arm Interactive Orthopaedic System

MAKO Robotic Arm Interactive Orthopaedic System® (**RIO**) provides to the surgeon intuitive and interactive tools, which increase the safety of the patients. The surgeon can grasp the cutting tool mounted at the end of the robotic arm and handle the arm in order to interact with the environment. The surgeon feels very comfortable to work with this robotic arm, resulting in an increase of rate acceptance of the surgeons. This robotic system is classified as a semi-active system, **hands-on** robot, since it does not perform surgical tasks autonomously but it allows the surgeon to freely operate it within a planned safe zone and it provides movement resistance when the surgeon's actions approach the boundaries of the safe zone. The **haptic force feedback** provides the surgeon an intuitive tactile feedback during human-machine interaction.

The interaction with the environment performed by the RIO® is based on haptic rendering. So, the virtual haptic environment is generated and it simulates a physical world with virtual objects.

RIO® is a **6 degrees of freedom** (DOF) manipulator that measures the pose of the tip and applies correction forces to the tool tip. In figure 20 it is possible to identify the degrees of freedom of this robotic arm. The robotic arm was projected to right-handed and left-handed surgeons. The manipulator helps the surgeon to perform the correct movement during the surgery and it prevents undesired cuts outside the planned region. The main advantage of RIO® system is that does not require to clamp the bone in a fixed place. The software compensates automatically the motion of the bone. Also, RIO® permits an intraoperative revision of the preoperative plan in the operating room, which causes optimized results and improves the longevity of the implants.

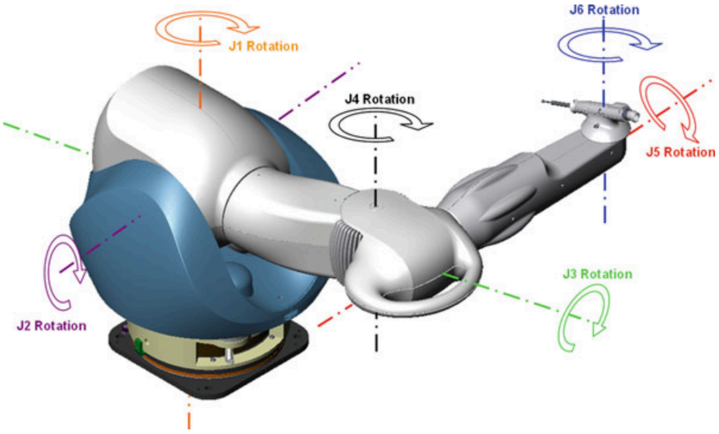


Figure 20 - Joint motion definitions of the RIO robotic arm [51].

This CAOS system is constituted by three principal hardware components as shown in figure 21. The robotic arm supports the **cutting system** and allows the surgeon to perform the pre-defined bone resections. The **Camera Stand** supports the computer monitor used by the surgeon to view bone resections that he is performing intraoperatively. It is used to track the patient anatomy through the use of tracking arrays mounted to the surgical object. And the **guidance module** is used to provide information to a technician to help the surgeon navigating through the implant planning and surgical application.

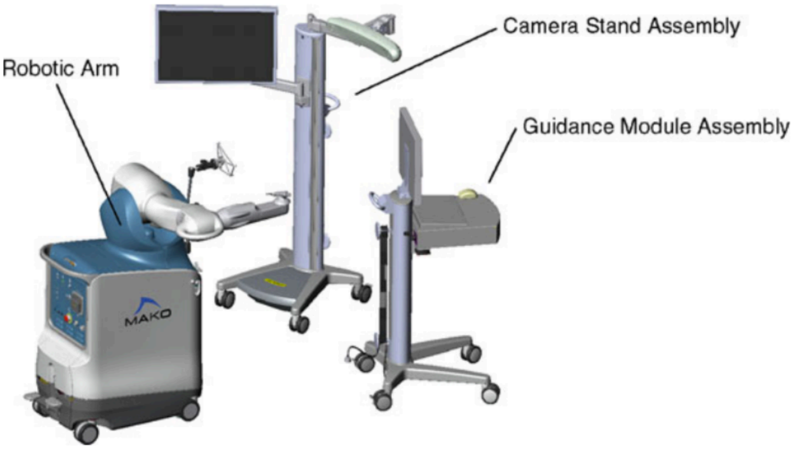
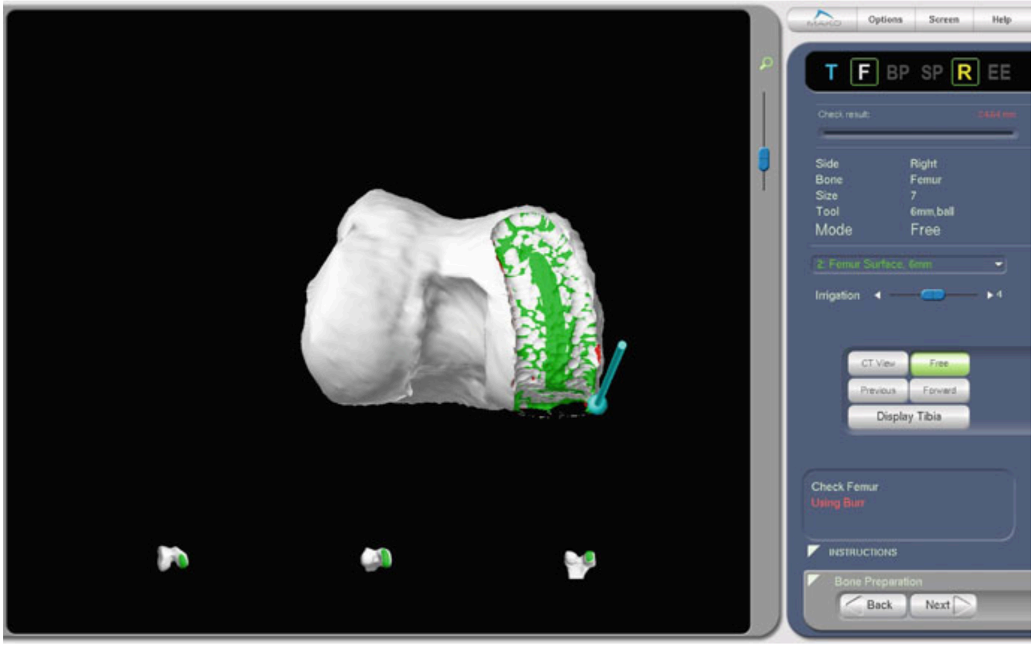


Figure 21 - MAKO RIO system setup [51].

MAKO RIO® system software provides to the surgeon his actions during the intervention as mentioned above. Figure 22 presents a screenshot of this software showing the virtual object, a femur bone, with the planned resection volume in green color as well as a portion of the bone already removed. This is the interface that the surgeon follows to guide bone resections. The main aim is to remove all green portion until the surgeon hits the planned boundaries shown in white. The robotic arm applies a force against the hand of the surgeon whenever he tries to move the cutting burr outside of the planned volume.

The free movement with low friction and low inertia of the RIO® robotic arm does not fatigue the surgeon during the surgical intervention what makes this CAOS system a great help in the operating room [46], [51]–[54].



Side Right
Bone Femur
Size 7
Tool 6mm,ball
Mode Free

Check Femur
Using Burr

Figure 22 - MAKO RIO system software showing the femur resection [51].

2.6.5 OmniBotic

The **OmniBotic**® robotic system has been released for TKR intervention and it has a bone-mounted robotic cutting guide to perform the intervention. The system allows the surgeon to define the cutting plans virtually in the software. Then, the two active rotational degrees of freedom of the robotic cutting guide allow the surgeon to perform the bone resections according to the pre-defined cutting lines.

Resorting to the robotic system, the cutting guides are actively placed at pre-defined positions to perform all femoral cuts.

At the begin of the surgery, the device is held to the femur with two pins. The 3D tracker is contained in the holder therefore no additional pins are required to hold it [55]–[58]. The navigation system and the planning software is similar to MAKO RIO®.

Figure 23 presents this surgical guidance system.

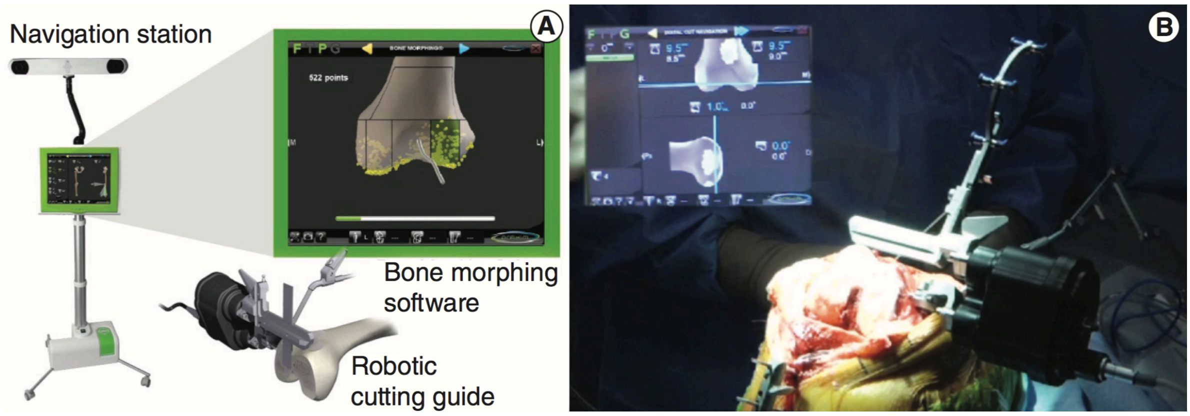


Figure 23 - OmniBotic system with the implant planning software (A); Omnibotic system in the operating room (B) [55].

2.6.6 OrthoPilot

OrthoPilot® is a passive CAOS system, which helps the surgeon to perform surgeries on the knee joint. Without preoperative CT exam, this system is based on intraoperative kinematic imaging of the hip, knee and ankle showing to the surgeon where the mechanical axes of the leg are situated.

The setup consists of a navigation system and its sensors to allow real-time spatial tracking of anatomic markers. In the navigation system is used the Polaris® infrared locator and passive markers that are fixed to the bone using special bicortical screws.

Also, this system provides a set of instruments useful for surgical interventions such as cutting guides with bone markers [59], [60]. OrthoPilot® navigation system and software can be seen in figure 24.

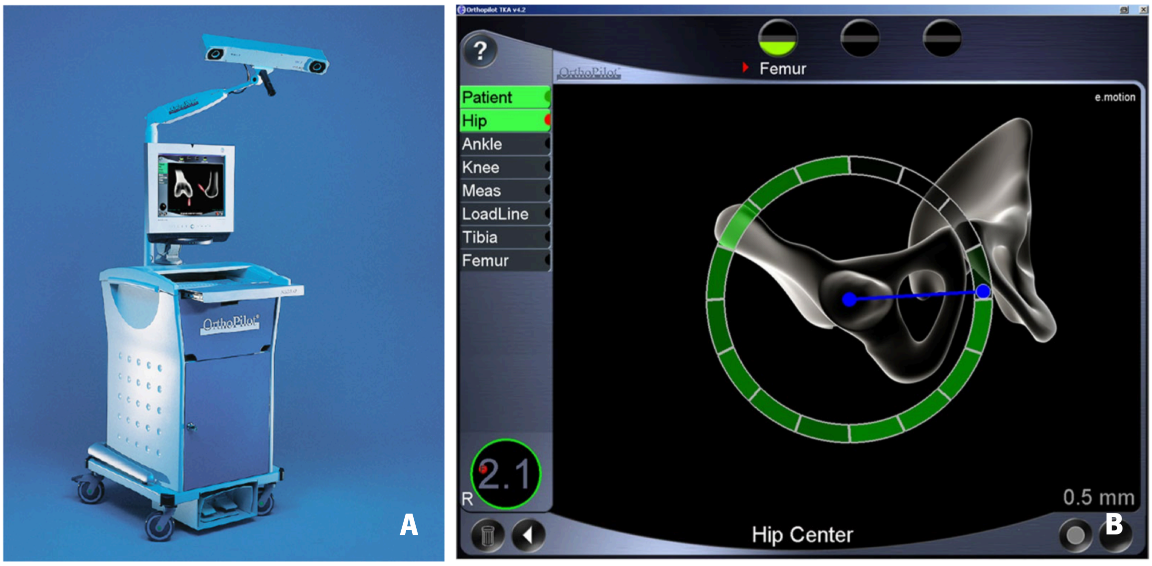


Figure 24 - OrthoPilot navigation system (A) [60]; OrthoPilot software acquiring the center of the hip [59].

3. SOLUTION DESCRIPTION

During this chapter, the requirements that the planned system has to fulfill in order to overcome the main limitations of the addressed intervention are presented. Also, the solution planning to implement in the operating room is described as well as the main modules that will be addressed during the present work.

As verified in the present state of the art there are no references to CAS systems performing the trochleoplasty intervention. The lack of such systems is the main motivation for this work. The traditional procedures performed to solve the trochlear dysplasia do not provide the precision, reproducibility and safety required in surgical interventions. For the surgeon, the traditional intervention is arduous and annoying to perform. For the patient, the risk that surgery incurs in other complications and the probability of recurrence of associated problems is significant. Sometimes, the intervention is sidelined due to these factors even though it could improve the quality of life of the patient.

It is important to refer that during this work some aspects of the trochleoplasty are not referenced in the literature since there are no addressed evidences about these. This is a new approach regarding this subject. Addressing a CAS system to this intervention is a pioneer study. As previously mentioned, this work had the support of a medical team from Hospital of Braga. Thus, all addressed points regarding the surgical procedures of the intervention, such as complications and requirements, are based on real and concrete items pointed out by an experienced medical team in this area.

Nevertheless, the previous presented analysis of the traditional procedures performed during this surgery enabled to verify and strengthen these arguments.

3.1 System Requirements

In order to define a solution, it is important to take into account the specificities of this surgery. All workflow of the intervention must be considered in order to implement the best solution for this case. A thorough study about the surgical procedures and the vast experience from the medical team were crucial to delineate the system setup to be implemented.

Regarding the surgery, the following list presents a set of topics that are important to accomplish a better outcome from the intervention and another set of topics that the system should overcome:

- The leg of the patient during the intervention should be freely positioned without any hard holder in order to allow the surgeon to change its position. The surgeons consider this is an important factor to facilitate and to contribute to an easier and comfortable intervention. In the traditional procedure, the mobility of the leg is a positive factor and the implemented system should conserve that.
- The cartilage is a crucial element in this intervention. The conservation of this knee structure is fundamental to the quality of life of the patient. In order to develop a confident and acceptable CAS system, the risks involved to the cartilage in this surgery should be eliminated. The setup planning must consider that the system has to actuate in a limited volume in order to perform the resections. The boundaries of this volume are the cartilage, in the upper limit, and the planned depth of the new trochlear groove in the subchondral bone, in the lower limit.
- One of the difficulties of the surgeons is to visualize the outcome of their actions in the new shape of the trochlea due to the restricted field of view. Since the cartilage is not removed during the intervention it always covers the operated region. Thus, a navigated surgery must be implemented to guide the surgeon during his surgical actions.
- In order to have as much as possible a less invasive surgery, the performed incision to reach the operated area should be as small as possible. The traditional surgery applies a small incision of 4cm and this size must at least be maintained. The intervention is performed with the surgeon placed in the lateral side of the operated knee.

- The medical exam to use in the evaluation of patellofemoral parameters must be the CT once it is a practical exam that demonstrates good results in the measurements of all parameters above announced [28], [30], [61].
- Lastly, as it can be verified, the new trochlear groove is intrinsically linked to the surgeon experience once there is no plan to follow during the intervention. The only evaluation performed in the operating room is a functional evaluation to realize if the patella is stable. The less positive outcomes from this surgery are associated to the lack of rigor of surgical procedures to delineate the new trochlear groove [6].

3.2 Solution Planning

After studying all these requirements and performing thorough analyses of the existing CAOS systems it was delineated that a CAS system including a robotic arm is the best solution to be implemented in this study. The present literature review about the CAOS systems in the previous sections clarifies what has been applied so far in the operating rooms to assist the surgeons. The addressed implemented systems provide several solutions for knee surgeries but trochleoplasty is not included. After verifying that none of the known existing CAOS systems can present a CAS solution for trochleoplasty, it was defined that this work would tackle the development of a CAS system for trochleoplasty.

The final setup was delineated in accordance with the medical team and the main components of a CAS system. A system overview of the entire setup is presented in figure 25.

The CAS system is presented comprising four main modules: **preoperative plan**, **surgical navigation module**, **tracking system** and **robotic system**. This agrees with the general composition of these systems. In the following, each one of these modules will be substantiated and described.

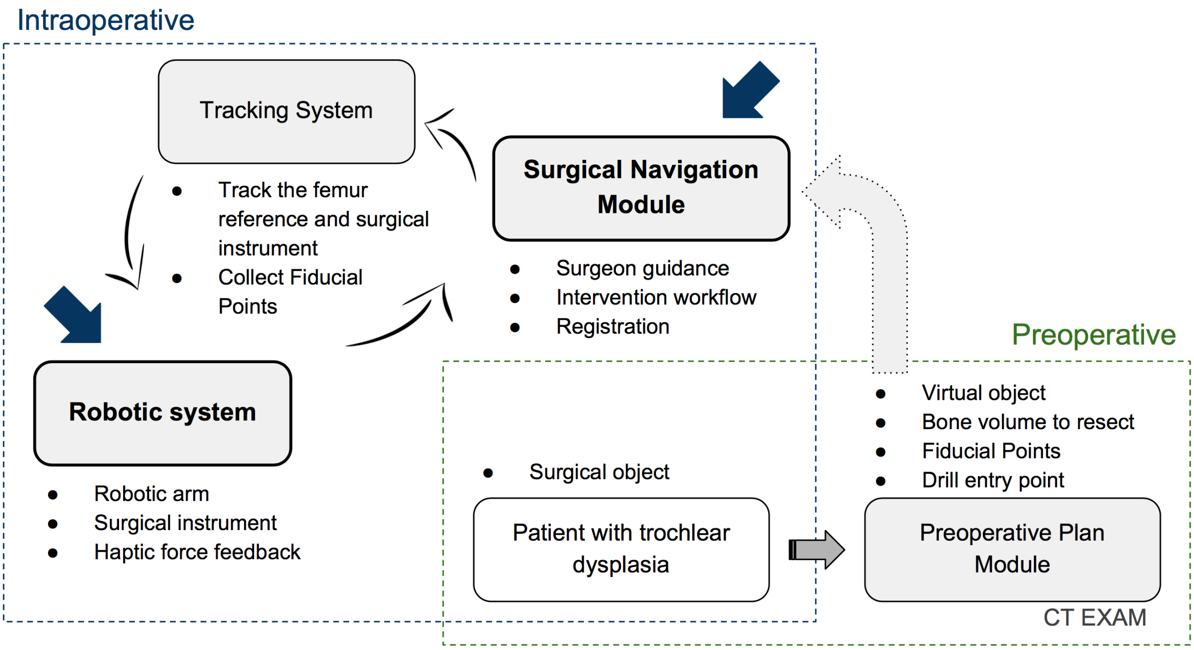


Figure 25 - System overview of the CAS system for trochleoplasty.

The **preoperative plan module** is part of a developed work at University of Minho during a master thesis project. This system setup has to interconnect this work with the different proposed modules. The preoperative module consists of two sections: the first allows the user to measure the patellofemoral parameters in order to confirm that the patient has trochlear dysplasia and the second section intends to perform the preoperative plan. This preoperative plan allows the surgeon to delineate the bone volume to be resected in order to obtain the new trochlear groove to oppose the patellar instability. A CT exam of the knee of the patient is required for this module. The parameters are measured using the different CT scans of the knee in the desired plane. The preoperative plan is performed resorting to a 3D bone reconstruction of the knee. This 3D reconstruction will be used as a **virtual object** in the **surgical navigation module**. Also, in order to be fully integrated with the planned CAS system, this preoperative module has the option to choose the fiducial points to be used during the registration procedure. The fiducial points correspond to the anatomical landmarks of the musculoskeletal structure of the patient. Lastly, in order to avoid the cartilage, the entry point of the **drill**, the **surgical instrument tip**, onto the volume to be resected is specified by the surgeon, by selecting the desired position to start the intervention. Thus, the preoperative plan module was structured to provide the virtual object, the bone volume to resect, the fiducial points and the drill entry point.

The **surgical navigation module** has to be planned to receive this data from the preoperative module and it will guide the surgeon during the intervention by following the detailed workflow of the surgery. Also, as it will be posteriorly described, it includes the **registration procedure**.

The **tracking system** is a work that is being developed in another master thesis project at University of Minho. The project consists on implementing a tracking system to track the surgical instrument and to track the tools to collect the fiducial points to perform the registration. It is being used a **dual Kinect system** as a navigator and after confirming its viability, it will be integrated in this CAS system.

The **robotic system** is the last module of this system. It was delineated that a navigated surgery would not be enough to reach the aim of this project. The robotic arm can provide a really important feature to this implementation: the **haptic feedback**. Inspired from MAKO RIO® operation, this feature can avoid undesired cuts when the tip of surgical instrument is reaching the boundaries of the predefined volume. With a long analysis regarding the kind of robotic arm to implement in this project together with medical team, it was reached the conclusion that a haptic robotic arm is the best equipment in order to allow the previously mentioned feature. The surgical instrument will be attached to the last link of the robotic arm and it will be studied the ergonomic factor for the surgeon to manipulate the robotic arm. Once in the traditional trochleoplasty, an unpowered tool is used, it is necessary to select one power tool to apply in this system.

Once the overall setup and its modules are identified, each of these modules will be addressed and implemented.

This thesis addresses both, the surgical navigation module and the robotic system. The main goal of this thesis is to implement these modules and their connection with the preoperative plan module, as shown in figure 25.

Regarding the robotic system, it is extremely recommended that all implementations are based on simulation results. In order to follow a conscious and well-founded work line, this master thesis project addressed the simulation of the robotic system that will be implemented at the operating room with the presented CAS system. A fully interactive simulation was implemented in order to reproduce the operating room environment as much as possible. Thus, this work presents a **robotic system simulation**, a **surgical navigation module** and the **interconnection** among them and the preoperative plan module. Thus, the entire intervention can be simulated without the tracking system. To achieve that, the fiducial points during the simulation were collected resorting to the robotic arm, as will be detailed next. Within the simulation, the world reference frame of the simulation environment is used as the main reference frame. The implemented work will be fully detailed in the next sections. Figure 26 shows the new system overview of the implemented solution.

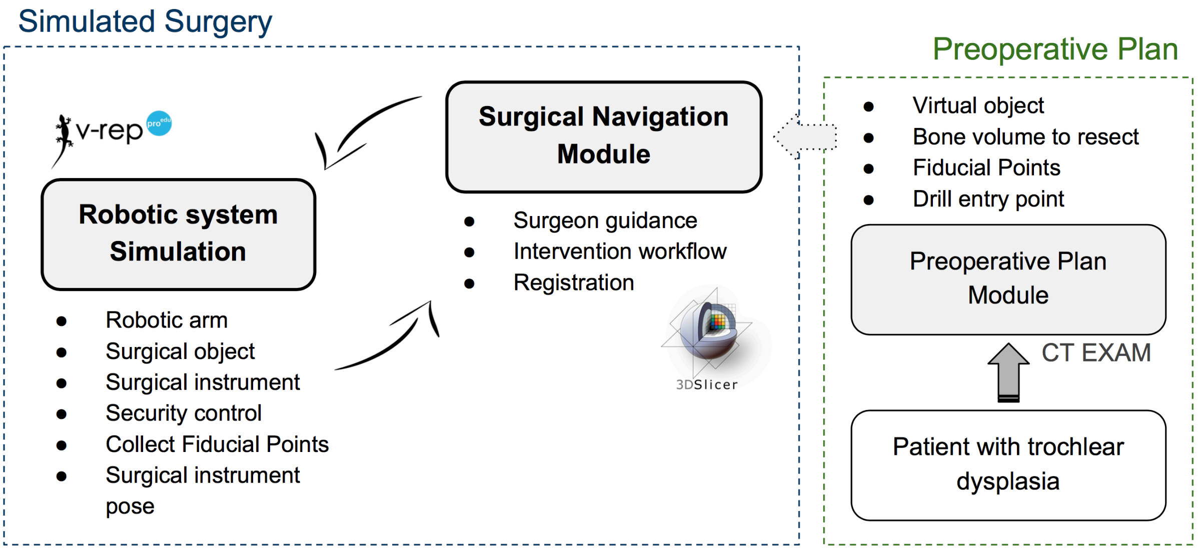


Figure 26 - System overview of the implemented solution.

The **robotic system simulation** was implemented in V-REP® simulator software with a connection to Robot Operating System (ROS). V-REP® is an open source software with a large available content to implement in the simulations, such as a large set of robotic arms, sensors and actuators. An important feature of this software is the bridge with ROS. The interaction between this system in a simple way is a great value. The V-REP has been referenced as very versatile simulator and ideal for multi-robot applications. The user acceptance shows the notorious emergence of this software in the simulators field [62]–[64].

The software used in this **surgical navigation module** was 3DSlicer®, an open source software that has a wide application in the computer-aided surgery projects. This software provides several predefined modules that address many medical fields. It allows the user to perform his own module using specific functions for the desired tasks. It is an important feature of this software to improve the user experience. By implementing a Graphical User Interface (GUI), as performed during this work, it is provided an easier and intuitive utilization of the 3DSlicer® functions. 3DSlicer® software has been used in surgical navigation projects with a good acceptance and the tools that it provides are deeply useful to this kind of applications [65]–[69].

Also, the surgical navigation module developed in 3DSlicer® software ensures full integration with the preoperative plan module, that was also developed in this platform.

3.3 Conclusions

The main challenges of this work are presented in this chapter. All limitations and complications enunciated by the literature and by the orthopaedic surgeons were presented.

The planning of a CAS system for trochleoplasty was performed since this system provides the required features to overcome the previously enunciated points. This CAS system has to integrate the preoperative plan module carried out at University of Minho from another work that contains one section to evaluate the patellofemoral parameters and another one to perform the preoperative plan to be used intraoperatively.

It was delineated that the robotic arm is a great added value to this system. Based on MAKO RIO® operation, the robotic system to be applied in this work should provide the haptic force feedback in order to assist the surgeon during the surgery by providing some restrictions to the movement when the surgeon is reaching undesired bone.

In order to simulate and to validate this proposed CAS system for trochleoplasty, this work will address two main modules. The robotic system simulation aims to simulate the implementation of the robotic system in the operating room environment and the surgical navigation module consists of a software that aims to assist the surgeon during the surgery by providing the required guidance to accomplish the entire intervention. The robotic simulation will be implemented in V-REP® software and the surgical navigation module in 3DSlicer®.

4. ROBOTIC SYSTEM SIMULATION

The robotic system to be implemented in this CAS system has to fulfil essential requirements specified in the previous section. A hands-on, or surgeon-controlled, robotic arm has to be placed in the simulation environment and the choice of the equipment to use has to be adequate and reasoned. Then, the simulation environment must represent the operating room environment as real as possible. The positioning of the elements in the surgical room must be taken into account and the robotic arm has to be manipulated in order to simulate the trochleoplasty intervention.

In this context, during this chapter it will be detailed the selection of the robotic arm to introduce in the simulation environment and then, the operating room environment construction. Two stages of the simulation are presented in this section. The final simulation environment and the implemented robotic arm manipulation are described at the end of this chapter.

4.1 Robotic Arm

The followed work-line to choose a suitable robotic arm to this project consisted on looking for the existing industrial collaborative robots and selecting the best option to adapt to a medical environment and to this specific application. In contrast to most industrial robots that were designed to operate autonomously, the **collaborative robots** were designed to interact with humans in a shared workspace with all guaranteed security for the operator due to built-in force-sensing causing the robots to automatically stop operating when they encounter obstacles in their route. This is a crucial requirement to this application [70], [71].

Considering this kind of robotic arms, it is necessary to focus some aspects that the selected model has to comply. A **force controlled** robot will be useful to implement the **haptic force feedback** as described before. The evaluated parameters consisted of **DOF**, **payload**, **repeatability**, **working range** and the **price**. Regarding the DOF, in this concrete application it is required a minimum of 6 DOF. Once the robotic arm will be used to meticulous procedures, that require setting the end-effector with a 3D position and orientation along roll, pitch and yaw axes, even though the end effector of surgical instrument is a drill. It is imperative to provide comfort and agility to the surgeon while using the robot. So, this is an important feature to allow all the freedom to the surgeon to manipulate the robotic arm. Once the surgical instrument will be attached to the last link of the robot, the payload must to be taken into account. As the surgical instrument was not defined at that moment, a payload minimum of 1kg was considered. Once again, due to the required accuracy of the surgical interventions, the repeatability is a crucial factor and the system must present the lowest possible value. As previously mentioned, the trochleoplasty intervention is performed with the surgeon laterally placed in relation to the operated knee. So, the work range of robotic arm has to ensure that the surgeon can reach all required areas of the knee during the surgery with the robot placed at a mobile base next to surgical table. At last, thinking in the viability of the project, the cost of the equipment is a factor that has an important role and, for this reason, this one has to be taken into account.

A lot of **collaborative robotic arms** were compared to understand what the market offers. After a thorough analysis of comparisons of these kind of robots, four collaborative robots were selected with the intended characteristics [72]–[74]. As the aim is to implement a hands-on robotic system, besides the mentioned specifications, the ergonomic and lightweight factors were taken into account to select the following robots. Table 2 presents the models of the robots and their characteristics.

Table 2 - Collaborative robots and their specifications

Model	DOF	Payload	Repeatability	Working Range	Price
FRANKA	7	3 kg	+/- 0.1 mm	800 mm	+
KUKA LBR iiwa 7 R800	7	7 kg	+/- 0.1 mm	800 mm	+++
UR5	6	5 kg	+/- 0.1 mm	850 mm	++
ABB Roberta	6	8 kg	N/A	800 mm	++

All robotic arms presented above match the requirements of the one required in this thesis. According to the literature, the **UR5** from Universal Robots has been the collaborative robot most used in industries and in the robotic research community. This model is characterized by its agility due to its light weight, speed, easy to program, flexibility, and safety [71], [75], [76].

Based on this, the UR5 was the selected robotic arm to use on simulation. The UR5 model is shown in figure 27.

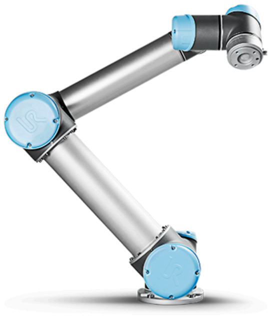


Figure 27 - UR5 robotic arm from Universal Robots [77].

In order to achieve a better comprehension of its applicability on this project, a script was performed in Matlab® software to build this robotic arm model, resorting to robotics toolbox. To create a simple representation of the robotic arm in Matlab® using the robotics toolbox, the Denavit-Hartenberg (DH) parameters of the robot model are required. The DH convention is the most used method in robotics to characterize the kinematic relations between the links of a kinematic chain connected by a revolute or prismatic joint. A robotic system with several links can be represented using the DH method to relate the position and orientation of the last link to the first [78], [79].

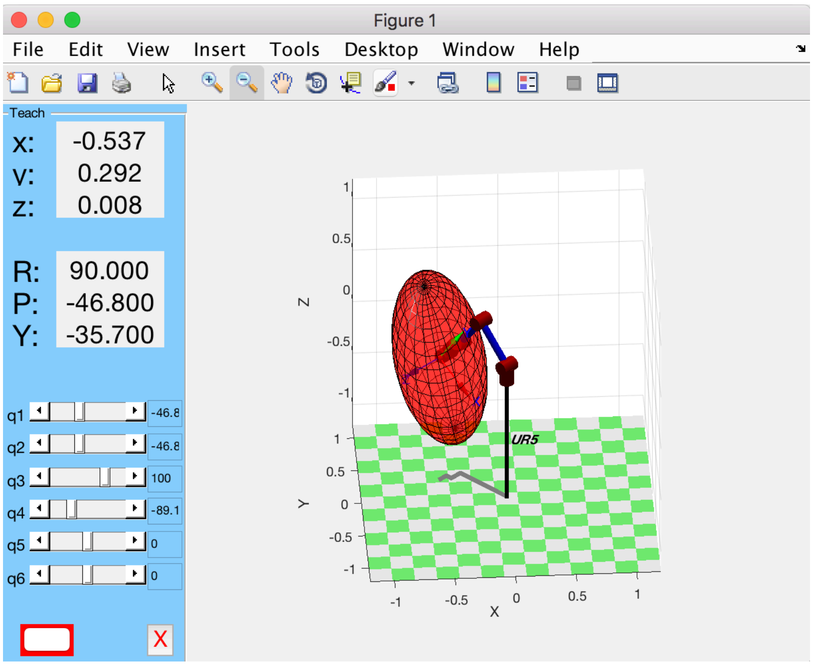
The DH parameters of UR5 robotic arm model are described in table 3 and they are used to build the robot representation in Matlab®.

Table 3 - DH parameters of UR5 robot [80]

Joint	a_i [m]	α_i [rad]	d_i [m]	θ_i [rad]
1	0	$\pi/2$	0.089	θ_1
2	-0.425	0	0	θ_2
3	-0.392	0	0	θ_3
4	0	$\pi/2$	0.109	θ_4
5	0	$-\pi/2$	0.095	θ_5
6	0	0	0.082	θ_6

Resorting to the **DH parameters** above presented, a script in Matlab® was performed that aims to display the robotic arm desired trajectories and also provide a Graphical User Interface (GUI) that contains a simple interpretation of **manipulability** of the robot in a specific position. The **manipulability ellipsoids** are a concise way to analyze the performance of the robotic arm regarding their capacity to influence velocities and accelerations at the end effector or to apply forces on the environment. Thus, the velocity manipulability ellipsoid corresponds to all possible normalized velocities at a given robot configuration. Visually, it is possible to interpret the ellipsoid shape and to conclude about the range of possible motions at that configuration. The biggest axis of ellipsoid presents the direction where a greater velocity value can be reached. The approximations to singularities can be identified when the smaller ellipsoid axis tends to zero. In the same way, the force manipulability ellipsoid has the same interpretation but with forces. This approach may be useful in the design phase to determine the viability of the manipulator structure and size, and to understand if the working range of the robot is adequate [81], [82].

Thus, the GUI with the model of the UR5 is presented in figure 28. On the left side, the desired configuration of the robot can be adjusted and on the right, the robotic arm links are positioned at the configuration provided and the force or velocity is actualized. Visually, the user can interpret about the manipulability of the robotic arm at that position. In this case, a velocity ellipsoid at an aleatory position is shown.



x: -0.537
y: 0.292
z: 0.008

R: 90.000
P: -46.800
Y: -35.700

q1 -46.8
q2 -46.8
q3 100
q4 -89.1
q5 0
q6 0

Figure 28 - GUI with the velocity manipulability ellipsoid of UR5.

This was used to check the viability of UR5 to this application. After the positioning of the robotic arm in the operating room environment, in the simulation software, as it will be detailed next, the configuration of the robotic arm when it is reaching the knee, the operating area, was collected and these values were used in the GUI. The achieved force and velocity ellipsoids at that configuration are presented in figure 29. The biggest ellipsoid corresponds to the force ellipsoid and the other corresponds to velocity ellipsoid.

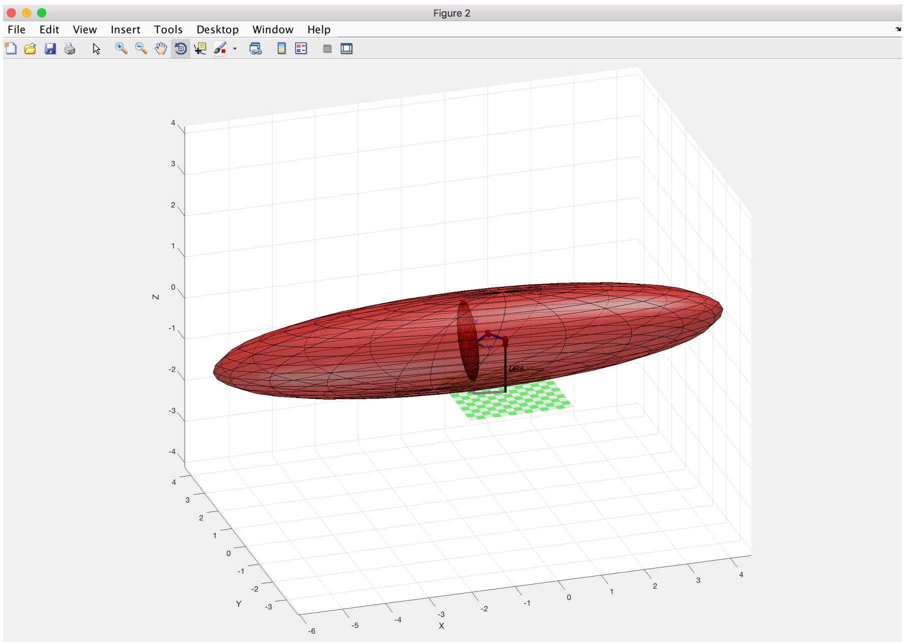


Figure 29 - Force and velocity manipulability ellipsoids of UR5 when positioned at the target position.

It was useful to check that the selected robotic arm does not present any inconvenience regarding its working range. By analyzing the ellipsoid shape, it is possible to verify that in the **target position**, the knee of the patient, the robotic arm is far from any singularity.

The main aim of this approach was solely to perform a simple visual interpretation about the viability of the position of the robot and its working range to perform the required tasks. It was not performed any thorough analysis regarding this subject once the provided information is enough so far.

4.2 Simulation Environment - First Stage

As previously mentioned, the simulation was performed in V-REP® software. To control each object or model in the simulation via embedded scripts, the programming language Lua was used. This software allows the interaction of its models with ROS. ROS topics can be subscribed or published during the simulation to receive and to send information in real-time across ROS. A ROS topic is a name that is used to identify the content of the message. Each ROS topic has a type of information and to access to this information this topic has to be subscribed. The implemented ROS communication will be detailed next.

A large set of models in the V-REP data base is one of the most appealing characteristics of this software. In order to build the operating room environment, a set of models had to be selected and when necessary, they had to be built by means of SolidWorks® software.

In the first approach, the operating room was built with few elements. A simple environment was built with the main components in order to visualize the applicability of the robotic arm in this context.

Starting with the robotic arm, V-REP data base provides the UR5 model. So, the used model of robotic arm is presented in figure 30.

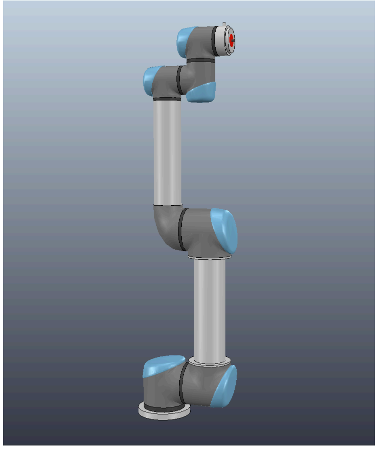


Figure 30 - UR5 model in V-REP software.

In order to set up the simulation environment, some main elements such as the surgeons, the tracking system, the monitoring screen and the patient have to be positioned in an adequate position regarding the operating room available space. Thus, it was necessary to collect 3D models of these elements to place in the simulation. 3D Warehouse and GrabCAD are the most known data bases of 3D models with a lot of free models. These models can be downloaded as collada file kind and next it is possible to import them into the simulation environment in V-REP. Then, some options to change the model appearance are allowed, such as to change the color and shape, add or delete components of a model or group a specific number of elements. After the final model is built, it is possible to position it at a desired position and orientation easily. The following 3D models presented in figure 31 were downloaded from databases above enunciated and were modified until to the final appearance.

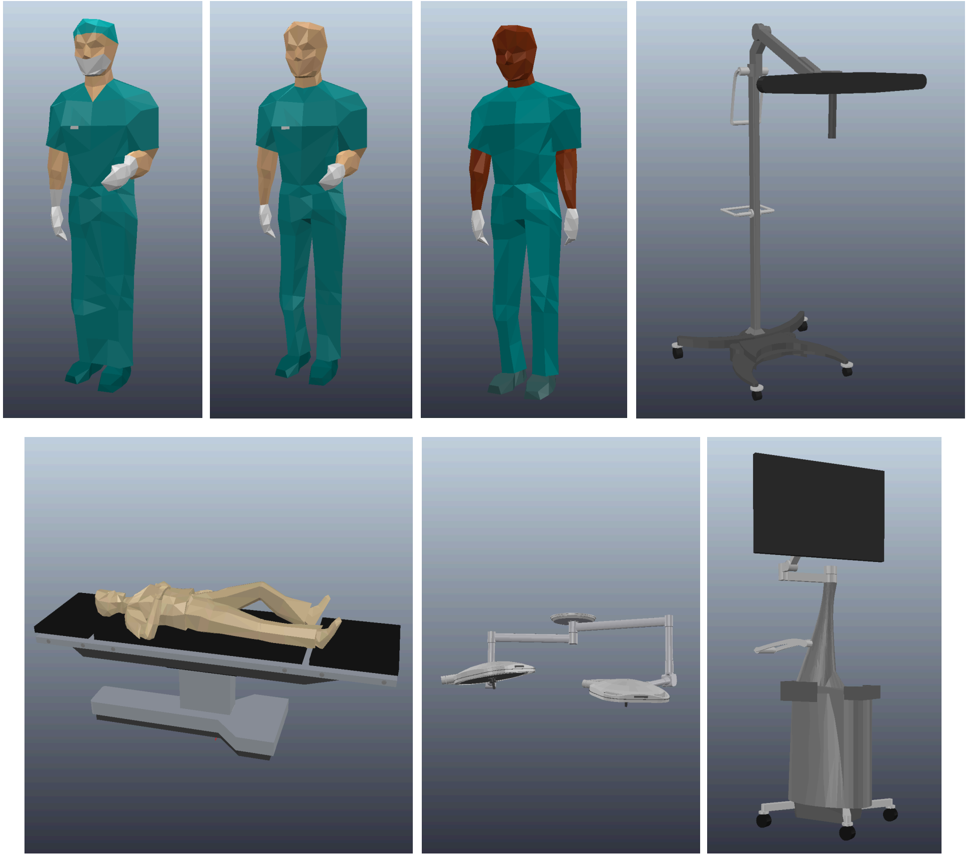


Figure 31 - 3D models used in the simulation environment.

Figure 31 presented the surgeons models, a model simulating the tracking system, the surgical table with the patient, the lights and the monitoring screen where it must be displayed the surgical navigation module.

Some necessary elements to the simulation were built resorting to SolidWorks® software. The robot must be placed at a mobile base to allow its mobility in the operating room. Even though during the intervention, the **robot base** is static, to allow the mobility of the robot between operating rooms it must have a mobile base with a lock system. Also, as previously mentioned, a **surgical instrument** has to be adapted to this robotic arm. In this first approach, a new design of a power tool was performed in SolidWorks®. The aim of this model is just to show the positioning of a possible surgical power tool and it was not based on a real surgical instrument. Figure 32 shows the mobile base of the robot and the surgical power tool performed in SolidWorks® software.

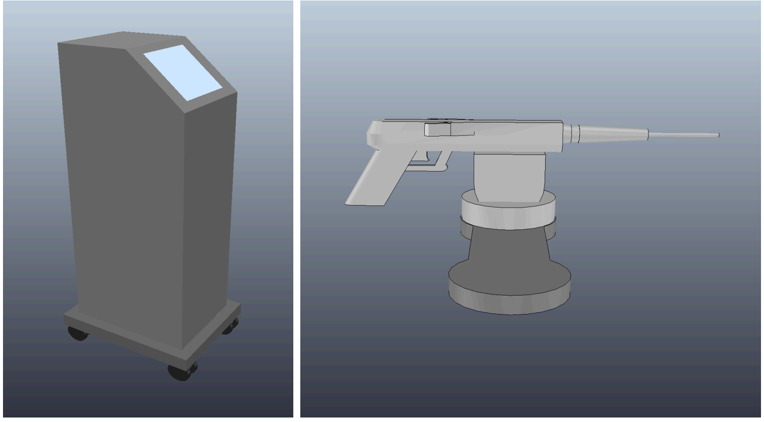


Figure 32 - 3D models built in SolidWorks software.

All the required elements of the simulation have been described. The next step is to position the elements in the simulation environment. One important thing to consider here is the robot position. As described previously the surgeon performs the surgery placed on the lateral side of the operated knee. So, the robot should be placed on the same side and one possible configuration of the operating room is presented in figure 33.

As it is possible to see, the robotic arm and the surgeon are placed on the same side and in front of the surgeon it is placed the screen to provide the intervention guidance during the surgery.

This was the first approach to the operating room environment. With that, it was already possible to identify some important factors such as the positioning of the surgeon and the robotic arm in relation to the patient and also the position of the screen to provide the information of surgical navigation module.

However, the disposition of the operating room is influenced for other components and factors that were taken into account in the next operating room environment as presented in the following.

Figure 33 - First operating room environment in V-REP®.

4.3 Final Simulation Environment

The positioning of the components in the operating room environment is very important to simulate the surgery. The space **availability** to the surgeon to perform the procedures, the **distance** of the robotic arm to the surgeon, the **field of view** of the surgeon, are factors that have to be taken into account when it is built the operating room environment. For this reason, the reproduction of an environment as close as possible to the reality is important in the simulation. This demands a new planning and positioning of the operating room environment. To be able to perform this new environment with more detail, a visit to the operating room at Hospital of Braga was booked. It was an important step for the present work. With the opportunity to visualize one complete knee intervention, it is possible to clarify some aspects such as the surgeon movements, the available equipment at the operating room, the positioning of the equipment and medical staff and the available space in the room.

Thus, this collected information allowed to build a new operating room environment with more equipment, more detail and a better positioning. It was possible to identify some points that could be improved in the first operating room created. One of these is the position of the **tracking system**.

That position could not be applied once it did not allow a direct view to the femur reference that must be placed at the femur bone close to the knee.

Also, considering that the final tracking system will contain a dual Kinect system (under development in another master thesis), this could be updated in the simulation environment. According to this, in order to implement this new operating room environment, a new set of 3D models was download resorting to the same data bases above mentioned. The new added models to the environment are presented in figure 34.

Figure 34 - 3D models used to complete the final simulation environment.

Regarding the **surgical instrument**, in order to address the surgical power tool that is used in the Hospital of Braga nowadays, this one was updated. Stryker® power tools are used in this Hospital as it was possible to verify during the visit to the operating room. One example of a Stryker power tool is presented in figure 35.

Figure 35 - Example of a Stryker power tool [83].

Again, the next models were built in SolidWorks. The goals were to create **a reference tool** to attach to the femur bone, that will be used in the tracking system and to create a representation of the Stryker® power tool presented above. In this case, the dimensions of the built model are similar to a general Stryker® power tool. With this, it is intended to reproduce as much as possible a real situation in the operating room.

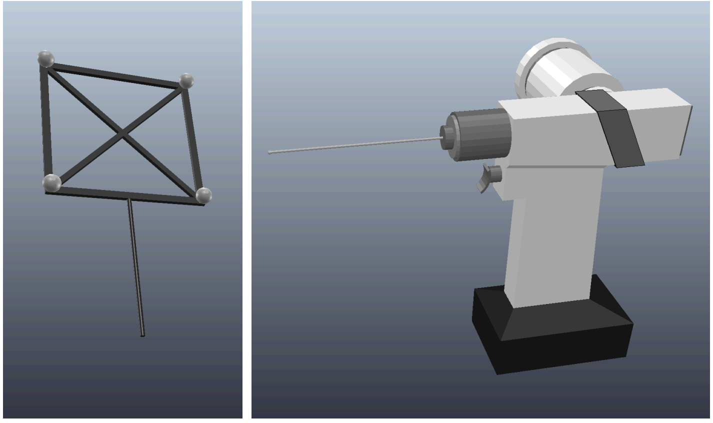


Figure 36 - Femur reference frame and representation of a Stryker® power tool models.

With these new contents, it was possible to plan and to build a more realistic scenario of the operating room. In figure 37, the **final operating environment** is presented with the new models and their positioning.

Figure 37 - Final operating room environment in the simulation.

In this environment, the reference tool is placed at the femur and the tracking system composed by dual Kinect system is placed at a position that allows more available space in the operating room and it avoids possible occlusions to the femur reference tool during the intervention. In order to realize what is the available space of the surgeon during the intervention, the figure 38 shows the field of view of the surgeon.

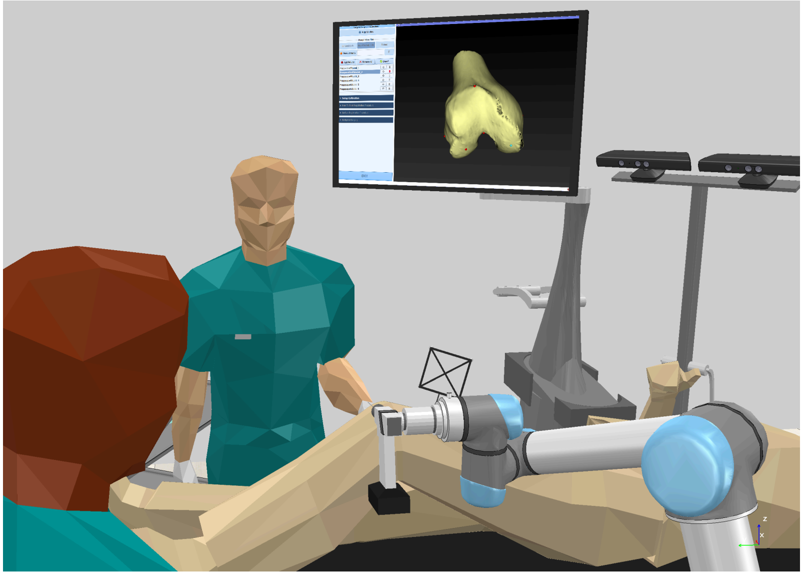


Figure 38 - Field of view of the surgeon during the intervention.

As the image shows, the surgeon has total access to the robotic arm and surgical instrument and a direct view to the screen where the surgical navigation module will be displayed.

Another analyzed aspect in the final operating room environment was the working range of the surgical instrument when attached to the robotic arm. In order to visualize its **workspace**, a script was performed in the UR5 model to draw the boundaries of its working range, taking into account that the considered end effector was the tip of the surgical instrument. The final result is presented in figure 39 and it is possible to see that the robotic arm, in the desired position, is adequate once the operated area is far from the boundaries of the workspace volume of the robotic system.

Figure 39 - Representation of workspace of robotic arm with the surgical instrument mounted.

4.4 Robotic Arm Manipulation

The planned solution includes a hands-on robotic arm that will be guided by the surgeon during the intervention. However, in a simulation the virtual surgeon cannot move the robot and a solution was planned in order to simulate the surgeon movements and move the robot accordingly.

Thus, in the first version of the operating room a simple manipulation of the robotic system was implemented in order to be able to place the drill, the tip of the surgical instrument in the desired pose. To achieve that, a GUI with 6 slide bars, one for each joint, was implemented. Here, a fast configuration of each joint can be chosen and the robotic arm is positioned in the selected configuration. The GUI can be seen on the upper left corner of figure 40.

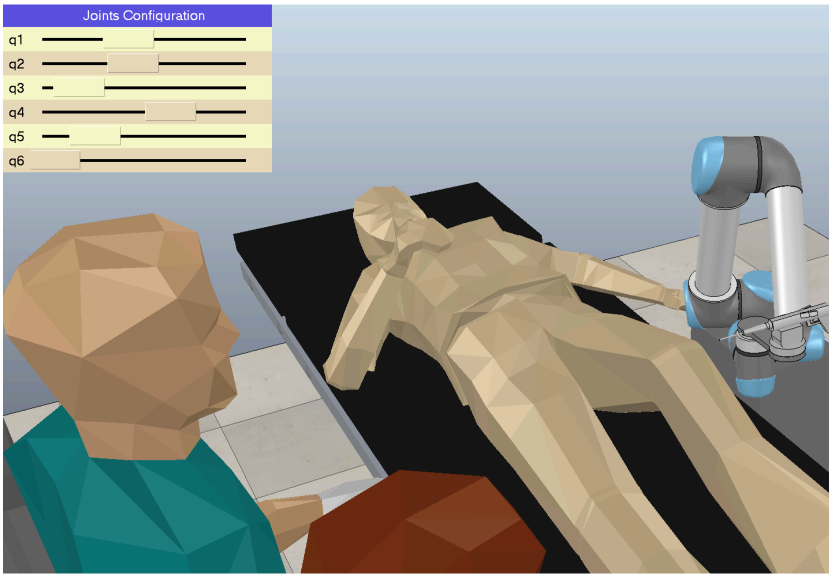


Figure 40 - GUI implemented to control each joint of the robotic arm.

To complement this robot manipulation, once the GUI does not allow a precise control of the joint configuration, it was implemented a keyboard control shown in figure 41.

Figure 41 - Keyboard control implemented to input a precise configuration of each joint of the robotic arm.

With this keyboard control, the fast configuration provided by GUI can be adjusted to a more precise configuration. In figure 41, the joints that are controlled by each key are identified and the increment or decrement has an accuracy of +/- 0.36 degrees. The return key opens a new window with the actual configuration of each joint in radians and in degrees.

This implementation of robotic arm manipulation was useful to manipulate the robotic arm in the operating room and to collect the configuration joints in the operated area. However, in order to fully simulate the intervention it is not adequate since it does not provide the required freedom of the robotic arm to simulate the procedures of the intervention. Thus, with the new operating room environment creation, the robotic arm manipulation was changed as well.

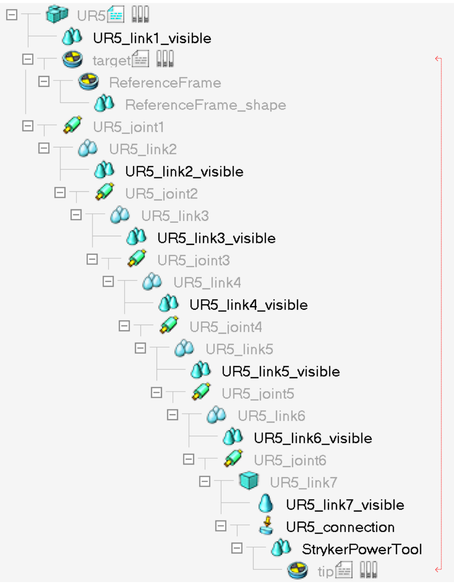
In order to achieve a more user-friendly robotic arm manipulation, 3 approaches were adopted: a Playstation (PS) 3 controller, a joystick and a Wii remote plus.

Figure 42 - Controllers implemented in the simulation to manipulate the robotic arm: Playstation 3 controller (A); Joystick Microsoft sidewinder precision 2 (B); Wii Remote Plus controller (C).

In order to use these devices in the simulation, their connection with ROS was required. First of all, the joystick_drivers package was installed on ROS. This package contains all necessary nodes and drivers to manipulate a robot with these devices. The main aim of this package is to convert the events from a device to ROS messages. These ROS messages can be read by subscribing the respective ROS topic.

For each device, a ROS node is created with several ROS topics. In the case of PS3 and joystick controllers, the ROS node created is the same, *joy_node*. For Wii remote plus, the *wiimote_controller* publishes the Wii remote sensor data.

In the simulation, in order to implement this robot manipulation, the inverse kinematics for UR5 had to be implemented. Two different reference frames were placed at the tip of the surgical instrument. In figure 43, it is possible to see the relationship between both reference frames, the target and the tip, in the screen shot of scene hierarchy from V-REP®.



- UR5
  - UR5_link1_visible
  - target
    - ReferenceFrame
      - ReferenceFrame_shape
  - UR5_joint1
    - UR5_link2
      - UR5_link2_visible
      - UR5_joint2
        - UR5_link3
          - UR5_link3_visible
          - UR5_joint3
            - UR5_link4
              - UR5_link4_visible
              - UR5_joint4
                - UR5_link5
                  - UR5_link5_visible
                  - UR5_joint5
                    - UR5_link6
                      - UR5_link6_visible
                      - UR5_joint6
                        - UR5_link7
                          - UR5_link7_visible
                          - UR5_connection
                            - StrykerPowerTool
                              - tip

Figure 43 - Scene hierarchy of UR5 model.

Basically, with the data from the ROS topic of each device, the pose of target frame is updated and the tip follows the target when the inverse kinematics is applied.

In order to understand the movements applied to the surgical instrument tip, in figure 44A it is presented the surgical instrument with the target reference highlighted. In figure 44B it is presented the roll, yaw and pitch angles in a reference frame. The target reference frame corresponds to the reference frame of the image, the blue axis corresponds to *z* axis, the green to the *y* and the red to the *x* axis.

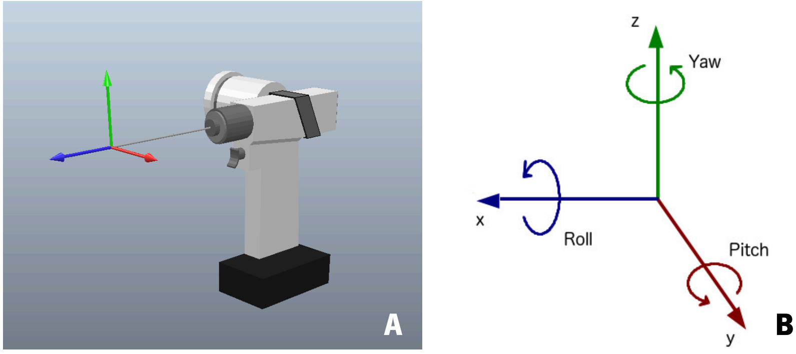


Figure 44 - Surgical instrument with target reference frame (A); Reference frame with the roll, yaw and pitch angels identified (B).

Considering this, it was implemented the manipulation of surgical instrument using the three devices described above.

First, regarding the **PS3 controller**, in the simulation script was subscribed the */joy* ROS topic provided from the *joy_node* ROS node. This topic has the data of all buttons of the controller. Thus, the simulation script has access in real-time to the inputs of the controller. Some buttons of the controller were selected to manipulate each DOF of the surgical instrument. In this way, the vertical and horizontal left analog button control the pitch and yaw angles, respectively. The left and right arrows manipulate the roll angle. Regarding the position in the space, the vertical and horizontal right analog button change the position of target in the *z* and *y* axes. The R1 and L1 buttons brings the surgical instrument to forward and backward, respectively. These buttons are identified in figure 45.

Figure 45 – R1 and L1 buttons of PS3 controller.

In the **joystick**, in relation to the ROS nodes and topics, they are the same that in the Ps3 controller. So, to control the orientation of target, the user has to press button 2 and move the joystick. The forward and backward movements in the joystick will change the pitch angle and the left and right movements will change the yaw angle. The roll angle will be modified with the torsion of the joystick. In order to change the position of the target along the *x* and *y* axes, the user must press button 3. While pressing the button, the forward and backward movements in joystick will change the position along *x* axis and the left and right movements will change the position along *y* axis. Lastly, to move the target to upper and down along the *z* axis, the user has to activate the up or down arrow in the little analog button with the thumb.

At last, the **Wii remote plus** is different from the two other devices. This controller is composed by motion sensors that allows an interactive and haptic manipulation of surgical instrument in the simulation. This was an approach to provide an interaction with the simulation more realistic and more intuitive to the user. The Wii remote plus is composed by an accelerometer and a gyroscope. In this application, only the data from the gyroscope was processed. In the simulation script, the */imu/data* and */joy* ROS topics were subscribed. The */imu/data* ROS topic contains the data from gyroscope and the */joy* ROS topic the data from the buttons. In order to achieve a better perception about the movements in the Wii remote plus, the figure 46A shows the target reference frame overlapping the device. Thus, it is possible to visualize the effects of the controller motion in the target reference frame.

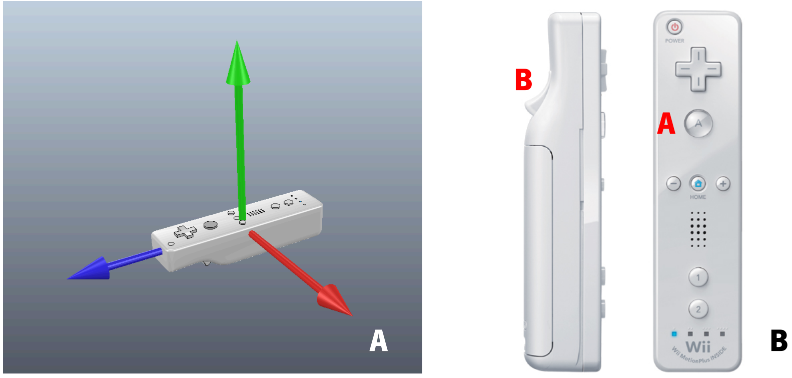


Figure 46 - Wii remote plus with the reference frame (A); Buttons A and B of Wii remote plus (B).

Therefore, while pressing the button B (figure 46B), the orientation of the target is changed according to the motion of the device. If the gyroscope detects an angular velocity, a rotation, around the red, green or blue axes, the pitch, yaw and roll will be changed, respectively. To modify the position along the *y* and *z* axes, the user must rotate the Wii remote plus around the green and red axes, respectively, while pressing the minus button. And finally, to move forward and backward along the *x* axis, the user has to press button A (figure 46B) and rotate the controller around the red axis.

4.5 Conclusions

The robotic arm UR5 was selected to implement in this robotic system to be applied to a CAS system addressed to the trochleoplasty. This robotic arm has 6 DOF with a working range of 850mm. It is a collaborative robot that allows to be force controlled and its repeatability is +/-0.1mm. When compared with other robots, UR5 was selected since it is largely used on research and this could be a great factor during the further steps of this work. In order to achieve a better perception about its manipulability in the operating room environment, an implemented GUI shows the force and velocity ellipsoids for a specific configuration of each joint of the robotic arm. After the robotic system simulation has the operating room environment created, the robotic arm was configured to reach the surgical object. This configuration was studied in the GUI to perceive if the working range of the robotic arm is enough.

A first approach to create an operating room environment resulted in an operating room with the surgeons, the patient, the robotic arm with a surgical object, the tracking system and the screen to display the surgical navigation module. In order to improve the positioning of all equipment and to create a more realistic operating room environment, together with the surgeons that supported this work, it was planned a visit to the operating room at Hospital of Braga to visualize a knee surgery.

A more realistic operating room and with a better positioning allows to study the field of view of the surgeon, the positioning of the tracking system and the femur reference and the workspace of the surgeon to perform the surgery.

In order to simulate a surgeon-controlled robotic system, it was study which kind of manipulation of the robotic arm could be implemented. Three devices were implemented to manipulate the robotic arm and the surgeon instrument in order to conclude which the device is more intuitive to simulate the surgery. The used devices were the PS3 controller, the Wii remote plus and a joystick. With this implementation, it is possible to manipulate the surgical instrument simulating the surgeon procedures intraoperatively.

5. SURGICAL NAVIGATION MODULE

In this chapter it is presented and described the implementation of the surgical navigation module for trochleoplasty intervention. In this context, the main components integrated in this module and the algorithms of the registration are highlighted. At the final of this section, the final surgical navigation module will be presented in a case study where the entire workflow of the navigated surgery, using the present module, is shown.

As mentioned before, this module was implemented in 3DSlicer® software, an open source software with a large community of users in medical imaging and surgical navigation, for example. Next, some useful features of this software to this application are mentioned and a general overview of this platform is presented.

5.1 Overview of 3DSlicer Software

As an open source software, the **3DSlicer**® provides a lot of predefined modules that can be applied in different medical areas. Also, the developer tools provided by this software allow the user to perform his own module using specific functions for the desired assignment. To develop the present module, some native modules were implemented in order to achieve a fast processing and to implement an integrated and robust surgical navigation module.

This is a powerful tool to analyze medical exams, such as CT and MRI. These are files with DICOM format and can be imported to 3DSlicer using the “DICOM” module. A patient and an image library are generated and it is possible to choose between complete studies or only a specific data [66], [69].

Considering the main window of this software, it contains a toolbar where the main tools are contained. In this toolbar, all native modules can be accessed in the toolbar under the heading of “Modules”. Besides these, the modules developed by the user resorting to developer tools are contained in this section.

In the main window, it is possible to identify two distinct areas. On the left side, the GUI of the selected module is presented. On the opposite side, it is shown the imaging visualization. This area can be configured to display the desired plane of the patient exam, axial, sagittal and coronal, or a 3D view. There is an option to show all mentioned views at the same time in four small windows.

Other feature very important for this application is the possibility to install 3DSlicer® extensions that provide a lot of extra tools to biomedical applications. In this implementation, the SlicerIGT extension was used to perform some tasks. This extension consists of a set of modules that assist the development of image-guided interventions. The tracking system, a main component of this kind of interventions, can be connected to 3DSlicer® by means of this extension through OpenIGTLink network, allowing real-time update of tracked models and images [65], [84]. Also, the robotic system can be connected to the 3DSlicer® resorting to this network protocol. This will be an important tool to perform the patient **registration** to the navigation coordinate system in 3DSlicer®. In a CAS system, the registration is the main factor to ensure the success and great accuracy of the intervention. The detailed approach to perform the registration, applied in this module, is presented below.

5.2 Registration

As enunciated before, an accurate registration between the patient and the preoperative plan is a key for the **navigated surgery**. With this procedure, the surgeon is able to move the patient during the surgery to a more convenient position and the surgical plan is adjusted accordingly. The navigation system needs to display the current tool location in the coordinate system of the virtual scene. The virtual surgical tool pose in relation to the virtual object in 3DSlicer® must be the same that the relative pose of the surgical instrument to surgical object. In general, the coordinate system of the virtual scene differs from the coordinate system of the navigator intraoperatively. The mathematical relationship between both coordinate spaces needs to be determined in order to uniform and to place both coordinate systems with the same referential. This corresponds to the **registration procedure**, or matching [85], [86].

As will be described next, in this surgical navigation module, the registration procedure is divided in two steps. The literature presents the **point-to-point registration**, or point-based registration, and the **surface registration** as two different ways to perform the registration procedure. To achieve the most accurate registration possible, the procedure was performed applying the point-to-point registration followed by the surface registration in the rotated model previously obtained from point-to-point registration.

5.2.1 Point-to-Point Registration

The **point-to-point registration** is the simplest step in the registration procedure. It consists in matching two sets of points. One set is defined preoperatively in the virtual object, while the corresponding set of points is collected on the surgical object intraoperatively, using a pointer tool. It is important to note that the order of the collected points has to be respected. Basically, this approach assumes n points of the reference surface $pi = p(xi,yi,zi)$, with $i = 1,\dots,n$ and spatial coordinates xi, yi, zi, are ordered in pairs with n points $qi = q(xi,yi,zi)$ of the test surface.

With the minimization of equation (1), the sum of the squared error, a linear transformation matrix R and a translation offset vector t, that aligns the reference with the test surface, are estimated.

$$E\,(R,t) = \sum_{i=1}^{n} \| \, pi - Rqi - t \, \|^2 \qquad (1)$$

Thus, it is possible to verify that the geometric distance between the reference surface and the transformed test surface should be as small as possible. When the correct correspondences are known a unique solution for R and t is given [87]–[90].

Although point-to-point registration is easy to solve mathematically, it depends on an optimal selection of points and the exact identification of the associated pairs. Once some anatomical structures in the surgical object are difficult to achieve with precision by the pointer tool, the surface registration will improve the outcome from point-to-point registration.

5.2.2 Surface Registration

The **surface registration** will match the surface of virtual object with the fiducials collected by the surgeon intraoperatively. This method uses the points that compose the surface of the virtual model and a new set of fiducial points of the surgical object.

In the literature, two popular methods of surface registration were compared: iterative closest point (ICP) and coherent point drift (CPD) algorithms. It was verified that ICP results in a better registration accuracy [85]. The ICP algorithm consists in pairing each collected point from the surgical object with the nearest point of the virtual object surface. Then, the transformation that will minimize the mean square of the distances between pairs is estimated. The points are then re-paired and this process is repeated until the stopping conditions are met or a predefined number of iterations is achieved. This algorithm gives the transformation of the points collected from the surgical object to the virtual object.

In this case, once the surface registration is applied after point-to-point registration, the initial parameter of the iterative loop is already closed to the final transformation what results in a better outcome from the registration procedure [85], [86], [91].

5.3 Surgical Navigation Module Planning

In order to delineate the architecture of the module, it was necessary to consider the main aspects of the CAS systems and how should be implemented the connection between them. During the planning of the present module, the main focus was to provide to the user, in this case the surgeon during the intervention, a fast and intuitive interaction.

Note that this surgical navigation module is to be used intraoperatively to guide the surgeon during the intervention. Although the setup system includes the robotic simulation instead of the real devices, with the simulation it is possible to allow a fully integrated system with all components of a CAS. This allows to plan the module with all of these connections just as it will be implemented in the operating room environment.

To plan the implementation of the surgical navigation module, some points were identified as key points to be fulfilled. It is important to keep in mind the main goal of this module: guide the surgeon during the surgery. All steps to follow in order to achieve the navigated surgery should be clear and concise. A workflow of the intervention was planned to be applied in this module.

First of all, the existent **preoperative plan** should be integrated in this module. This has to be the first content of the module. It is necessary to allow the surgeon to access to the file with the preoperative plan and to import its content. It will be useful during the all intervention. Note that the content provided from the preoperative module includes the virtual object, the bone volume to be resected, the preoperative fiducials and the entry point to the surgical instrument tip.

After the preoperative plan is available, it has to be performed the **connection** and calibration of all equipment. The medical staff before proceeding to the intervention has to ensure that all system is connected. In the implementation of the present CAS system for trochleoplasty, a tracking system and a robotic arm will be placed in the operating room. This section has to consider these connections.

Already with the all system configured and calibrated, the **registration** can be performed. In this context, it is necessary to separate the point-to-point and surface registration. As above mentioned, the module has to guide the surgeon to perform the point-to-point registration first, and after it has to indicate the procedures to perform the surface registration.

Once concluded all these steps, the **navigated surgery** can be performed and the module must provide the necessary information to guide the surgeon during the trochleoplasty procedure.

5.4 First version of the Surgical Navigation Module

Based on the considerations above mentioned, a first version of the module is presented. The Python language was used. The main aim of this module was to provide an intuitive GUI to guide the surgeon. Contemplating all required sections to perform a navigated surgery, in next figures are some screenshots of the first implementation of the module. This is the primordial version of the surgical navigation module.

Figure 47 shows the preoperative plan section of the first module. In order to integrate the preoperative plan, a “Load Data” button is used to import the preoperative plan into the surgical navigation module. This scene is presented in the right side with the virtual model and preoperative fiducials. The “Redefine Fiducials” button is activated during the screenshot.

The detailed workflow of the module will be presented below. Here, the main goal is to present the main aspect of the first approach to the surgical navigation module. Some screenshots of this first version were chosen in order to present its appearance.

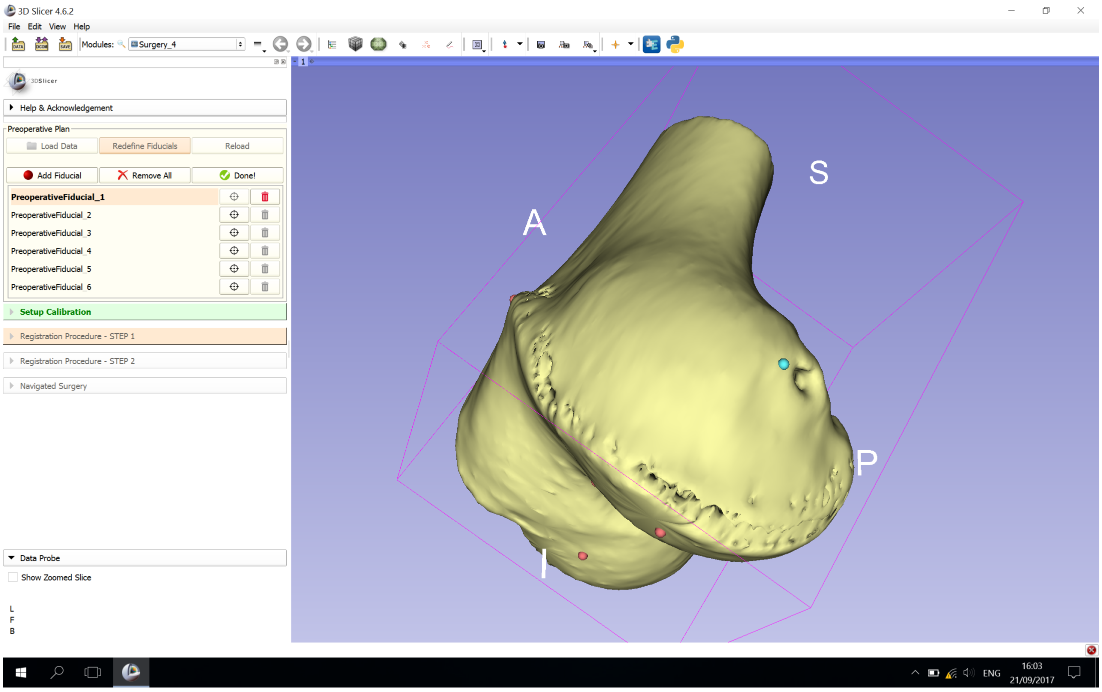
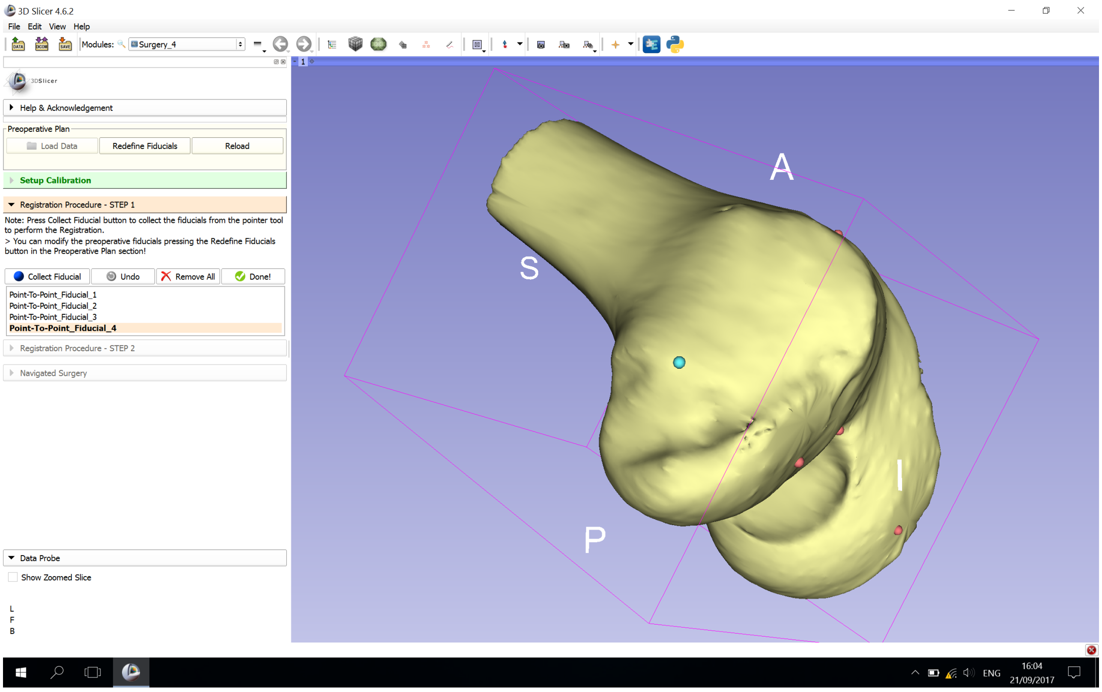


Figure 47 - Preoperative plan section of the first surgical navigation module.

In these, are present three sections of the module. The first one, the preoperative plan section, was already described above. Next, it is shown the first step of the registration procedure. This first step of the registration consists of the point-to-point registration and its aim is to indicate to the surgeon the fiducial that he has to collect along the surgical object. Each fiducial in the virtual object is highlighted and the camera is changed to obtain a better view to the fiducial. This section it is presented in figure 48. The last step of registration, the surface registration, is not present here but in the following workflow presentation it will be described. The last screenshot, presented in figure 49, contains the last section of the module: the navigated trochleoplasty. At this moment, the surgeon can start to resect the bone using the surgical instrument. The visual feedback provided from the surgical navigation module can be seen in figure 49. When the surgical instrument tip is reaching an undesired area, the volume changes to red color.

This first implementation of the module was improved in several ways. In order to do not turn this section repetitive, a brief view of the first module was presented. Next, it will be presented the final version with a thorough analysis of each section and the detailed workflow.



Note: Press Collect Fiducial button to collect the fiducials from the pointer tool to perform the Registration.
> You can modify the preoperative fiducials pressing the Redefine Fiducials button in the Preoperative Plan section!

Point-To-Point_Fiducial_1
Point-To-Point_Fiducial_2
Point-To-Point_Fiducial_3
Point-To-Point_Fiducial_4

Figure 48 - Step 1 of registration procedure section of the first surgical navigation module.

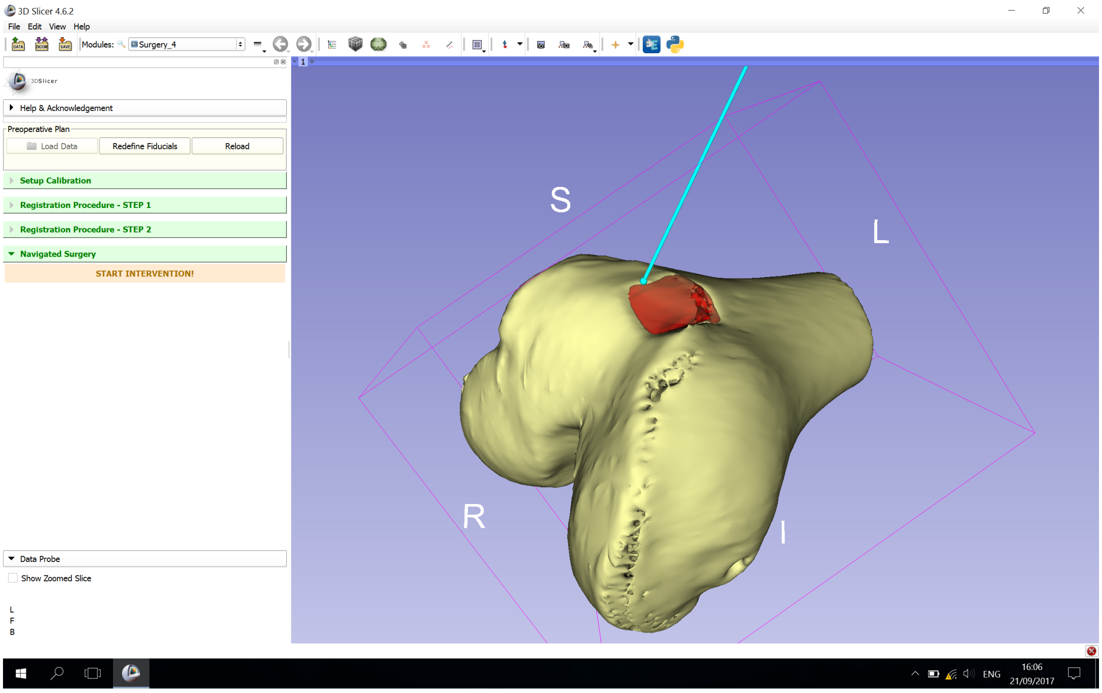


Figure 49 - Visual feedback provided by the first surgical navigation module during the intervention.

5.5 Final Surgical Navigation Module

The final **surgical navigation module** is to be displayed on a screen during the intervention, as it was possible to see in the simulation environment in the previous chapter. Therefore, the contrasts, the colors, the buttons and the text are important factors to provide a good performance.

Together with the surgeons that supported this work, it was delineated that the first version of the module must be improved to provide a better experience to the user. With a good acceptance regarding the functionality of the module and the implemented workflow, the enunciated graphical aspects should be improved, since in the operating room it is necessary to have all the information as much as readable and highlighted possible to simplify its usability.

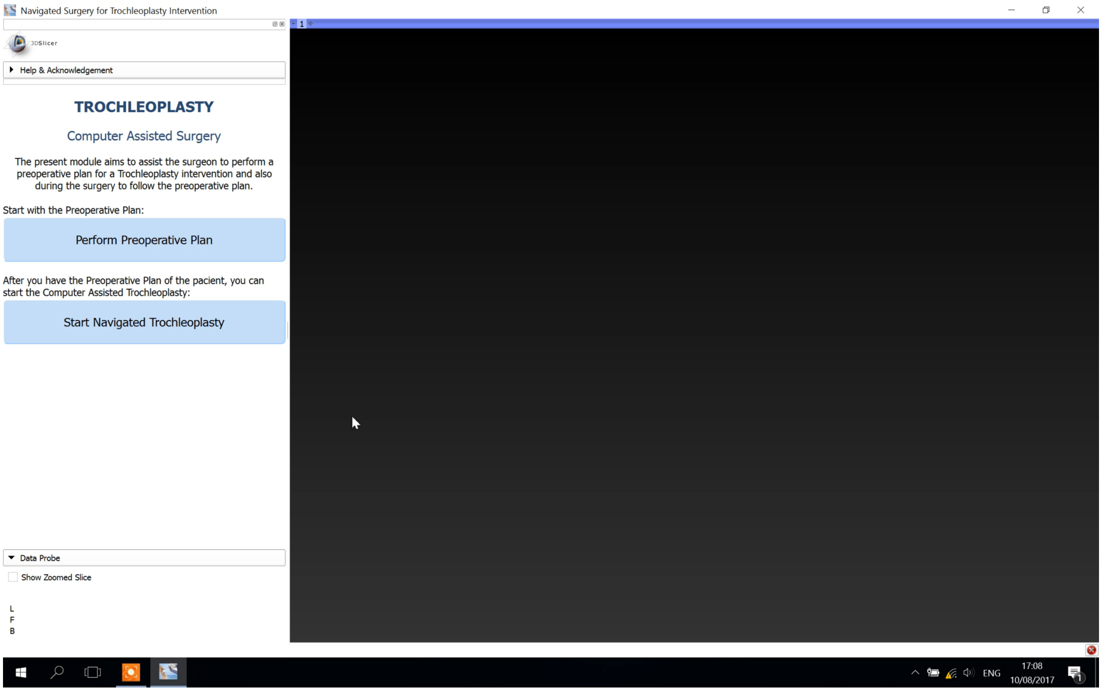
All these considerations were taken into account and a new version of the module was implemented. In addition to the mentioned parameters, the size of the useful area of the module was rethought and some new features were implemented.

In order to provide all the content of this surgical navigation module, it will be presented its entire workflow accompanied with print screens of the sections. Thus, each section will be detailed.

5.5.1 Surgical Navigation Module Workflow

Here it is presented all information about the implemented surgical navigation module. One of the things that was improved in relation to the previous version was the interconnection with the module that aims to perform the preoperative plan. Herein, the surgeon has all the information in a single module. It is possible to perform the preoperative plan pressing the “Perform Preoperative Plan” button as shown in figure 50. The button opens the module that contains the planning of the trochleoplasty. If the surgeon has already performed the preoperative plan of the patient, he must press the “Start Navigated Trochleoplasty” to open a new window with the surgical navigation module.

Once opened, a window in full screen mode is displayed with the surgical navigation module that can be seen in figure 51.



The present module aims to assist the surgeon to perform a preoperative plan for a Trochleoplasty intervention and also during the surgery to follow the preoperative plan.

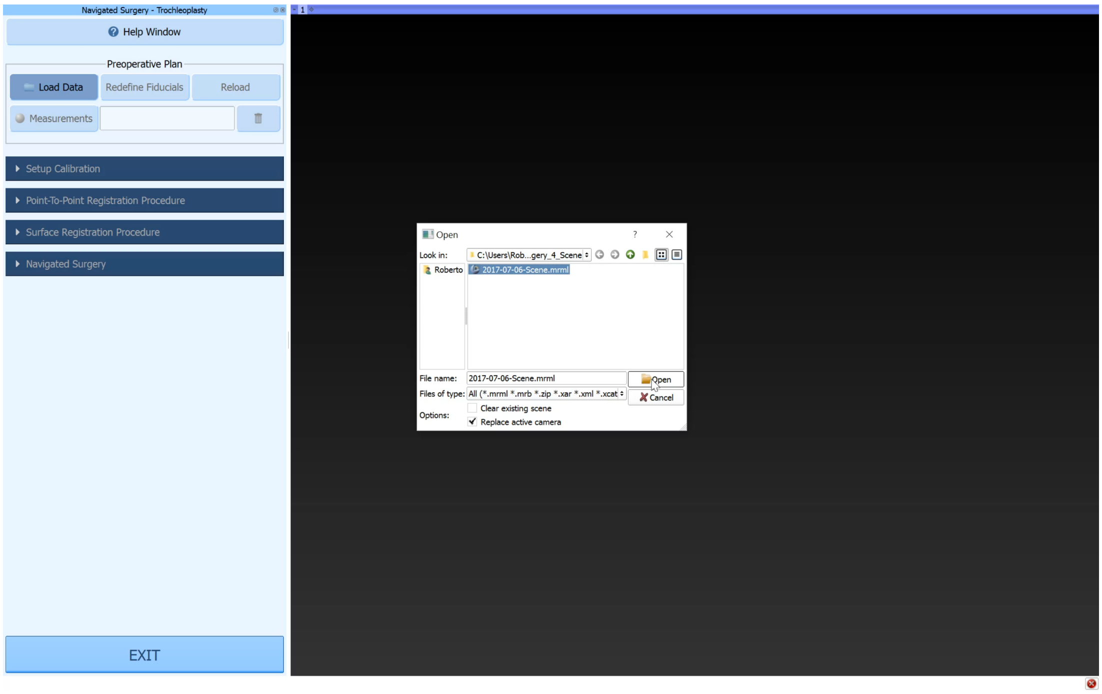
Start with the Preoperative Plan:

After you have the Preoperative Plan of the pacient, you can start the Computer Assisted Trochleoplasty:

Figure 50 - Screenshot of the main window of the surgical navigation module.

A black screen on the right side is displayed in order to provide more contrast to the virtual object. As it is possible to verify, the colors, the text and the buttons were improved to provide a better experience to the user. It is more user-friendly and appealing with a largest area to the module column and to the virtual object manipulation provided by the full screen mode.

To start with the import of the preoperative plan, the user must press the **“Load Data”** button and the window that is shown in figure 51 is displayed in order to choose the file with the preoperative plan. This window allows the user to navigate along the computer folders to choose the desired directory where it is saved the file. As it is possible to see in same figure, the first button of the module is the **“Help Window”** button. A help window opens when the user presses the button, figure 52. The main aim of this window is to provide an overview of the entire workflow of the module. It pretends to clarify the user about the steps to accomplish and the functionality of all buttons. Each section is identified in the help window and the goal of each one of them is described.



Look in: C:\Users\Rob...gery_4_Scene

File name: 2017-07-06-Scene.mrml

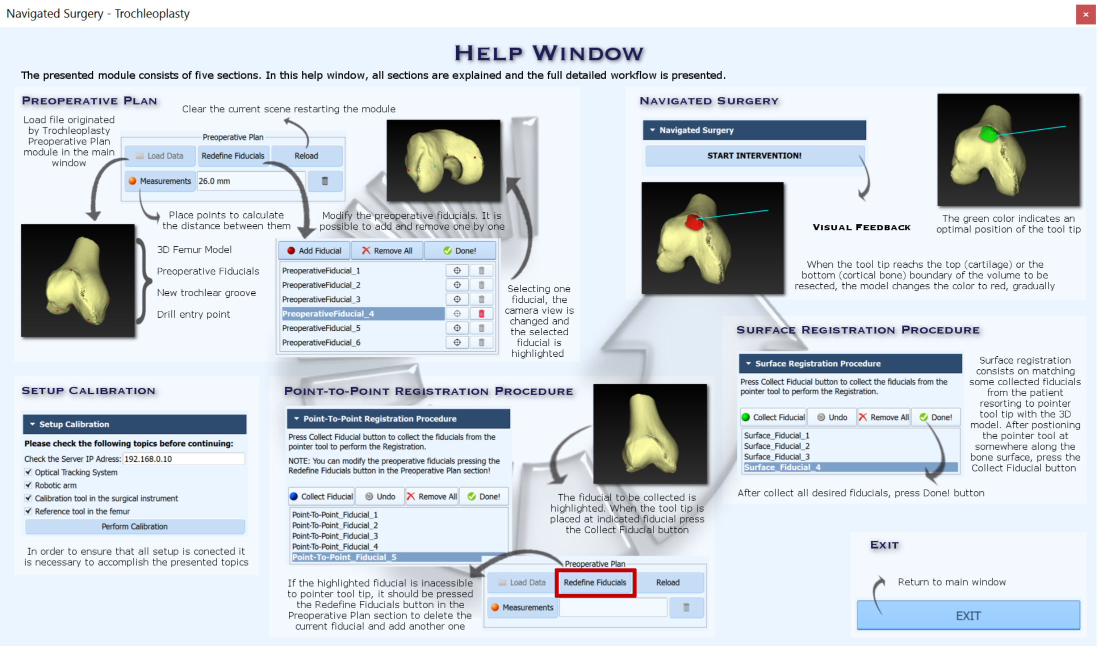
Files of type: All (*.mrml *.mrb *.zip *.xar *.xml *.xcat

Options:

☐ Clear existing scene

☑ Replace active camera

Figure 51 - Screenshot of the “Load Data” window of the surgical navigation module.



Navigated Surgery - Trochleoplasty

HELP WINDOW

The presented module consists of five sections. In this help window, all sections are explained and the full detailed workflow is presented.

PREOPERATIVE PLAN

Load file originated by Trochleoplasty Preoperative Plan module in the main window

Clear the current scene restarting the module

Place points to calculate the distance between them

Modify the preoperative fiducials. It is possible to add and remove one by one

Measurements: 26.0 mm

Selecting one fiducial, the camera view is changed and the selected fiducial is highlighted

NAVIGATED SURGERY

VISUAL FEEDBACK

The green color indicates an optimal position of the tool tip

When the tool tip reachs the top (cartilage) or the bottom (cortical bone) boundary of the volume to be resected, the model changes the color to red, gradually

SURFACE REGISTRATION PROCEDURE

Press Collect Fiducial button to collect the fiducials from the pointer tool to perform the Registration.

Surface registration consists on matching some collected fiducials from the patient resorting to pointer tool tip with the 3D model. After postioning the pointer tool at somewhere along the bone surface, press the Collect Fiducial button

After collect all desired fiducials, press Done! button

SETUP CALIBRATION

Please check the following topics before continuing:

Check the Server IP Adress: 192.168.0.10

☑ Optical Tracking System

☑ Robotic arm

☑ Calibration tool in the surgical instrument

☑ Reference tool in the femur

In order to ensure that all setup is conected it is necessary to accomplish the presented topics

POINT-TO-POINT REGISTRATION PROCEDURE

Press Collect Fiducial button to collect the fiducials from the pointer tool to perform the Registration.

NOTE: You can modify the preoperative fiducials pressing the Redefine Fiducials button in the Preoperative Plan section!

The fiducial to be collected is highlighted. When the tool tip is placed at indicated fiducial press the Collect Fiducial button

If the highlighted fiducial is inacessible to pointer tool tip, it should be pressed the Redefine Fiducials button in the Preoperative Plan section to delete the current fiducial and add another one

EXIT

Return to main window

Figure 52 - Help window of the surgical navigation module.

Inside the preoperative plan section there is a button named **“Redefine Fiducials”** that provides a full interaction with the fiducials delineated during the preoperative planning. It opens a section, as shown in figure 53, that allows to choose and delete each fiducial, individually. When a fiducial is selected, the view of the virtual object is changed to provide a direct view to the checked fiducial. If the user wants, he can add a fiducial in a specific position or delete all of them to place another set of fiducials. In this preoperative plan file, the virtual model contained 6 preoperative fiducials. They were placed on lateral and medial epicondyles, lateral and medial condyles and on the most posterior and anterior points of the trochlear groove.

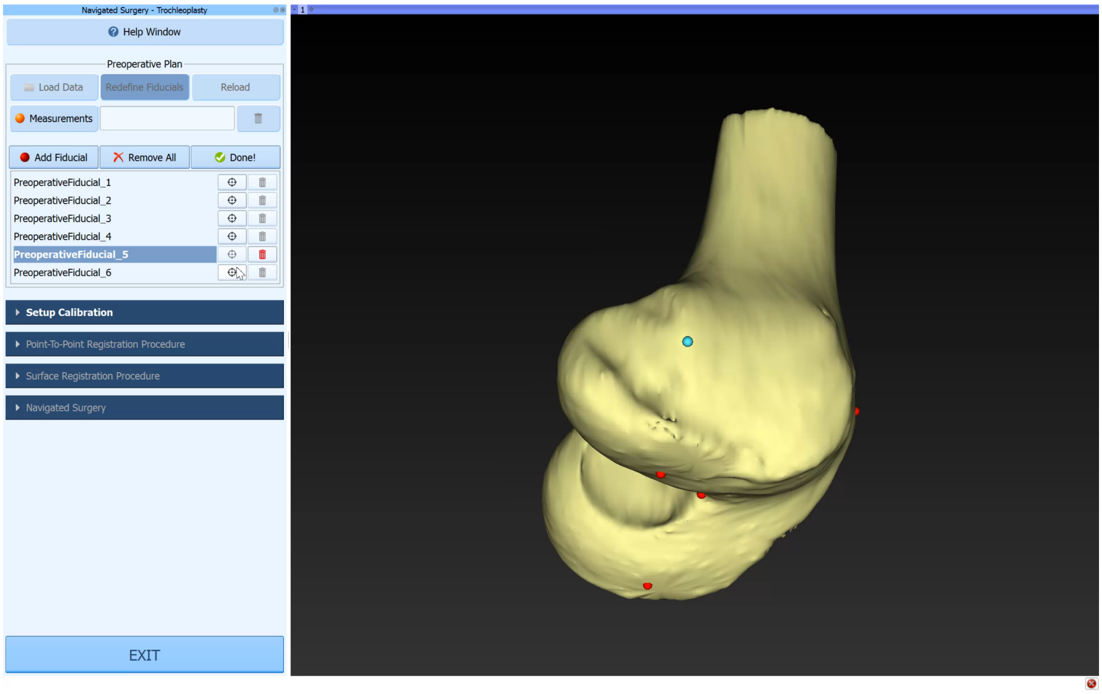
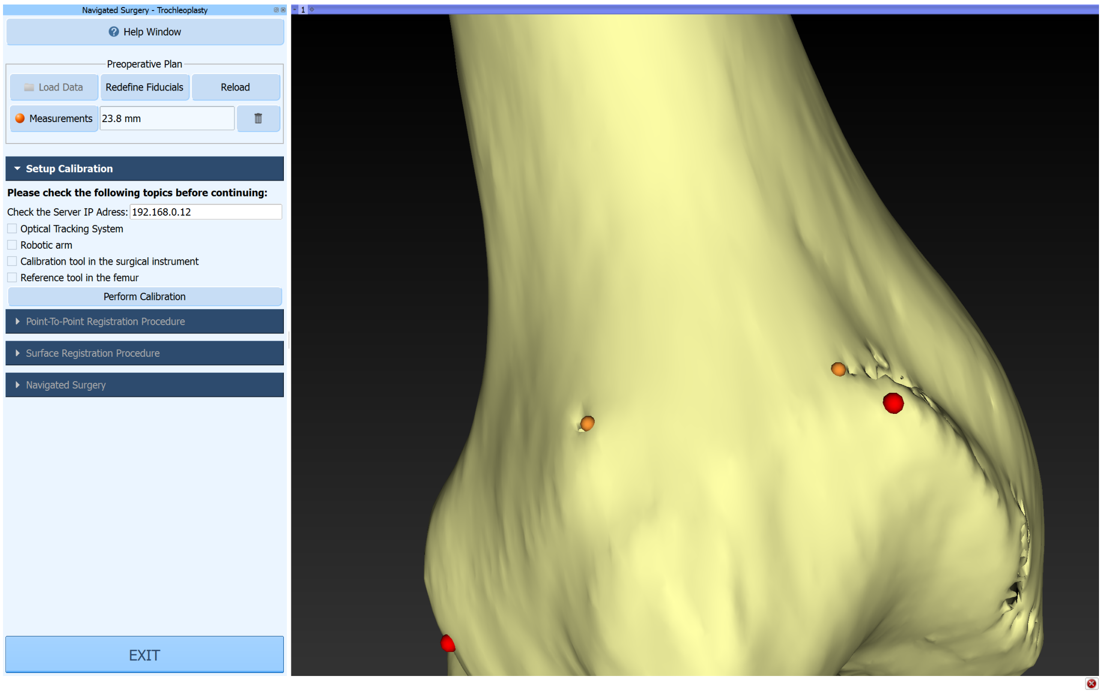


Figure 53 - Screenshot of the “Redefine Fiducials” section of the surgical navigation module.

Still in the preoperative plan section, it was implemented a tool to facilitate the surgeon intraoperatively. The **“Measurements”** tool was a requirement of the surgeons. They consider that it is important to have, as a resource, a tool that can perform measurements in the virtual object in order to compare them with the surgical object. And thus, it helps the collection of fiducials during point-to-point registration allowing a better identification of the position of the fiducial to be collected. To perform a measurement in the virtual object, the surgeon has to place two points to measure the distance between them. So, he must press the “Measurements” button to place the first point and press again to choose the second point. The distance in millimeters between them is displayed in the text box. The points that are placed with the “Measurements” tool, are smaller and orange in order to allow to distinguish between the preoperative fiducials as it is presented in figure 54. After concluding the task, the surgeon can press the trash button to clear the text box and to remove the auxiliary points used to perform the measurement.



Measurements: 23.8 mm

Please check the following topics before continuing:

Check the Server IP Adress: 192.168.0.12

☐ Optical Tracking System
☐ Robotic arm
☐ Calibration tool in the surgical instrument
☐ Reference tool in the femur

Figure 54 - Demonstration of the “Measurements” tool of the surgical navigation module.

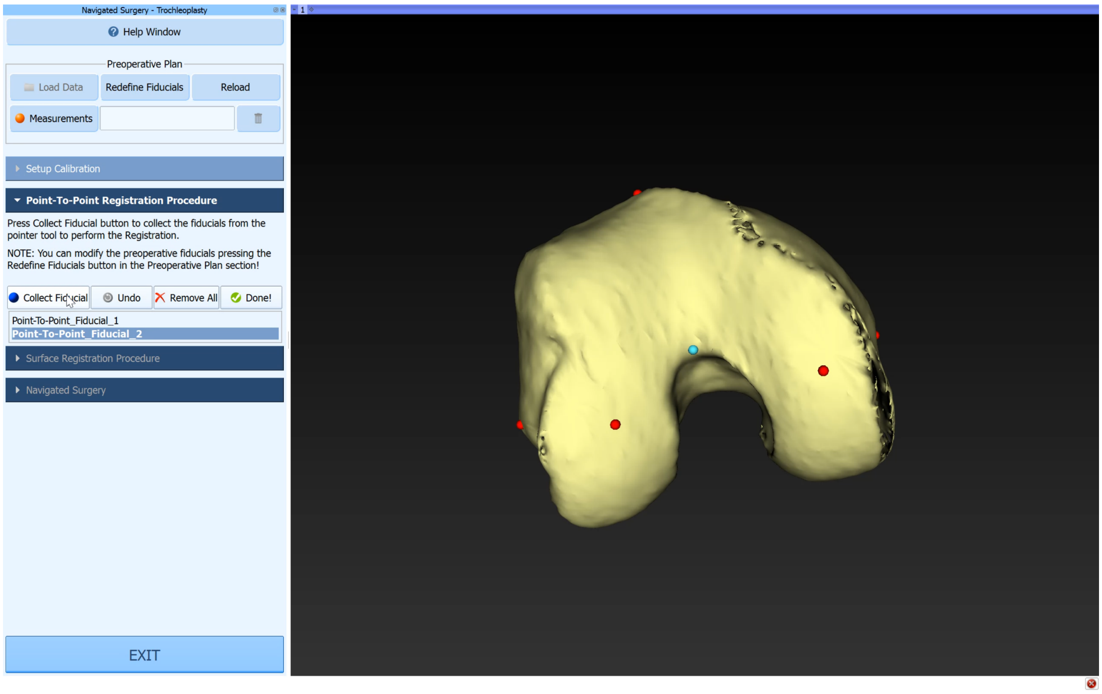
In same figure, it is possible to verify that the section of **“Setup Calibration”** is already activated. To ensure that the user accomplishes the desired workflow, the next section is activated just when the previous step is done. This was the approach implemented along all module. Another important feature to note is that the preoperative plan section is always available during all procedures. This allows the surgeon to access to the preoperative fiducials and the measurements tool at any time during the intervention. Also, the “Reload” button can be pressed at any time. It allows to clear the current virtual scene and to restart the module.

The **“Setup Calibration”** section consists of a set of parameters that should be fulfilled before proceeding with the intervention. Here, all equipment is connected with the 3DSlicer software and their connections are performed. It is important to take into account that this section was planned considering the application of this module into the operating room. In the present work, with the connection between the 3DSlicer® and simulation environment, only the “Robotic arm” check list is used. It is only necessary to ensure that the simulation is running to perform the simulated trochleoplasty. In a future work, with the application of this module in the operating room with all equipment, it will be necessary to check all the presented items.

When the “Perform Calibration” button is pressed, the pose of the drill, the surgical instrument tip, is received and it will be always used from here.

Once the transformation matrix with the pose of surgical instrument is calculated, the **“Point-To-Point Registration Procedure”** can be performed. In this section, it is intended to collect all preoperative fiducials from surgical object. To identify a correct order to collect them and the specific position of them, the preoperative fiducial to be collected is highlighted in blue and the surgeon has to place the pointer tool along the surgical object in the exact place that is identified on the display, as it is presented in figure 55. When the surgeon reaches the desired fiducial, he must press the “Collect Fiducial” button and the fiducial from surgical object is received. The procedure is the same until the last preoperative fiducial and then the system will ensure if all fiducials were correctly collected opening a check window to confirm that. Then, the registration is performed moving the virtual object to the collected fiducials from surgical object.

The functions “Undo” and “Remove All” are available if an error occurs. Also, if the surgeon cannot reach the highlighted preoperative fiducial, he can delete it resorting to “Redefine Fiducials” from “Preoperative Plan” section.



Press Collect Fiducial button to collect the fiducials from the pointer tool to perform the Registration.

NOTE: You can modify the preoperative fiducials pressing the Redefine Fiducials button in the Preoperative Plan section!

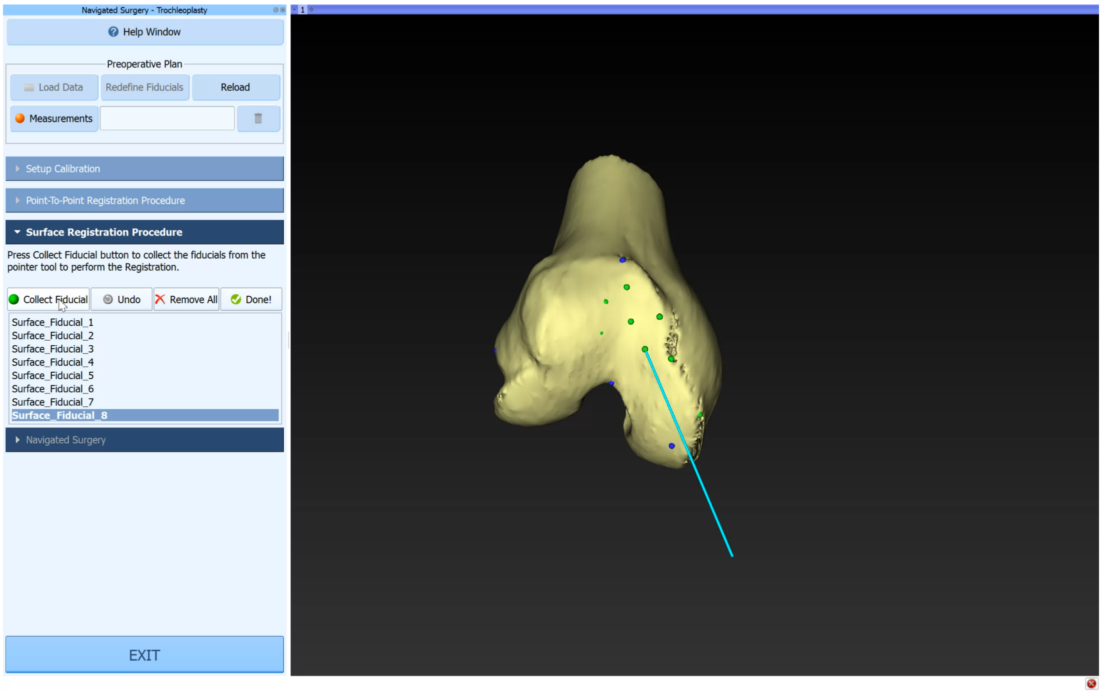
Point-To-Point_Fiducial_1
Point-To-Point_Fiducial_2

Figure 55 - Screenshot of the “Point-To-Point Registration Procedure” section of the surgical navigation module.

In figure 56 it is possible to verify that the point-to-point registration already rotated and moved the virtual object so the collected fiducials (blue color) are matching the virtual object. Also, it is possible to see the needle model that is placed on the virtual scene after the point-to-point registration. The needle model is representing the drill ant it is updated in real-time according to the position and orientation of the surgical instrument.

The next step, will just optimize the registration outcome and after that, the registration is completed and the relative pose of the surgical object with the surgical instrument is the same that the relative position of the virtual object with the needle model.

The last step corresponds to **"Surface Registration Procedure"** and it consists in collecting fiducials from the surgical object, this time without any order or a specific location. The surgeon must choose fiducials from the treated area touching the surgical object surface. When the surgeon collected all desired fiducials, he must press the "Done!" button and the registration is performed updating again the pose of the virtual object to the final one.



Press Collect Fiducial button to collect the fiducials from the pointer tool to perform the Registration.

Surface_Fiducial_1
Surface_Fiducial_2
Surface_Fiducial_3
Surface_Fiducial_4
Surface_Fiducial_5
Surface_Fiducial_6
Surface_Fiducial_7
Surface_Fiducial_8

Figure 56 - Screenshot of the "Surface Registration Procedure" section of the surgical navigation module.

Finally, the surgeon can perform the navigated trochleoplasty. When he presses the "Start Intervention" button in **"Navigated Surgery"** section, the predefined volume in the preoperative plan is displayed and the surgeon can follow the screen with the virtual object to perform the intervention. A visual feedback was implemented to provide to the surgeon the information about the pose of the drill. The drill, the blue needle model in figure 57, is updated and according to its position, the volume changes the color. When the drill is resecting the desired volume of bone, the volume is green. The color of the volume will change gradually the color until the red color, that indicates that the drill is reaching an undesired volume of bone. The volume is translucent in order to provide the exact perception of the tool tip pose inside of the volume.

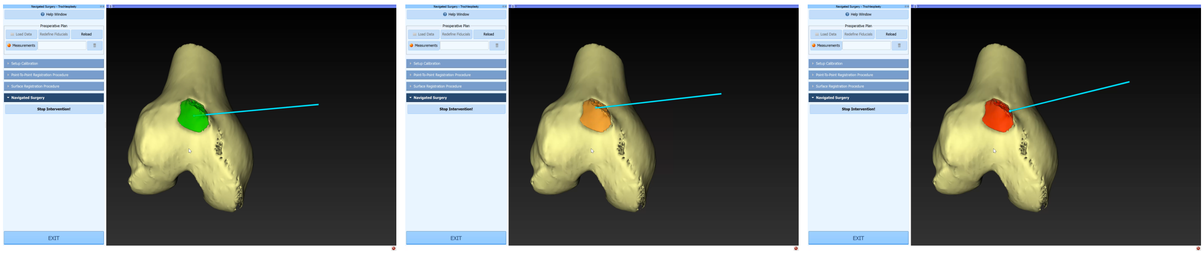


Figure 57 - Screenshots of the visual feedback provided by the surgical navigation module during the intervention.

5.6 Conclusions

With the implementation of the presented surgical navigation module the surgeon can perform the trochleoplasty intervention based on a detailed preoperative plan that provides the required information to perform the surgery. The registration between the surgical object and the virtual object is achieved resorting to point-to-point registration and the surface registration. The navigated trochleoplasty provides to the surgeon the visual feedback about his surgical actions. The surgeon can perceive the position of the drill tip with the information provided by the display. The implemented surgical navigation module indicates that the surgeon is complying the preoperative plan by displaying the volume to be resected in green color. To indicate that the surgeon is approximating the volume boundaries the volume changes the color to red gradually.

6. SIMULATION OF COMPUTER-ASSISTED TROCHLEOPLASTY

In the previous two chapters, it was presented the implemented robotic system simulation and also the surgical navigation module. One of the main goals of this project was to verify the functionality and viability of the proposed CAS system. In order to allow this evaluation, the full connection between the simulation environment and the surgical navigation module was implemented.

This chapter aims to present to the reader the final results of the developed work. It will be described the followed steps to achieve the connection between the both environments and it will be presented the final simulation of computer-assisted trochleoplasty.

6.1 Interconnection between the robotic simulation and the surgical navigation module

In order to achieve the simulation of the entire procedures implemented in the surgical navigation module, a fully integrated and real-time connection is required between the V-REP® and 3DSlicer® environments. Afterwards, it is possible to simulate the entire implemented setup.

Some issues have to be planned to achieve the simulated surgery.

6.1.1 Surgical Object in the simulation

First of all, in the simulation environment it is necessary to have a **surgical object**. The CT exam used in the preoperative plan module that was imported to the surgical navigation module in the previous chapter was performed from a patient with dysplasia trochlear. In order to have a surgical object exactly equal to the virtual object, in the 3DSlicer® software, the virtual object was exported to a 3D model so that it could be imported into the V-REP® environment. Then, the 3D virtual model was imported and positioned in the patient knee in the simulation environment. The surgical and the virtual object have exactly the same shape and dimensions. The 3D model of the surgical object implemented in the V-REP® environment is presented in figure 58. Also, in figure 59, the surgical object is already placed at the final operating room environment.

Figure 58 - 3D model of the surgical object used in simulation environment.

6.1.2 Tracking System connection

The tracking system is a required component in CAS systems. As mentioned above, the tracking system was inserted into the simulation environment. Then, the RGB images and Depth information from the Kinects, that compose the tracking system, were published as ROS topics. Thus, the */rgbImage* and */depthImage* ROS topics contain all the information about the tracking system and it can be read subscribing the desired ROS topics. In order to evaluate the occlusions of the femur reference during the intervention and to evaluate the best position of the tracking system in the operating room considering its field of view, the RGB image from the tracking system is displayed during the simulation. It can be seen in figure 59, in the upper right corner.

6.1.3 GUI to select the device to manipulate the robot

In the robotic system simulation chapter was described that three different devices were used to manipulate the robotic arm. In order to integrate these three different devices in the same simulation environment, a **GUI** was built to allow the user to select the desired device to manipulate the surgical instrument in the simulation. The present GUI has three buttons, each one of them corresponds to one device. The GUI is presented in figure 59 in the upper left corner and in figure 63.

Select Controller

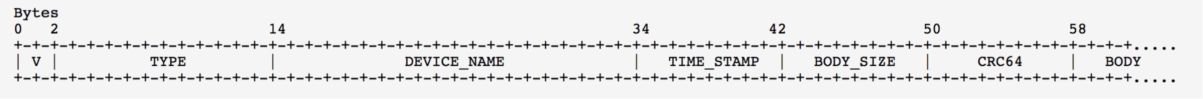
Press the button:	PS3	Wii	Joystick
Place on Point Fiducial	Button X	Button 1	Button 7
Place on Surface Fiducial	Button O	Button 2	Button 6

Figure 59 - Final operating room environment during the simulation.

6.1.4 Setup Calibration – Transformation matrix from V-REP

When the simulation starts, one of the scripts of the simulation sends the information relative to the surgical instrument tip pose via ROS. A ROS topic named ***/UR5TransformMatrix*** is created with the transformation matrix of the surgical instrument tip. A python file was created to subscribe the ROS topic and to send it to 3DSlicer® via OpenIGTLink protocol. **OpenIGTLink** is a protocol that provides the communication with 3DSlicer® allowing the real-time tracking using the SlicerIGT extension. This network protocol was designed for use in the application layer on the TCP/IP stack. The OpenIGTLink protocol defines five default data types: ‘Image, ‘Position, ‘Transform, ‘Status’ and ‘Capability’. In this work, only the ‘Transform’ data type was used. According to this protocol, the message begins with a

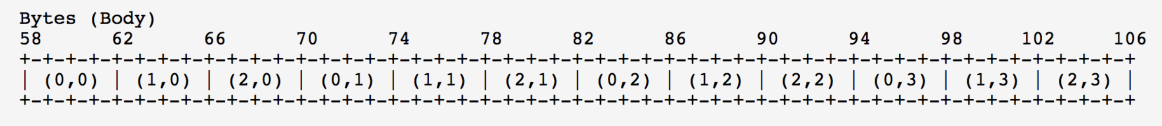
58-byte header section, whose structure is presented in figure 60. This header is common to all types of data, followed by a body section [92].



```
Bytes
0   2                       14                                      34              42              50              58
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+.....
| V |         TYPE          |              DEVICE_NAME              |  TIME_STAMP   |   BODY_SIZE   |     CRC64     |  BODY
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+.....
```

Figure 60 - Header structure of OpenIGTLink protocol [93].

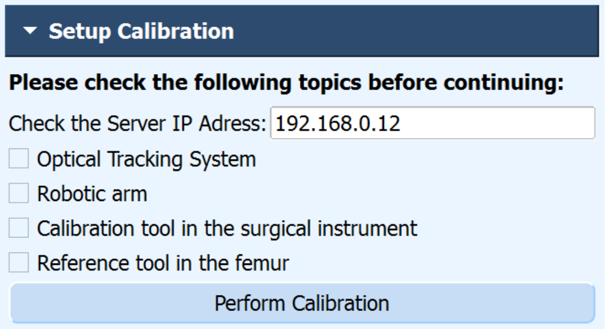
The format of the body section is dependent of the data type, specified in the header section. The 'Transform' data is constituted by the upper three rows of the 4x4 homogeneous transformation matrix. Each element is a 4 byte (32 bit) float. Thus, the entire body of a 'Transform' data is constituted by 48 bytes in total, as presented in figure 61.



```
Bytes (Body)
58      62      66      70      74      78      82      86      90      94      98      102     106
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| (0,0) | (1,0) | (2,0) | (0,1) | (1,1) | (2,1) | (0,2) | (1,2) | (2,2) | (0,3) | (1,3) | (2,3) |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 61 - Body section of 'Transform' data type according to OpenIGTLink protocol [93].

Therefore, the python file that sends the transformation matrix via OpenIGTLink had to respect this protocol so that 3DSlicer® can read the data. Based on the provided code from [94], the python file was created with only the 'Transform' data type connection. Once the data from */UR5TranformMatrix* is read and processed, the script allows to send it via OpenIGTLink protocol. Based on TCP/IP communication, it was chosen the port number 18944, and the text box in the surgical navigation module, figure 62, was created to input the IP from the computer server.



Please check the following topics before continuing:

Check the Server IP Adress: 192.168.0.12

☐ Optical Tracking System

☐ Robotic arm

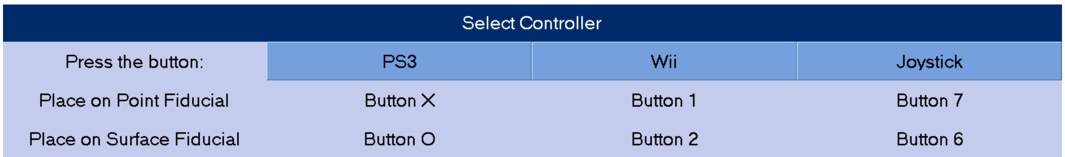
☐ Calibration tool in the surgical instrument

☐ Reference tool in the femur

Figure 62 - "Setup Calibration" section of the surgical navigation module.

6.1.5 Registration Simulation

During the **registration** procedure in a real situation, the surgeon has to collect the fiducials from the surgical object with a pointer tool or the surgical instrument by placing the tool tip in the specific fiducial. During the simulation, it was possible to simulate the fiducials acquisition resorting to the robotic arm and the mounted surgical instrument and using one of the developed ways to move the robot. This allows to manipulate the surgical instrument tip until the fiducial location. But, in order to be as precise as possible in the fiducials collection, another approach was implemented. Basically, dummy structures, that are reference frames, were placed along the surgical object in the simulation in the positions that correspond to the planned point-to-point fiducials in the preoperative plan. Resorting to the inverse kinematics, the surgical instrument tip reaches exactly the planned points. The same approach was implemented to surface registration, placing 8 dummy structures along the surgical object surface. To be easy during the simulation to collect the fiducials, each developed way to move the robot has two buttons that allow to place the surgical instrument tip at the specific fiducial by their order. One button corresponds to point-to-point fiducials and the other the surface fiducials. The specification of these is presented in the GUI implemented to select the way to move the robot, as shown in figure 63.



Select Controller

Press the button:	PS3	Wii	Joystick
Place on Point Fiducial	Button ✕	Button 1	Button 7
Place on Surface Fiducial	Button ○	Button 2	Button 6

Figure 63 - GUI implemented to select the way to move the robot during the simulation.

6.1.6 Robot Control during the simulation

In the solution description chapter, it was planned that in a real situation a haptic force feedback provided from the robotic arm should be the best option to implement in this work. In order to simulate one of the main advantages of the implemented robotic system, a basic controller was implemented based on the distance from the surgical instrument tip to the planned volume boundaries. When the “Start Intervention” button is pressed in the “Navigated Surgery” section of the surgical navigation module, an *observer* calculates is applied in order to calculate the distance from the tool tip to the nearest point of the planned volume surface whenever the tool tip changes the position. This distance is send via TCP/IP to a python file in the other device. The selected port number was 5000 and the IP address is the same that was inserted in the "Setup Calibration" section of surgical navigation module. The python file is reading the data from 3DSlicer® and creates a ROS topic named ***/SecurityDistance*** where it is published the distance value.

In the simulation, this ROS topic, */SecurityDistance*, is subscribed and this value is used to control the movement of the robot. The control is based in the inverse proportionality of this distance value from */SecurityDistance* ROS topic. Thus, as the surgical tool tip is reaching the boundaries of the planned volume, the movement of the robot advances with smaller increments. This control is started after the first time that the surgeon reaches the inside of the planned volume with the drill.

6.1.7 ROS communication

Figure 64 shows the active ROS nodes and topics during the surgery simulation, depicting a general overview of the workflow.

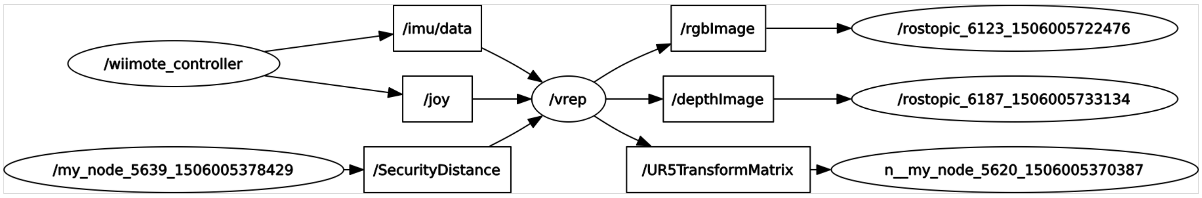


Figure 64 - ROS Computation Graph with the implemented ROS nodes and ROS topics.

6.2 Presentation of Computer-Assisted Trochleoplasty simulation

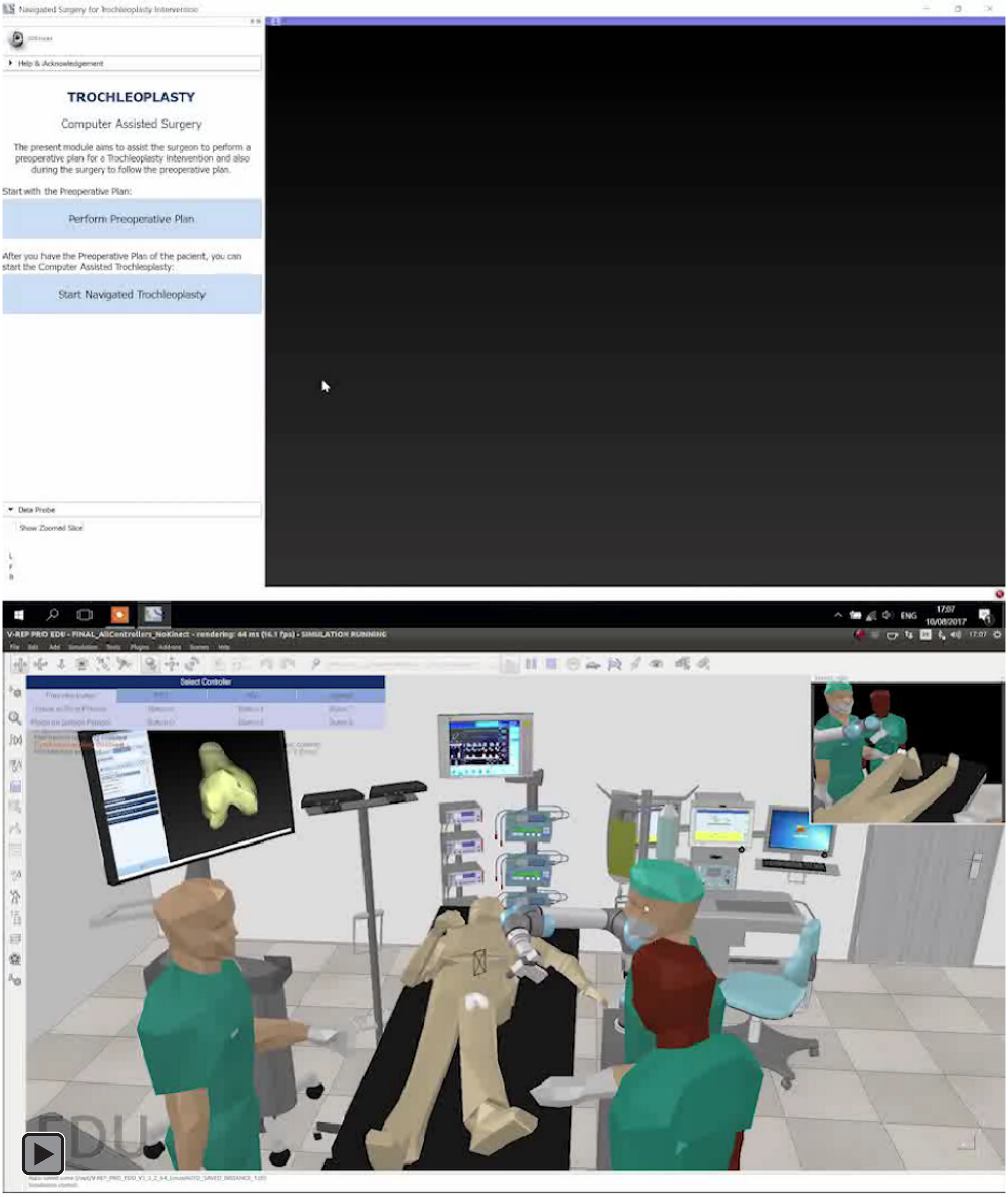
Figure 65 shows the final setup implemented to perform the simulation of the Computer-Assisted Trochleoplasty. The setup is composed by two computers, one with the simulation environment in V-REP® (right computer in the figure) and another one with the surgical navigation module in 3DSlicer® (left computer in the figure). Both computers are connected to the same network in order to enable the communication between them. The three devices that can be connected to the simulation are also part of this setup.

Figure 65 - Implemented setup to simulate the Computer-Assisted Trochleoplasty.

Figure 66 shows a video that presents the Computer-Assisted Trochleoplasty simulation. It consists of two screen records from different computers, one with the robotic simulation and another one with the surgical navigation module. The screen records are synchronized in order to understand the entire implemented workflow and to visualize how this connection works. In this trial, the device selected to manipulate the robotic arm was the Wii remote plus.

6.3 Conclusions

The main goal of this work was achieved in this chapter. The implementation of the communication between both environments enabled to connect the robotic arm to the surgical navigation module. Thus, the integrity and the functionality of the surgical navigation module can be studied. This interconnection between both modules presents a real-time communication and thus the surgical procedures performed intraoperatively resorting to this system can be simulated using the developed work.



The present module aims to assist the surgeon to perform a preoperative plan for a Trochleoplasty intervention and also during the surgery to follow the preoperative plan.

Start with the Preoperative Plan:

After you have the Preoperative Plan of the pacient, you can start the Computer Assisted Trochleoplasty:

Figure 66 - Video that presents the Computer-Assisted Trochleoplasty simulation.

7. VALIDATION OF SURGICAL NAVIGATION MODULE

The surgical navigation module is of major importance with regard to the computer-assisted trochleoplasy. This component is part of the planned setup to implement in the operating room in order to assist the surgeon during the trochleoplasty intervention. Thus, with the robotic system simulation connected to this module, it was possible to perform an evaluation of its viability and acceptance by an orthopaedic medical team.

With the support of medical team that supported this work and the Hospital of Braga, a validation of this module was performed resorting to a questionnaire and the entire implemented setup addressed during this work. This validation was performed with the target users of this implementation, orthopaedic surgeons, and the main results of this validation will be described during this chapter. This enables to achieve a user-centered approach by including the final users in the development and evaluate the proposed solution in a step-wise fashion.

The surgical navigation module was designed considering that its purpose is to be applied in the operating room and it has to be prepared to the operating room conditions. During chapter 5, all parameters and features that characterize this module were addressed. The design and planning phase of the module were guided by the medical team and the final implementation is in accordance with their necessities and requirements. In order to strengthen the validation of this module it was necessary to pursue an evaluation with the target users about the functionality of the module. For this reason, a validation of the present module was performed at Hospital of Braga with orthopaedic surgeons. Eight orthopaedic surgeons contributed for this validation.

This validation was performed resorting to the surgical navigation module and the robotic system simulation presented during this work and a questionnaire was created to evaluate the functionality and acceptance of the module by the medical team.

The procedure followed to have a robust validation was the same, in order to keep coherence during all trials. Each trial was performed with the orthopaedic surgeon using the surgical navigation module while the robotic system simulation was controlled by the developers. The goal of this evaluation was not to verify which was the best device to move the robot. This will be the aim of another ongoing study and is under the scope of this thesis. The trial started with a brief introduction of computer-assisted surgery systems and their operation. After the contextualization of the project and of the integrity of the entire system setup, the computer-assisted trochleoplasty simulation started and the surgeon followed the entire workflow of the module.

The questionnaire delivered to the surgeons after the computer-assisted trochleoplasty simulation is presented in appendix I. The present questionnaire intends to evaluate some features of the module regarding its functionality, ease of use, applicability to the operating room and its clarity of the implemented steps. The questions were delineated together with the surgeons.

7.1 Results

In this section, the results obtained from the validation procedure are presented. A brief description of the orthopaedic surgeons that have participated in this survey is presented in table 4.

Table 4 – Characterization of the surgeons involved in the proposed validation (number, gender, mean ± SD age, mean ± SD years of surgical experience and experience with CAS system)

Number of orthopaedic surgeons	8
Female	2
Male	6
Mean ± SD Age	30 ± 4.25
Mean ± SD years of surgical experience	4,75 ± 3.8
Experience with CAS systems	
Yes	1
No	7

Note that the participants of this survey are orthopaedic surgeons with an average value of years of surgical experience of 4,75. Only one of the surgeons has experience in CAS systems. It is an important factor to conclude about the acceptance of the present system by a medical team without any experience in CAS systems. The passage from the traditional procedures to a CAS system is complex and with this survey it is possible to perceive the receptivity of the orthopaedic surgeons to a computer-assisted trochleoplasy system.

The answers to the questionnaire were analysed and their contents were treated in order to provide a simple presentation of the results to the reader. The figure 66 presents the obtained average value for each question of the questionnaire.

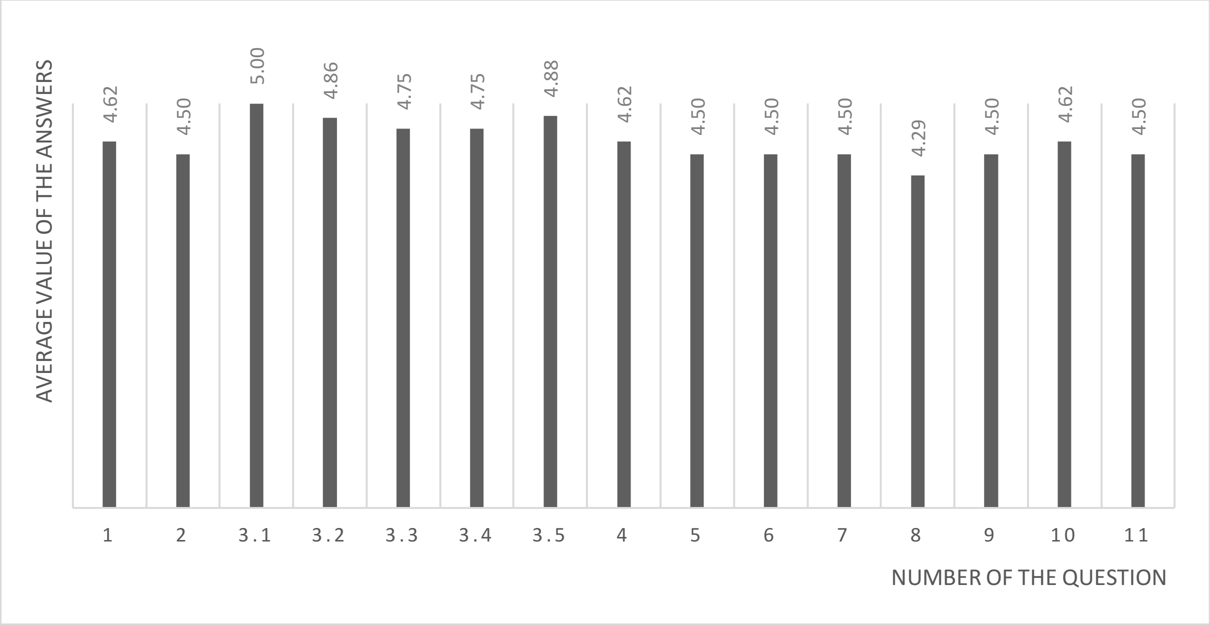


Figure 67 – Graph with the average values of the answers for each question of the questionnaire.

The presented graph shows the obtained results from the questionnaire. Note that each question was evaluate by the surgeon using a scale from 1 to 5, as it is possible to see in the questionnaire in Appendix I. The option *"No opinion"* was answered by one surgeon to the question 3.1, 3.2 and 8.

7.2 Conclusions

With the present validation of the module it was possible to conclude about the perception of the orthopaedic surgeons about this CAS system delineated and implemented for trochleoplasty intervention. Considering the obtained results from the questionnaire in the graph of figure 66, it is possible to conclude that the results were very positive with all evaluated parameters rated with more than 4 in respect to the average values.

Therefore, the present results show a very positive acceptance by the orthopaedic surgeons to the surgical navigation module and to the implemented system setup of CAS system for trochleoplasty.

The question number 8, regarding the interconnection between all sections that compose the module has obtained the weaker rating, with an average value of 4,29. Even though this value is a great result, the connection between the sections should be rethought in order to provide a better user experience. An introduction to each section of the module could overcome this factor allowing the user to have an overview of the workflow more present in addition to the presented overview in the help window.

These results indicate that this implemented system setup is ready to the next step: to be implemented into operating rooms for surgical procedure assistance.

The validation of the surgical navigation module should be continued with more orthopaedic surgeons. The performed validation, with the respective number of trials, was a great beginning to validate this system setup implementation and to conclude about the acceptance of the surgeons of a CAS system for trochleoplasty intervention. Trials with orthopaedic surgeons from other medical centers are the next steps to include more diversified data in order to perform a more robust validation.

8. CONCLUSIONS

Trochleoplasty is an orthopaedic surgical intervention that aims to correct the trochlear dysplasia, the main predisposing factor of patellar instability. Due to the complexity of this surgery and the lack of solutions to improve this surgical procedure, this work was implemented.

This work was proposed by orthopaedic surgeons from Hospital of Braga that have supported this work. These orthopaedic surgeons are looking for a solution to overcome the limitations and complications that this surgery involves. The main limitation consists of the reduced field of view of the surgeon to the treated area. The cartilage coats the subchondral bone and the surgeon has to elevate the cartilage to remove the bone. Another important aspect is that the surgeon has to have an added careful to do not damage the cartilage during the procedures. This work is addressed to overcome the real necessities from this medical team. The detailed necessities of these surgeons were presented during the document and a solution planning was performed to address the main components of the system setup.

The work carried out in this thesis addresses the design and planning of one CAS system for trochleoplasty. Two main modules of this system setup were addressed during this thesis: the robotic system simulation and the surgical navigation module. The robotic system simulation is a great tool to implement the planned robotic system and to study its performance. On the other hand, the surgical navigation module provides to the surgeon the required information about his actions during the intervention in order to achieve the desired accuracy of the surgical procedures.

Before proposing a system setup to be implemented in this work, an extensive survey of the traditional procedures was performed to identify the main limitations of this intervention. Together with the medical team, a set of points with the requirements of this intervention was enunciated in order to justify the implemented approach presented in the solution description. Also, a state of the art regarding the CAS systems addressed to knee interventions was performed in this thesis in order to accomplish a comparative analysis between the different CAS systems that are being used in operating room assisting the orthopaedic surgeon. Further, this state of the art enabled to raise the current challenges still to be addressed.

Considering that there are no references to a CAS system addressed to trochleoplasty intervention, a design and planning of a CAS system for trochleoplasty was performed aiming to overcome the main limitations of the trochleoplasty surgical procedures. This system presents greats outcomes in the accuracy of the procedures. A CAS system with the assistance of a robotic arm and surgical navigation provides to the surgeon the required assistance to perform the trochleoplasty. The navigated surgery overcomes the reduced field of view of the surgeon during the intervention. The robotic arm ensures that the surgeon does not resect undesired bone and ensures the accuracy of the planned resection. The main modules addressed during this thesis were the simulation of the planned robotic system and an implementation of a surgical navigation module.

Regarding robotic system simulation, the robotic arm UR5 was selected to provide surgical procedure assistance. It consists of a robotic arm with 6 DOF with an adequate working range for this application, 850mm. Also, it can be controlled by force what allows the implementation of the haptic force feedback. Its repeatability is +/- 0.1mm, is an optimal value for this application. A hands-on system composed by the robotic arm and the surgical instrument from Stryker power tools was planned.

The robotic simulation contains the information about the operating room environment and the positioning of its components that leads to a better perception of the workspace the surgeon has to manipulate the robotic arm during the intervention. It was an important tool to plan the better positioning of the tracking system taking into account the robotic arm movements and the reference placed at the femur. The ideal position of the tracking system avoids the occlusions of the femur reference allowing the navigated surgery during the entire intervention without interruptions. Also, an intuitive manipulation of the robotic arm and the surgical instrument was implemented in order to simulate the movements that the surgeon has to perform during the surgical procedures. Three different devices were studied to achieve this manipulation of the robot: A PS3, a Wii remote plus and a joystick. These were used to simulate the surgeon-guided robotic system using inverse kinematics for UR5 in the simulation environment.

In this thesis, the surgical navigation module to be implemented in an operating room to guide the trochleoplasty was performed according to the planned system. This module implemented the connection with the preoperative plan module provided from another project carried out at University of Minho, that allows the surgeon to have access to the preoperative and the intraoperative sections in the same module. The point-to-point registration and the surface registration were implemented in order to achieve the navigated surgery. Thus, the coordinate systems of the surgical object and the virtual object are placed on the same reference frame. To provide the guidance to the surgeon during the bone removal, a visual feedback was implemented that displays the correct position of the surgical tool according to the color of the volume in the virtual object. When the surgical instrument is resecting in the desired volume, it is green. When the drill is reaching the boundaries of the volume, the color of the volume changes to red, gradually.

Finally, with the connection of the robotic system simulation and the surgical navigation module it was possible to present a simulation of a computer-assisted trochleoplasty. A control was implemented in simulation in order to provide feedback to the surgeon. Resorting to the distance between the drill tip and the volume boundaries, as the drill tip is reaching the boundaries, the movement of the robot advances with smaller increments.

Based on this connection between the both environments, a validation of the surgical navigation module was performed with orthopaedic surgeons and its results showed a great acceptance of the module by the surgeons.

The work accomplished in this thesis contributed to knowledge concerning the development of a CAS system for trochleoplasty that addressed the main challenges in this field. All the main goals proposed in this thesis were accomplished.

This work presents a concrete application of the Biomedical Engineering, breaking the barriers between the medical field and the engineering. The interaction with the orthopaedic surgeons was really important to reach the present work. The exchange of knowledge provides the implementation of this CAS system for trochleoplasty that fulfill the requirements imposed by the surgeons. Also, it presents to be a promising work once the orthopaedic surgeons have shown a great acceptance and this reinforces its viability in the operating room.

8.1 Future Work

The presented work in this thesis denotes a significant advance in the development of a CAS system for trochleoplasty intervention. The interconnection between the robotic system simulation and the surgical navigation module allowed to provide a great perception about the performance of the planned CAS system for trochleoplasty. This was an innovative approach that has a long way of research until the system is applied in the operating room in surgical procedures assistance.

As future work, the implementation of the simulated robotic system it is required to proceed with the validation of the system. The UR5 robotic arm should be used with a surgical instrument attached to its last link as presented in the simulation. It is the main step to achieve. With the robotic arm, the connection of the main components of a CAS system can be performed. It corresponds to the interconnection between the surgical navigation module carried out in this thesis with the robotic arm and the tracking system that is being developed in another master thesis project at University of Minho. Further tests can be performed resorting to this system implementation.

Another aspect is regarding the surgical instrument. So far, the planned system to perform the computer-assisted trochleoplasty addresses the Stryker power tool once it is a tool that is used at Hospital of Braga. However, the size and ergonomics of this tool is not adequate to perform this intervention with the robotic system assistance. The design and planning of a surgical instrument more small, lightweight and ergonomic should be performed in order to attach it to the robotic arm.

Another future task is relative to surgical navigation module. Besides the strengthening of the module validation, as previously mentioned, some features of the module should be improved in order to answer to the requirements of the surgeons. The questionnaire used in the validation of the surgical navigation module had a section where the surgeons could add their comments and opinions about the module. Two important opinions were written and the next step regarding the surgical navigation module should to implement that. One of them is about the provided feedback to the surgeon during the surgery. The bone volume that the surgeon has to resect should be updated during the bone removal. Another point that should be improved is the virtual object manipulation. The surgical navigation module should provide a simple way to the surgeon manipulates the view of virtual object during the intervention.

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APPENDIX I – SURGICAL NAVIGATION MODULE – QUESTIONNAIRE

VALIDATION OF "NAVIGATED TROCHLEOPLASTY" MODULE DEVELOPED IN 3DSLICER SOFTWARE

The present survey intends to evaluate the functionality of developed module in 3DSlicer software that aims to implement an application that allows to guide the surgeon during a navigated trochleoplasty. The presented module consists of 5 sections. The first one, contains the preoperative plan. The following sections are composed by a set of steps to do in order to perform the registration procedure and, at the end, to start the navigated surgery. It intends that the following questions are answered in a scale starting from 0 to 5, corresponding to "Disagree" and "Agree", respectively. The NO option corresponds to "No Opinion".

	1	2	3	4	5	NO
1. Using the module was easy and intuitive.	○	○	○	○	○	○
2. The provided information given by help window was useful and enough to clarify all procedures to perform.	○	○	○	○	○	○
3. The steps to perform were clear, in the section						
3.1. "Preoperative Plan"	○	○	○	○	○	○
3.2. "Setup Calibration"	○	○	○	○	○	○
3.3. "Point-to-Point Registration Procedure"	○	○	○	○	○	○
3.4. "Surface Registration Procedure"	○	○	○	○	○	○
3.5. "Navigated Surgery"	○	○	○	○	○	○
4. In the "Setup Calibration" section, it is clear that the elements of the check list have to be fulfilled before to continue to the next section.	○	○	○	○	○	○
5. During the procedures regarding the registration, it was clear that the points to collect during the point-to-point registration must be the highlighted points and in the surface registration, the number of points to collect and their position are chosen according to the surgeon criterion.	○	○	○	○	○	○
6. During the point-to-point registration, it was clear that the highlighted point to collect by the surgeon could be modified in the preoperative plan section, if the surgeon cannot reach it.	○	○	○	○	○	○
7. The provided visual feedback to show the right positioning of the surgical instrument during the navigated surgery is adequate and enough.	○	○	○	○	○	○

8. The interconnection between all sections of the module and their contents are adequate.	○ ○ ○ ○ ○ ○
9. It is clear when each step should end.	○ ○ ○ ○ ○ ○
10. The manipulability of the view of the 3D bone model in the software resorting to a mouse was easy.	○ ○ ○ ○ ○ ○
11. Regarding to the graphical issue, the size of the buttons and the text and the selected colours in the present module are adequate.	○ ○ ○ ○ ○ ○

Aiming to contribute to an improvement of the analysed module quality, please write some suggestion or review about any content of the module.

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Name: ____

Gender: M ○ F ○

Age: __________

Years of surgical experience: __________

Experience with Computer-Assisted Surgery systems: Y ○ N ○