Computer-aided Surgery Planning for Lower Limb Osteotomy

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Abstract

Osteotomies around the knee address lower limb deformities that affect the leg posture and especially the knee joint. Knee arthritis is a very common age-related joint disease that can be treated with osteotomy, as an alternative to knee replacement by implants.
The preoperative planning process is demanding and significantly determines the surgical outcome of the osteotomy. The choice of the osteotomy type and the determination of parameters, like the correction angle, are crucial for long-term success.
We present a software tool for the preoperative planning of opening, closing and derotation osteotomies. This tool is based on patient specific 3D bone models and allows the user to position cutting planes and to simulate the cut and alignment of the bone.

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Finally, I thank my family for their help and for providing a home where I could complete my writing.

Declaration

I declare that this Bachelor thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

Hiermit erkläre ich, dass ich die vorliegende Bachelorarbeit vollkommen selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

Magdeburg, 28. September 2010 ____________________

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Chapter 1

Introduction

Knee osteoarthritis is a disease that affects 30% of people older than 60 years. Patients suffer from pain and functional impotence. Knee stress arises when the articular cartilage is worn up and the bones rub on each other. Very often the medial part of the knee in affected.
Lower limb osteotomies correct the malalignment to transfer load to the relatively unaffected knee compartment and thus to relief pain.
In contrast to a total knee replacement, osteotomy is a surgery that does not replace articulation surfaces by implants, but it potentially increase the longevity of the native knee joint. Besides osteoarthritis, other indications, like (posttraumatic) bone deformities or disturbance in gait, demand a lower limb osteotomy.
Osteotomies around the knee are technically demanding surgical procedures where bones of the lower extremities are cut through and adjusted. It requires accurate preoperative planning and precise surgical technique.
90% of the osteotomies are performed on the upper tibia [26]. The short term results of these surgeries are good. Even though osteotomy provides good relief of pain and restoration of function in 80-90% of patients at five years, it is only 50-65% in ten years [11]. Thus for about a half of the patients it leads to complications and re-surgery.
The success of a lower limb osteotomy depends on the patient choice, preoperative planning, precise osteotomy tools and a stable fixation. The surgeon must be aware of the biomechanics and the load distribution in the knee if good long-term results want to be achieved.
"Even today the process of patient selection and evaluation, of preoperative planning, and of surgical correction of a deformity around the knee is demanding. The definition of the site of correction, of the angle of correction, the choice of the osteotomy procedure, and the fixation device is complex, and various pitfalls may compromise the result." [26]

This Bachelor-Thesis is about planning lower limb osteotomies and what computer support can contribute to it. A 3D planning system is presented, which allows surgeons to virtually explore the patient's bones and to plan the surgery.
Computer support in planning should lead to faster preparation, better long-term results and fewer complications.

1.1 Context

EOS imaging develops solutions for orthopedic imaging. Their ultra low dose x-ray, vertical distortion free (radiographic scan from head to toe) modality *EOS* can acquire simultaneously a frontal and a lateral radiograph. The included software *SterEOS* allows the review of the 2D radiographs and a three-dimensional reconstruction of bones, like the spine, the pelvis and leg bones.
In order to model a bone, the user identifies on the two perpendicular radiographs special anatomical

points. The radiographs and the user input data are compared to a generic bone model in order to approximate the real bone through a 3D model. In addition to this explorable bone model the user obtains a set of clinical parameters.
The focus of this work was the development of a prototype for planning methods for lower limb osteotomies. The exploration of clinical needs for the osteotomy planning proceeded the implementation. The purpose of prototyping was to illustrate the communication between the developer and potential users, and to test basic properties and realization methods for such a software tool. The main goal of the prototype development was to test and validate a technical functional solution, before integrating an osteotomy planning tool in SterEOS.
The targeted users for the implemented application are surgeons.

1.2 Motivation

Today a vast majority of osteotomies are planned based on 2D analogue or digital radiographs, with a ruler and a pencil, or with the help of software tools. Reasoning with 2D images when objects are in three dimensions results in more effort in imagination and in more errors, e.g. the misestimation of anatomical aspects which are not visible in a frontal radiograph.
On the other hand these planning methods are established and have been in use for decades. This new planning method must be better in all aspects to persuade surgeons.
The three dimensional skeletal imaging was made possible by computed tomography (CT), but because of a low cost-benefit ratio and high exposure it is not worth for osteotomy planning. The possibility to simply acquire 3D images by means of the lower dose EOS, demands new adapted software.

1.3 Preview of Results

The prototype for planning lower limb osteotomy in 3D developed in this work is called *OstEOS*. It is based on the models of the bones operating as the knee articulation: the femur and the tibia. This application allows the preoperative planning of varus and valgus correction, as well as derotation osteotomies.
The process of planning these surgeries includes the calculation of various parameters like angles between bones, bone length and correction angle. Given those parameters, a 3D representation of the bones is shown to the user. He can now interact: position the cutting plane, and simulate the cut and alignment of the bone. Various parameters, calculated in real-time, can be seen while the user changes the cut parameters and the bone alignment.

Chapter 2

Medical Background

This chapter starts with a discussion about the disease knee osteoarthritis and possible operational therapies. Following, anatomical basics concerning the knee joint, including interacting bones, ligaments and cartilage, and possible movements are presented.
At the end, introducing the next chapter, technical terms concerning knee malalignment, lower limb axes, anatomical planes and clinical parameters, like angles and bone lengths are explained.

2.1 Knee Osteoarthritis

Knee osteoarthritis (OA), also known as degenerative joint disease, is caused by biomechanical stresses affecting the articular cartilage of the knee. This disease will cause pain and functional impotence and affects 30% of people older than 60 years [40, 11].
OA is mainly a mechanical problem associated with limb malalignment, bone deformation, ligamentous instability and disruption of the menisci.
Medial or lateral femorotibial compartment or patellofemoral compartment may be involved (cf. section 2.3). It starts with local cartilage damage and can spread out over the articulation and become more severe.
OA is the typical pathology demanding a lower limb osteotomy. The most common osteotomy type performed on arthritic knees is high tibial osteotomy (HTO), popularized by Coventry in 1973 [14]. Figure 2.1 shows osteoarthritic knees.

2.2 Knee Surgery

If conservative treatment fails or posttraumatic, knee surgeries are done to relief pain and reinstate the joint functionalities. Currently, there are three operative options: a unicompartmental knee arthroplasty, a total knee arthroplasty or an osteotomy.

The **lower limb osteotomy** tries to reconstruct the articulation functionality without replacing the joint. The indication for this surgery is unicompartmental OA which is characterized by worn up articular cartilage in the medial or lateral part of the femorotibial joint. Subsequent or alternatively to an osteotomy, a knee replacement can be done.

A **knee arthroplasty** consists of replacing used up bone surfaces in femur and tibia by implants. This can be done entirely (Total knee arthroplasty = TKA) or partially (unicompartmental knee arthroplasty). Indications for a knee replacement are heavy, age-related osteoarthritis or injuries.

The decision between knee replacement and knee osteotomy is taken with regard to many factors, e.g. the stage of the osteoarthritis, the ligamentous status and the age [34]. The ideal osteoarthritic patient for osteotomy is younger than 60 years with good range of knee motion and good ligamentous stability [9]. This is the conclusion of a literature review about a long-term follow-up of high tibial osteotomy. Patients in this category showed the best long-term surgery results. If these condition are not fulfilled, the risk of complications is higher and the doctor can alternatively prescribe a knee arthroplasty.

Today, over 120.000 osteoarthritis patients in Germany per year receive a TKA. About one third of these patients are potential candidates for an osteotomy. Reasons for this inappropriate overuse are the short-term success of TKA and attractive industrial conditions. However, in loading the leg and especially in sports activities patients with TKA risk the failure of the artificial joint. Especially patients under 60 years are not satisfied with the result, mainly because of remaining pain and stiffness [26].

This experience shows that knee arthroplasty should not replace osteotomy and that the promising development of planning and surgery techniques should be proceeded.

2007, in the DK Henriettenstiftung Hannover, Germany, 31% of unicompartmental OA patients were treated with osteotomy. Other procedures done were TKA (43%) and unicondylar knee replacement (26%) [26]. 2003, in France, about 10000 high tibial osteotomies were performed [10].

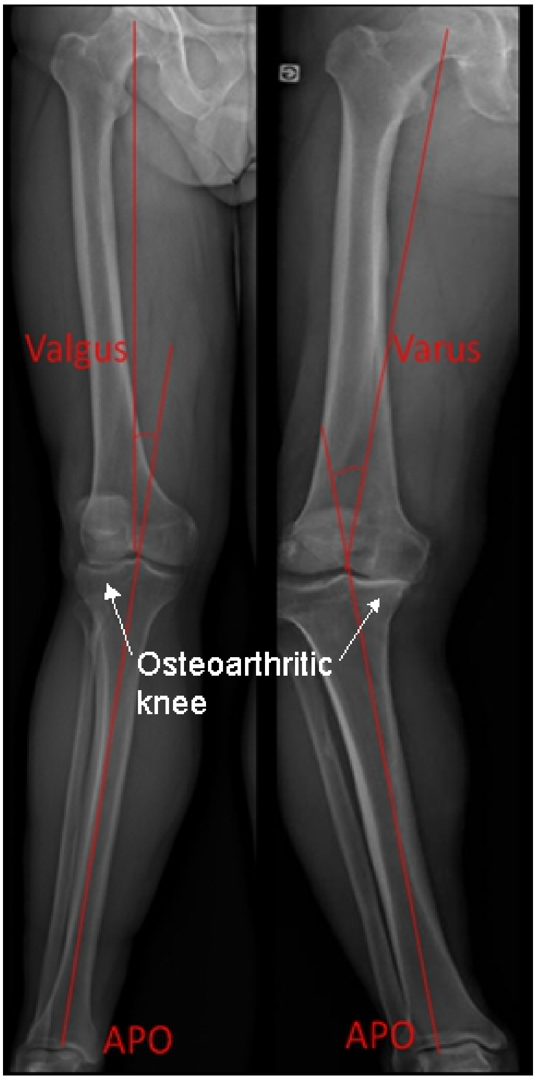


Figure 2.1: Two frontal leg radiographs of osteoarthritic knees (adapted from [17]). Left: Valgus knee. Right: Varus knee.)

2.3 Anatomy of the Lower Limbs and the Knee Joint

This section presents the lower limb bones, and in particular focusses on the femur and the tibia. These are long bones and have different parts: the epi-, meta- and diaphysis (see figure 2.6).

2.3.1 Femur

The thigh bone (femur) is the longest bone of the body (see figure 2.2(a)). Both ends are articular extremities. The femoral head on the upper end is connected with the pelvis, they build the hip articulation.
The femoral neck connects the femoral head and the shaft. Besides the head are two other eminences: the lesser and the greater trochanter.
Distally the femur has two eminences: the larger medial condyle and the smaller lateral condyle. Together with the tibial plate they form the knee articulation. Where the femur articulates with the tibia, the bone surface is covered with articular cartilage.
At the anterior distal end lies the patellar surface, a depression in which the knee cap slides, when the knee is extended and flexed. Posterior, the condyles are separated by the intercondylar fossa, a deep depression. The most distal point in the intercondylar fossa is called trochlea [21, 4].

2.3.2 Tibia

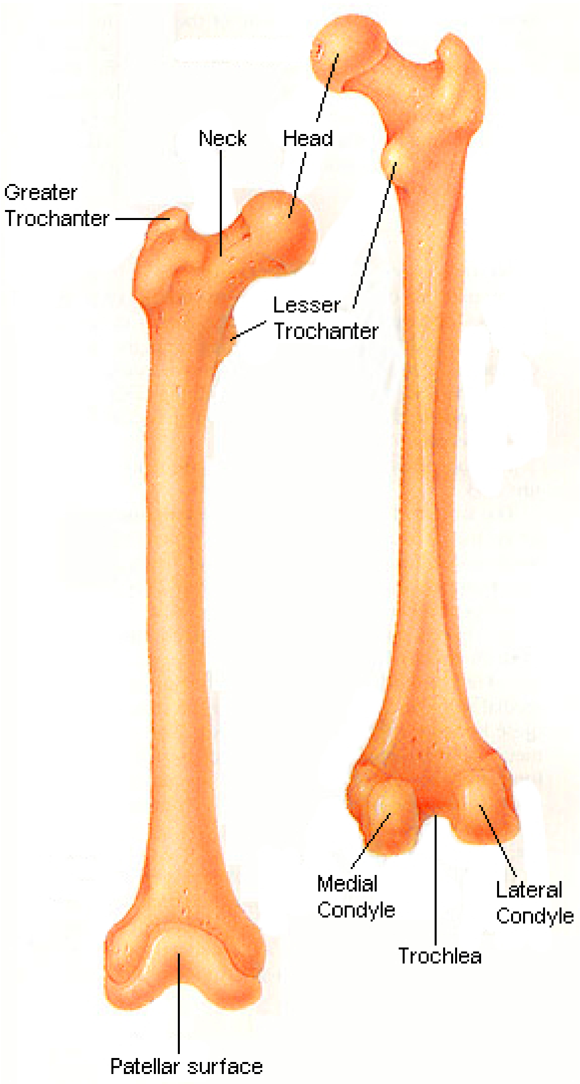
The shinbone (tibia) is the larger and stronger of the lower leg bones and connects the knee with the ankle [8]. Its upper extremity is the joint socket for the distal femur end and consists of two parts: a medial and a lateral condyle. These articular surfaces are called tibial plateaus. Between the medial and lateral tibial plateaus is the intercondylar eminence which terminates in two peaks: the intercondylar tubercles [21].
Laterally, the tibia and the fibula are connected with ligaments.
At the distal end, the tibia builds together with the fibula and the talus bone the ankle joint. The medial surface of the tibia is distally prolonged and is called the medial malleolus [21].
Figure 2.2(b) shows a scheme of the human tibia and fibula.

Fibula

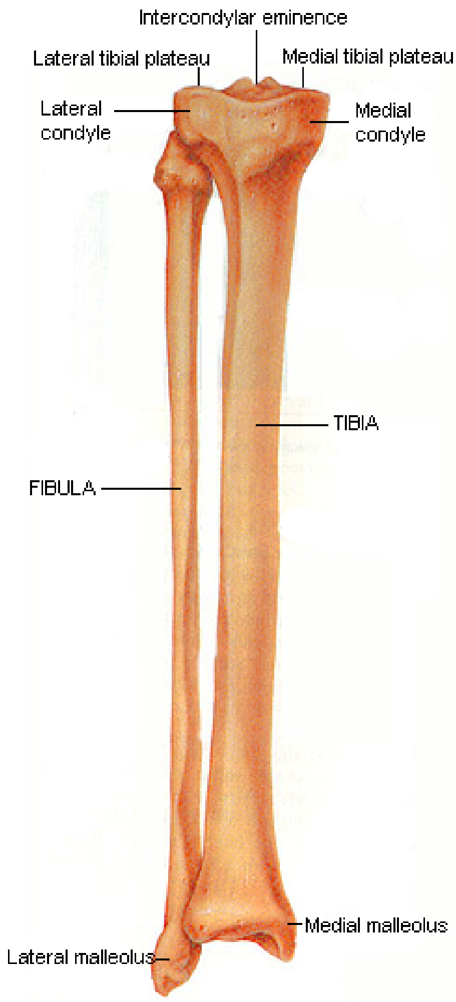
The fibula is the smaller of the two lower leg bones and runs laterally parallel to the tibia. The lower and upper epiphysis of the fibula are connected with the tibia.
Its distal end is the lateral malleolus and forms the lateral part of the ankle joint. The fibula has no functional influence on the knee articulation [21].

Patella

The knee cap (patella) is a flat, triangular bone and is located at the anterior surface of the knee joint[21].



(a) Femur in front and back view



(b) Tibia and fibula in front view

Figure 2.2: Human lower limb bones (adapted from [7]).

2.3.3 Knee Joint

The knee joint is very complex and the largest joint in the human body. It comprises the four bones (femur, tibia, fibula and patella) which are held together by ligaments and muscles. Cartilage and menisci allow a smooth movement. The joint is embedded in the joint capsule, an envelope consisting of fibrous tissue and a layer secreting articulation fluid.
The knee consists of two articulations: one between the femur and the patella and another between the femur and the tibia. The latter femorotibial articulation incloses the medial and lateral condyles of the femur which bear on the two sockets of the tibia, and will be the focus of the further discussions. The surfaces of distal femur, the proximal tibia and the posterior patella are covered with cartilage. The intra bonal gap between femur and tibia is filled by the lateral and medial menisci [20, 1].
Figure 2.3 shows a scheme of the knee joint in flexed position. The joint capsule is not pictured, the patella ligament is detached and the knee cap is fold up to give a view to the inner part.

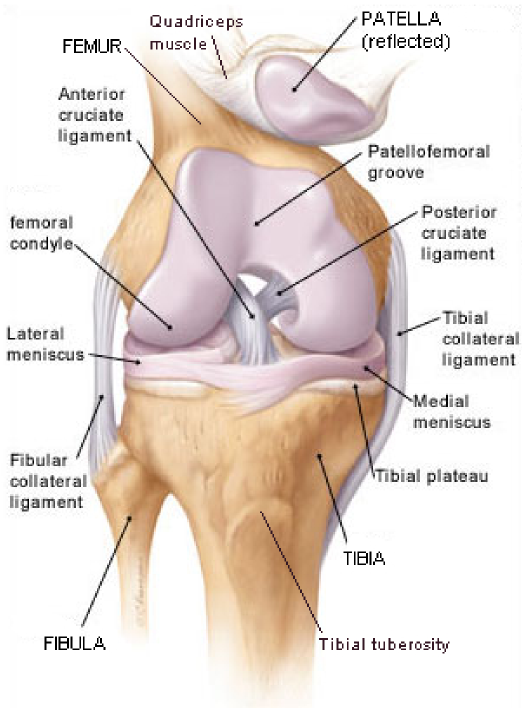
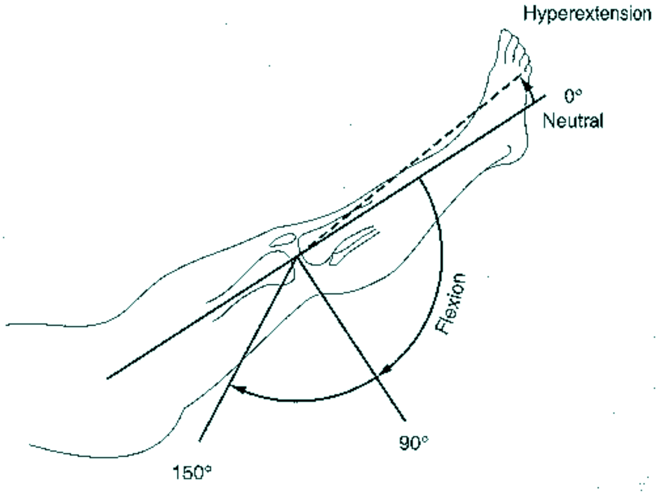


Figure 2.3: Human knee joint (adapted from [37]).

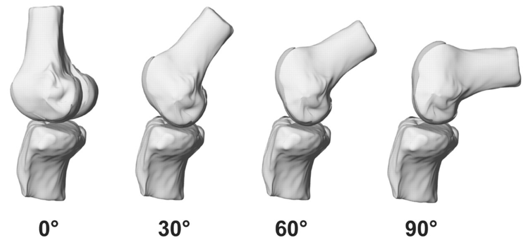
Ligaments. A pair of cruciate ligaments (posterior and anterior) is situated in the centre of the knee. Their purpose is to keep the bones close to each other and to prevent femur and tibia of sliding apart forwards or backwards [20].
Another two ligaments are the collateral ligaments which run along the sides and limit the sideway motion of the knee.
The patellar ligament connects the patella with the tibial tuberosity and prevents it from sliding laterally [1].

Menisci. The knee joint contains two half-moon shaped fibrous cartilage disks called the medial and the lateral meniscus.
They lie on the tibial plateaus and articulate with the condyles of the knee. They protect the femoral and tibial bone ends from rubbing on each other and assume a smooth sliding in flexion and extension of the knee. The menisci also act as shock absorbers and help transmit the weight of the body [1].

Movement. The knee joint's main movements are flexion (up to 150°) and extension (up to 5-10°) [1]. Figure 2.4(a) shows the maximum movements and 2.4(b) different degrees of flexion.
In addition to this rotation about a virtual transversal axis, in flexed position, a slight medial and lateral rotation occurs. During the movement, the femur condyles roll and slide over the menisci. The total range of motion is dependent on the individual patient's anatomy [1].



(a) Flexion and extension of the knee articulation in lateral view [5].

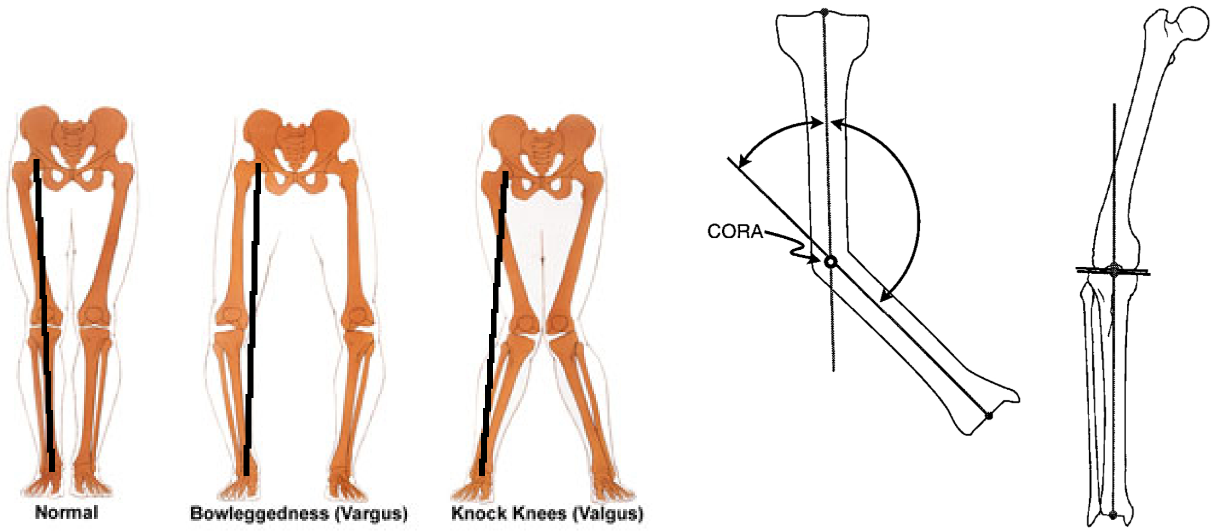


(b) Degrees of knee flexion [6].

Figure 2.4: Knee movement.

2.4 Knee Malalignment

The term *alignment* in knee orthopedics refers to the relative position of the lower limb bones and their adjacency in the joints. If the knee is perfectly aligned, the leg load bearing axis runs straight through hip, knee and ankle articulations and makes a certain angle with the femur and tibia axes. If the leg axis is derived from the straight axis one speaks of knee malalignment [2, 3].
Evaluating the alignment of the legs, the knee loading in upright position and during physical activity should be taken into account.
The origin of malalignment can be the articulation itself or a deformity in the femur or tibia. Unbalanced bearing of the femur condyles on the tibial plateaus and the subsequent axis malalignment is a risk factor for osteoarthritis [3] (see section 2.1).
Figure 2.5(a) shows a normal alignment compared to varus and valgus knees. This malalignment has its origin in the knee articulation.
Figure 2.5(b) illustrates deformations in tibia and femur. The centre of rotation of angulation (CORA) represents the position of the bone deformity. It is the intersection of the proximal and the distal anatomical axis and it can be used for osteotomy planning [30].



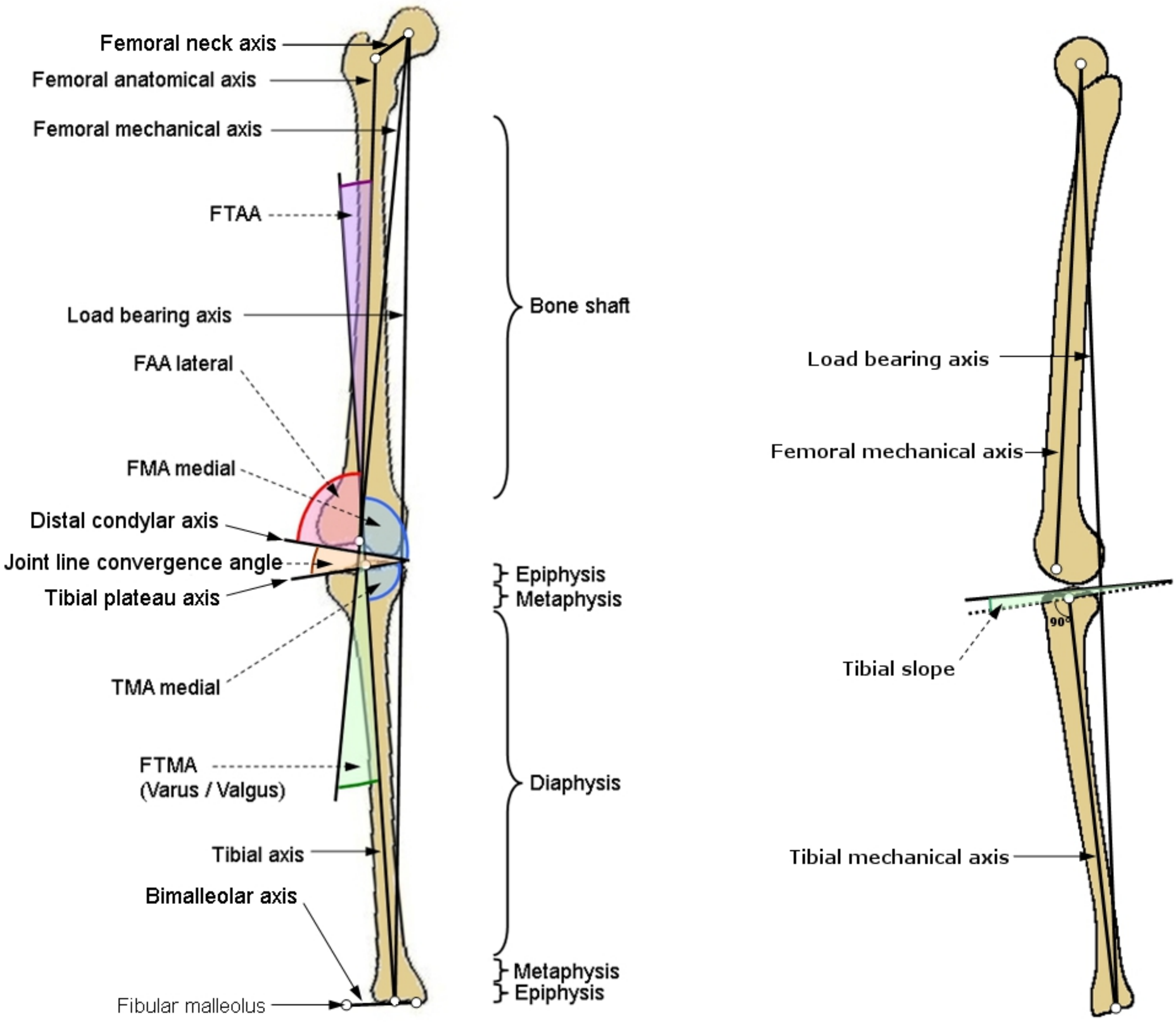
(a) Leg posture: normal, varus, valgus. Bones with load bearing axis (adapted from [43]).

(b) Deformity in the bone itself: tibia and femur. The center of rotation of angulation (CORA) can be located [30].

Figure 2.5: Origins of knee malalignment.

2.5 Axes of the Lower Limb Bones

In order to describe functionality and anatomy, and to make linear and angular measurements, reference axes of the femur and the tibia were defined [31]. The measurement of parameters, like angles and lengths, serves to compare the anatomy between specimen and pre- and postoperative situations of the same patient.
Axes are found by connecting landmarks of the lower limb bones. A generally admitted exact definition of the reference points does not exist. The definitions of the lower limb axes are not standardized and depend on the form of the femoral and tibial shafts, and the size of the radiography [31].
In general, an anatomical axis describes the direction of the bone shaft, whereas a mechanical (functional) axis describes the direction of a force.
The tibia mechanical and anatomical axes are parallel and nearly identical.
Table 2.1 and figure 2.6 show the definition of femur, tibia and leg axes which are used in following discussions.



(a) Femur and tibia in frontal view.

(b) Femur and tibia in lateral view.

Figure 2.6: Axes, angles and parts of the lower limb bones.

Bone	Axis	Reference points
Femur	Mechanical axis	trochlear centre femoral head centre
	Anatomical axis	trochlear centre femoral shaft centre
	Condylar axis	central point of the medial condyle central point of the lateral condyle
	Distal condylar axis	most distal point of the medial condyle most distal point of the lateral condyle
	Posterior condylar axis	most posterior point of the medial condyle most posterior point of the lateral condyle
	Femoral neck axis	centre femoral head femoral neck base
Tibia	Mechanical axis	ankle centre intercondylar eminence centre
	Anatomical axis	ankle centre tibial shaft centre
	Tibial plateau axis	central point of the medial plateau central point of the lateral plateau
	Posterior tibial plateau axis	most posterior point of the medial plateau most posterior point of the lateral plateau
	Bimalleolar axis	central point of the medial malleolus central point of the lateral malleolus
Lower limb	Load bearing axis (LBA)	femoral head centre ankle centre

Table 2.1: Definition of the lower limb axes

2.6 Anatomical Planes and Projections

An ordinary radiograph in anterior posterior direction performs a 2D projection onto the frontal (coronal) plane. Similarly, projecting in medial lateral direction generates a lateral (sagittal) plane projection. These projection planes are called machine planes because they do not depend on the patient's position.
Generating projections onto planes different from the frontal or lateral one, are very complicated with ordinary x-ray methods. For instance, in order to project along the anatomical femur axis, the patients leg has to be put in a certain position and the x-ray tubes and detectors have to be reoriented. The resulting radiograph is a bone plane image.
Using a 3D model of the bone allows the simulation of each projection. Thus projection planes can be set more exactly after the acquisition and in a repeatable way. In order to project in the bone plane, a bone coordinate system has to be defined (see section 5.4.2).

Using traditional planning methods, clinical parameters are calculated based on projections. Now, having 3D bone models, the parameters can be calculated in three dimensions. Length of bones can be calculated more pertinently based on 3D coordinates. However, some parameters like angles are more pertinent in 2D calculated based on projected points.

2.7 Clinical Parameters

Clinical parameters serve to describe a patient's anatomy in a detailed way and are crucial for surgery planning.
Osteotomy planning is mainly based on the angles between lower limb axes. The lengths of bones and entire extremity should be kept in mind, and big differences between the opposite legs should be avoided.

2.7.1 Lower Limb Angles

In 2D planning, angles are measured on radiographs. SterEOS enables 3D measurements, angles between lower limb axes were found to be more pertinent in 2D [28]. Therefore all the angles are determined by projecting the line defining points on a plane and calculating the angle between the resulting vectors.
Figure 2.6 illustrates angles measured in frontal and lateral plane and table 2.2 shows definitions and standard values of the lower limb angles.
The standard values arise from studies with a sample of normal subjects without lower limb complications. That means that under physiological conditions, people have on average those values. They can slightly differ from one paper to another and are often indicated as intervals.
For both, femur and tibia, one can determine angles at proximal and distal end, as well on medial and lateral side. Since the angles near the knee joint are more significant for osteotomy planning, the distal femoral and the proximal tibial angle are mentioned. The laterality, medial or lateral, is chosen according to the value. For this reason surgeons often refer to the angle which is less than 90°.

Projection plane	Name	Abbreviation	Reference axes	Standard value in °
Frontal	(Distal) Femoral Mechanical Angle	(D)FMA	-Femoral mechanical axis -Condylar axis	lateral: 87,5 ± 2,5
	(Proximal) Tibial Mechanical Angle	(P)TMA	-Tibial mechanical axis -Tibial plateau axis	medial: 87,5 ± 2,5
	Femorotibial Mechanical Angle	FTMA	-Femoral mechanical axis -Tibial mechanical axis	1 - 3 (Valgus)
	Femorotibial Anatomical Angle	FTAA	-Femoral anatomical axis -Tibial anatomical axis	6 - 10 (Valgus)
	Joint Line Convergence Angle	JLCA	-Tibial plateau axis -Distal condylar axis	medial: 0 - 2
Lateral	Tibial Slope	TS	-Tibial plateau axis -perpendicular axis to the tibial anatomical axis	dorsal: 6 - 10
⊥ to femoral mechanical axis	Femoral Torsion	FT	-Femoral neck axis -Posterior condylar axis	femoral neck in anteversion: 15.6 ± 6.7
⊥ to tibial mechanical axis	Tibial Torsion	TT	-Post. tibial plateau axis -Bimalleolar axis	external: 23.5 ± 5.1

Table 2.2: Lower limb angles are calculated between two axes and on a certain plane [30, 26, 31].

Valgus/Varus. The FTMA projected on the frontal plane is called either Valgus or Varus, depending on the medial or lateral orientation of the knee.
Table 2.3 shows the specification of these two cases of angulation: 'Genu Valgum'and 'Genu Varum'. When femoral and tibial mechanical axis are lying on the load bearing axis (LBA), the LBA runs through the center of the knee.

	Genu Valgum	Genu Varum
Common name	Knock-knees	Bow-legs
FTMA alternative name	Valgus	Varus
FTMA value	FTMA>0°	FTMA<0°
Knee deviation	medial	lateral
Overloaded knee compartment	lateral	medial
Therapy	Varus Osteotomy	Valgus Osteotomy
Opening wedge base position	lateral	medial
Closing wedge base position	medial	lateral

Table 2.3: Characteristics of Genu Valgum and Genu Varum.

2.7.2 Lower Limb Lengths

The lengths of bones ideally should be measured in three dimensions. Measuring distances in projected images can only approximate the real value and is not pertinent. The following table shows the calculation instructions for the length of the leg bones and the entire leg used in the prototype.

Bone	Reference points
Femur	trochlear centre femoral head centre
Tibia	ankle centre intercondylar eminence centre
Leg	femoral head centre ankle centre

Table 2.4: Calculation of bone and leg lengths: 3D distance between the reference points.

Chapter 3

Lower Limb Osteotomy

Osteotomies allow the surgeons to correct knee malalignment and thus to relief pain and improve the longevity of the knee articulation. Osteoarthritis, gait disruption, knock or bow legs are possible pathologic and cosmetic reasons for this surgery.
Varus/valgus osteotomy is performed to correct angulation malalignment and derotation osteotomy is performed to correct rotational malalignment. These surgery goals can be achieved in different ways.

Surgeons differentiate between several types of lower limb osteotomy. The osteotomy term is determined by the following factors:

- Goal of the surgery (to correct a certain clinical parameter in a certain way)
- Realisation of the goal (manner of the surgery)
- Bone to cut (e.g. the right femur)
- Cut level (e.g. distally)
- Character of the cutting face (e.g. in a planar way)

Further specifications are shown in the tables A.1.
A typical valgus osteotomy is shown in figure 3.2. It corrects the FTMA angle in Valgus sense by doing a medial opening osteotomy at the proximal tibia with a planar cut.

The surgery procedure begins with anesthesia and sterilization of the lower extremity. The access to the bone may be accomplished minimally invasive or with bigger incisions. Several instruments allow a relative exact cut and alignment. Afterwards, the two bone parts, and optionally the inserted wedge, are fixed with plates and screws or other instruments (see figure 3.2).

3.1 Valgus / Varus Osteotomy

Discrepancies from the load bearing axis to the knee articulation in valgus or varus sense can result in unilateral knee loading and damage the medial or lateral femorotibial compartment. This disease OA (see section 2.1) can be treated by varus/valgus osteotomy that try to relieve the damaged part of the knee by transferring the patient's weight on the other, healthier compartment. By moving the knee centre closer to the load bearing axis, the surgeon changes the force transmission through the joint and improves its biomechanics.
In other words, varus/valgus osteotomies correct angles: FTMA and FTAA and, according to the cut bone, FMA or TMA. The postoperative FTMA should be equal to the one of the opposite leg or the standard value (see table 2.2) [30]. Coventry recommend a slight overcorrection, because he achieved best long-term results with a postoperative FTMA of 3-5°[15].
In valgus/varus osteotomy, a bone opening or closing is performed (see figure 3.4). The bone and the cutting level depend on the centre of deformity and the surgeon's experience. The most performed and established osteotomy is the high tibial osteotomy (HTO). According to Paley and Pfeil [30], and Stindel [38], the cut should be at the level of deformity, whether femur or tibia. Better access and healing are reasons to cut the bone near the knee articulation, at metaphysis level (see figure 2.6). The surgeon may not totally cut the bone apart, but leave a superficial periosteum connection of 2-3mm between upper and the lower part [39].

Varus osteotomy can be undertaken to align knock-knees.

Valgus osteotomy means to correct the bone alignment in valgus sense. The indication is an overloading of the medial knee compartment, caused by a varus malalignment. Varus OA is common and 90% of all performed osteotomies are tibial valgus osteotomies [26] .

Femur vs. Tibia Osteotomy

High tibial osteotomy is the most frequent one and is nearly always applied on medial osteoarthritis arisen out of a varus deformity [26].
Whereas a valgus deformity (lateral osteoarthritis), especially in strong cases (FTMA >12°) can be addressed with femoral osteotomy [27].
The femur is usually cut distally, above the condyles to not risk fracturing them. The high tibial cut is done at a minimal distance of 15mm of the tibial plateaus to reduce the risk of a tibial plateau fracture [39]. When the cut is performed on the tibia, in very little cases, the fibula might be cut as well [23].
In complex osteotomies, it arises that both, femur and tibia, are cut or that one bone is cut at different levels.

Influenced Clinical Parameters

Varus/valgus osteotomies may have unexpected side effects on the patient's anatomy. Even though it appears that only the FTMA angle should change when realigning the lower limb in varus or valgus sense, other clinical parameters may change as well.
A special regard should be on the tibial plateau which may tilt, especially if the patient has a ligament insufficiency. In frontal view one speaks about an oblique joint line, the plateau tilting medially or laterally. In a sagittal radiography the tibial slope, an angle between a perpendicular axis to the tibial anatomical axis and the medial tibial plateau, can be measured (see figure 2.6). If the tibial slope is too big, the femur can slide backwards [31, 36]. This phenomena can easily be missed in 2D planning.

3.2 Derotation Osteotomy

Lower limb torsion can result in in- or out-toeing and cause functional disability. It is common during childhood, but for the major part, the torsion improves over time without surgical intervention. However, some cases require corrective derotation osteotomy. Lateral tibial torsion is often seen in patients with neuromuscular disease like cerebral palsy [35].
Derotation osteotomy is performed in order to change the torsion of a bone, thus to optimise the tibial or femoral torsion angle. In addition to the torsion angle, a surgery may involve other clinical parameters as hip rotation and foot angles.
Derotation osteotomy can be performed in a simple way but also in combination with a varus/valgus osteotomy. Indications for combined femoral varus-derotation osteotomy are inadequate coverage of the femoral head in the hip joint, pain, valgus angulation of the femoral neck, and dislocation of the hip [22].
In derotation osteotomy, it is common to operate the bone which holds the torsion. Tibial osteotomy is most often performed at distal level because of higher long-term success. Osteotomy at proximal level should only be performed in combination with a varus or valgus correction [25, 35].
Femoral derotation osteotomy (FDO) can be done at different levels. In proximal FDO, the femur is cut below the greater trochanter. In distal FDO, the surgeons cuts above the condyles, which is faster and causes a lower blood loss than the proximal FDO [32]. Figure 3.1 shows the effect of a distal FDO.

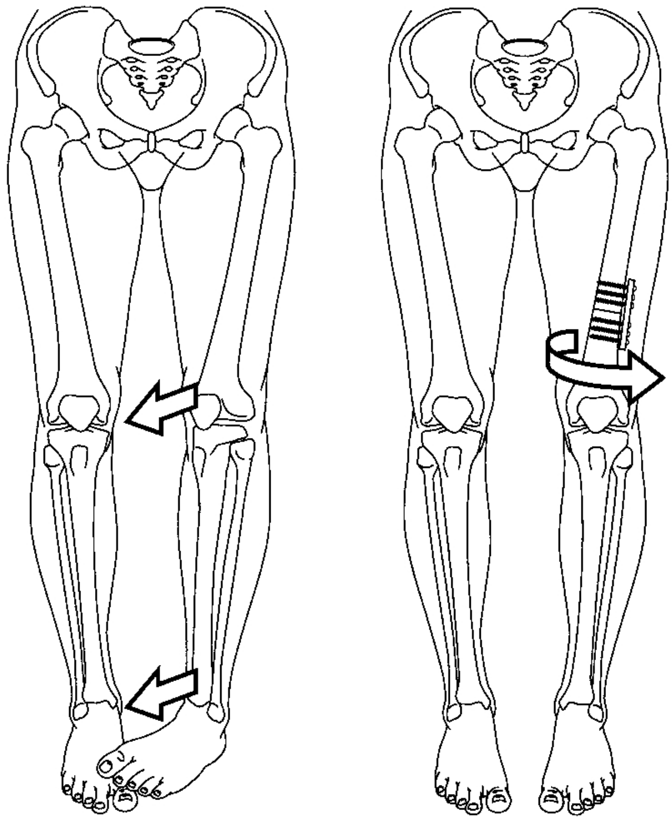


Figure 3.1: Effect of distal femoral derotation osteotomy [32].

3.3 Osteotomy Modes

Regarding the manner of surgery there are three different modes: opening, closing and derotation. The first two have a comparable effect. For instance, an opening osteotomy with the wedge base medially is comparable to a closing osteotomy with the wedge base laterally. In both cases the leg bends inward, bringing the leg from a bowlegged in a knock-kneed position.
In opening and closing mode, after the cut, the lower bone part is rotated around a hinge axis which is commonly perpendicular to the frontal plane. In 2D planning, this axis is projected to a hinge point and it is usually situated medially or laterally on the bone surface. It can be located outside or inside of the bone as well.
The third mode of derotation is different; after the bone is cut apart, the surgeon rotates the lower bone part around a bone axis.
All three modes can be applied comparably on femur and tibia.

3.3.1 Opening

In opening osteotomy, the bone is cut one time and the lower part of it is rotated around a hinge axis. The resulting gap can be filled with a wedge of artificial or natural bone or if it is small, it can be left. The correction angle is the angle of opening, so the angle between the two bone cutting surfaces.

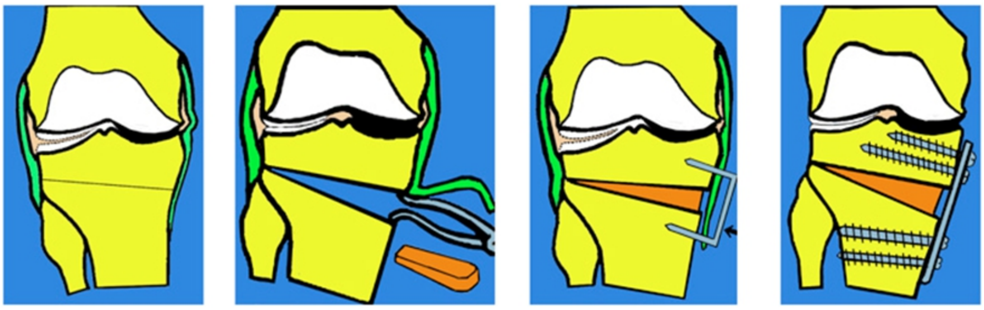


Figure 3.2: Opening osteotomy procedure: cut and opening of the bone, insertion of a wedge, fixing with staples or a plate and screws [18].

3.3.2 Closing

In the closing mode, two cuts are performed. Various instruments are used to achieve in a certain correction angle. The resected bone wedge is removed and the bone is closed by putting the cutting surfaces on each other.

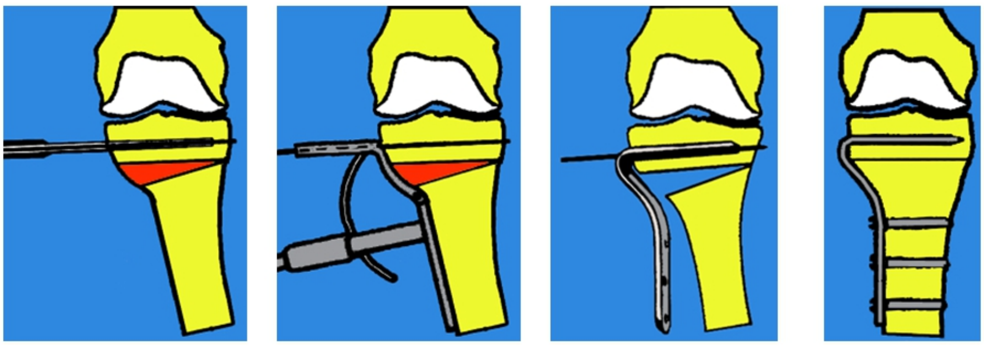
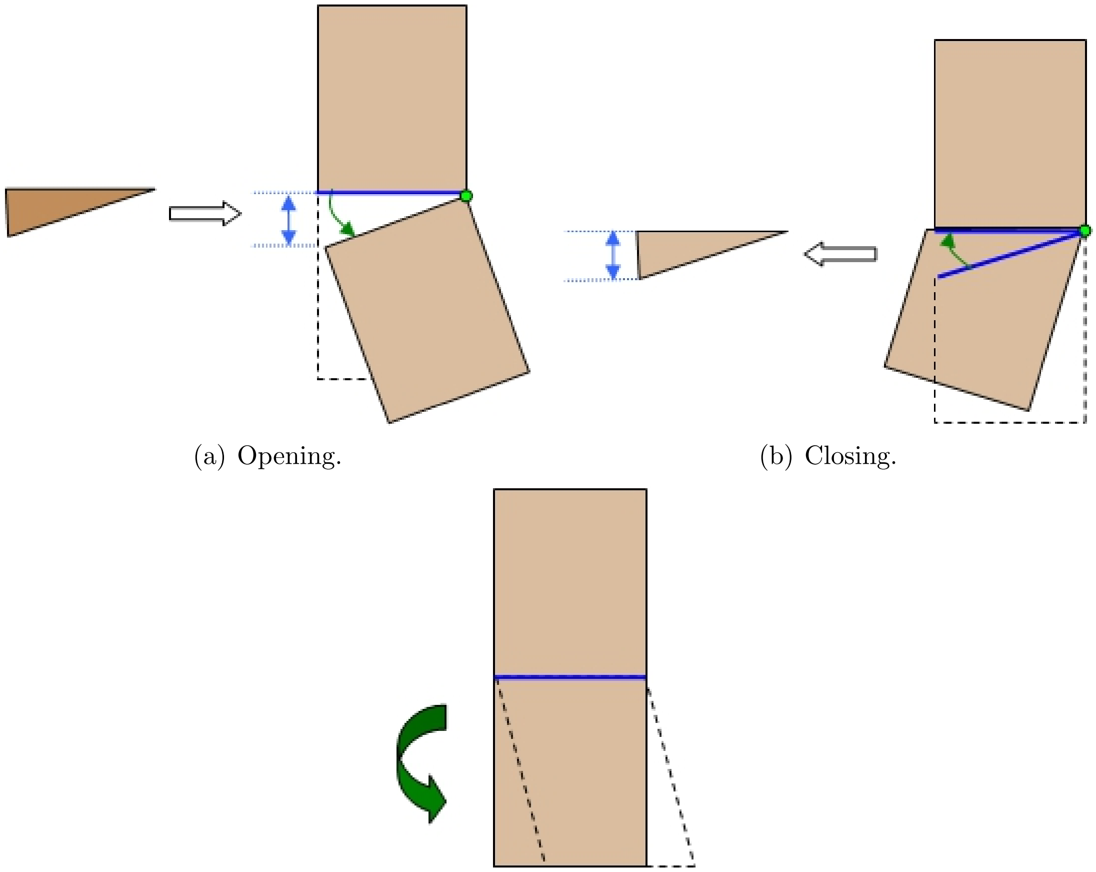


Figure 3.3: Closing osteotomy procedure: mark the cut position according to the correction angle, cut and closing of the bone, fixing with plate and screws [18].

3.3.3 Derotation

In derotation osteotomy mode, the bone is cut apart and the lower part is turned around a longitudinal axis. In contrast to opening and closing, no bone wedge is inserted or extracted, unless it is a combined osteotomy.



(a) Opening.

(b) Closing.

(c) Derotation.

Figure 3.4: Osteotomy modes.

3.4 Surgical Parameters

There are several parameters describing the surgical correction.
The **correction angle** is a very important and the most discussed one. It has a different meaning according to the osteotomy mode. Figures 3.4(a) to 3.4(c) show the correction angle in green.
The **wedge base height** is only defined in opening and closing osteotomy. It is measured in mm and depends directly on the correction angle. Figures 3.4(a) and 3.4(b) show the wedge base height in blue as the biggest height of the wedge.
Furthermore the **distance between cutting plane and knee articulation** is a parameter that has to be kept in mind (see subsection 5.5).

3.5 Preoperative Planning

Before it comes to a prescription of an osteotomy several steps are to accomplish. During a physical examination, the doctor assess the patient's leg posture and compares the concerned (painful) knee with the opposite one. Additionally to the static leg axis, the dynamical one can be examined with the patient's gait. Moreover, tests to assess the menisci and ligamental state can be performed. Afterwards preoperative radiography imaging is done. MRI is not important for the planning. Even if MRI images show soft tissue, e.g. cartilage, the resolution is insufficient to see little menisci disruptions [31].
After the acquisition, the lower limb axes are evaluated on the radiography and the preoperative planning begins. The work of Pape et al. [31] gives an excellent overview about common preoperative osteotomy planning methods.

The following planning steps are essential for a successful osteotomy (cf. table A.1):

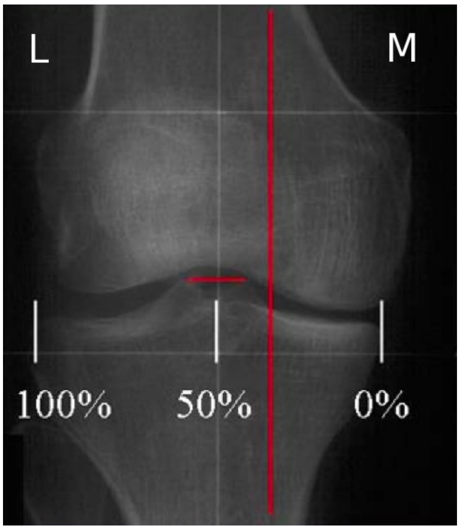
1. Precise the malalignment
   (a) Define lower limb axes
   (b) Calculate clinical parameters (angles, lengths)
   (c) Find out which parameter(s) are to correct and in which direction
2. Locate of the deformity and choose:
   - Osteotomy mode
     - If angulation malalignment: Choose opening or closing osteotomy (according to leg length, surgeon's experiences, available instruments, etc.) Choose medial or lateral.
     - If rotation malalignment: derotation osteotomy
     - If angulation and rotation malalignment: Choose combination of osteotomies.
   - Bone(s) to cut
   - Cut level
   - Cut character and orientation (according to surgical parameters)
3. Determine surgical parameters
   - Correction angle
   - (Wedge base height)
4. Determine the fixation
   - staples
   - plate and screws
   - others

The planning steps 1 to 3 should be facilitated with the developed planning software. The surgery success depends on the fixation as well. However, step 4 is not factored, because the software rather provides a biomechanical cut and alignment simulation than a loading simulation. This would be necessary to evaluate the suitability for a certain fixation instrument.

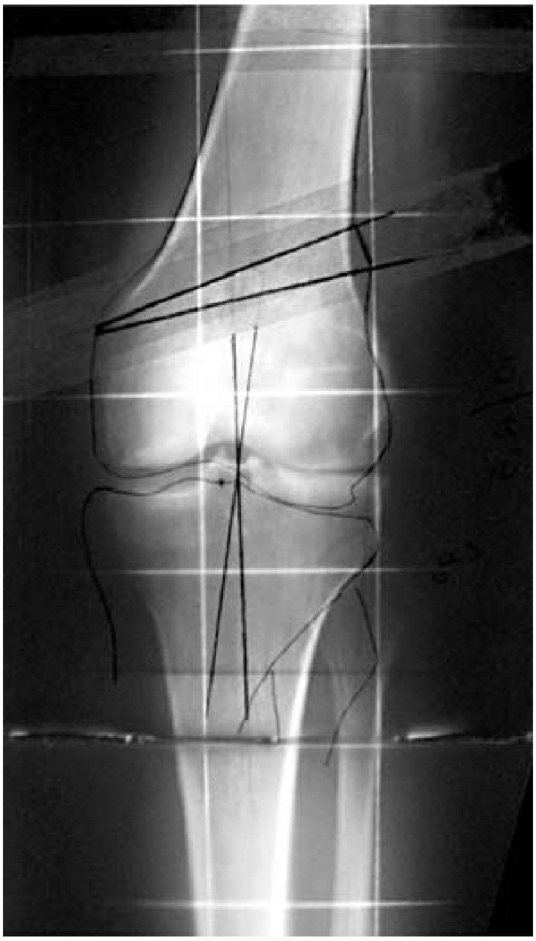
3.6 Traditional 2D Planning of High Tibial Osteotomy

This section discusses the traditional planning of high tibial osteotomy (HTO) as a therapy for valgus/varus malalignment. There are two approaches in surgery planning which differ in the clinical parameter the correction is referred to. Surgeons either plan to correct the femorotibial angle (FTMA or FTAA, see table 2.2) or the joint centre distance.

The **Joint Centre Distance** (JCD) is the distance between the load bearing axis and the knee centre. It is measured on radiographs on the tibial plateau line. The JCD is indicated in millimeters or as a percentage of the width of the tibial plateau. Figure 3.5(a) shows a radiograph of the knee with the tibial plate width and the load bearing axis (LBA) as a long red line.
For a healthy patient, the LBA runs in average 5mm medial to the knee centre [31, 30].



(a) Detail of a high frontal radiograph. Determination of the joint centre distance (JCD) based on the load bearing axis and the tibial plateau width (adapted from [31]).



(b) Small frontal radiograph used for planning based on anatomical axes: Outline the cut position; cut and adjust parts of the radiograph [11].

Figure 3.5: Traditional 2D osteotomy planning.

French surgeons, for instance, use the femorotibial angle and American surgeons prefer the JCD.

For the **Femorotibial Angle** approach, either the anatomical or the mechanical axis can be used. Formerly, surgeons used the anatomical axis, because size-limited radiographs showed only the knee, but not the whole extremities. Figure 3.5(b) shows the planning sketch on a small radiograph.
Today, higher radiographs which show the whole lower limbs are available. Thus measurement with mechanical bone axes and load bearing axis are possible. These axes are more reliable and allow a better planning [31].

3.7 Motivation for Computer Support

Osteotomy surgery requires precise preoperative planning in order to minimize the risk of under- or overcorrection, postoperative deformities and fractures. In order to obtain good long-term results, it is important to take into account the clinical parameters at large. Unintentional effects on other, not directly concerned parameters should be minimized.
The manual 2D calculation of parameters is very time-consuming and may be inaccurate. Angles and lengths of bones can be adulterated, if they are calculated based on a machine plane projection. Having 3D data, projections can be done continuable and based on any projection plane, e.g. in the bone frame.
Mental arithmetics and pencil and ruler techniques reach their limit in complex calculations, e.g. of the ideal correction angle (see subsection 5.5.2).
Depending on the number of calculated parameters a manual planning can take up to 15 minutes [33] Using computer tools, a great number of parameters can be calculated instantly and with a high reliability; this leads to a faster and more accurate planning process.

Computer support in medicine may cost quite an effort. Software systems have to be bought, the staff has to be convinced, that computer support can lead to higher surgical success, whereat their familiar methods lead to quite good results. The usage of a software system may entail further investments. For the realization of a correctly planned surgery, traditional instruments may be obsolete. There are intraoperative guidance systems (cf. section 4.2) which are not only software, but rather workstations, and require a complete replacement of surgery tools and equipment.

There are existing software tools for 2D and 3D osteotomy planning, that make the surgeon's work easier. 2D planning is even with computer support not optimal. The 2D frontal planning can tend to disregard the impact on parameters observable in the lateral view. Varus/valgus correction for instance has an impact on the tibial slope, which is only visible in the lateral plane. 3D osteotomy simulation takes those effects in space into account, which can be missed on a simple radiography. Thus anatomical and surgical parameters be evaluated in a better way.
A three-dimensional computed model has more in common with the later surgery situation in the operating room than a two-dimensional radiography. 3D computer support has potential to make osteotomy planning more intuitive. On the other hand, 3D interaction on a screen is not evident and has to be studied for surgery assisting software. Another potential in 3D osteotomy planning is to accommodate the anterior and posterior tilt of the cutting plane. Furthermore you can allow the hinge-joint axis to be any axis, and not necessarily perpendicular to the frontal plane [16].

A preoperative planning in 3D brings advantages in comparison to 2D planning, though due to the increased number of degrees of freedom it brings challenges and will require tests of pertinence and usability.

Chapter 4

Existing Software Tools for Osteotomy Planning

Many software tools exist to asses bone anatomy in 2D and 3D, but the most part concern knee arthroplasty. Nevertheless, there are some tools for computer-aided osteotomy planning, some of them simply prototypes and others commercial products.
This section presents 2D and 3D tools for preoperative or intraoperative planning and intraoperative navigation and guidance.

4.1 2D Tools

The following 2D tools allow the planning of varus/valgus osteotomies. The planning of derotation osteotomy is provided by none of them.

TraumaCad - a Preoperative Planning System

The commercial software TraumaCad[1] provides several surgery planning modules.
They provide a module for planning lower limb deformity corrections based on a digital frontal radiograph, showing the whole extremities. This tool enables the surgeon to measure and display the bone axes and to establish the CORA. Angles are calculated and the correction can be simulated, interacting with the two-dimensional image.

OASIS - a Preoperative Planning System

In 1995, Chao and Sim [12] evaluated the Osteotomy Analysis and Simulation Software - OASIS, a software tool using a standing radiograph in AP projection and based upon a 2D 'Rigid Body Spring Model'.
Taking into account the impact of ligaments, muscles and cartilage as springs, this approach goes well beyond a bone axis based geometrical planning. Even though OASIS, simulating the postoperative bone geometry and loading conditions depending on the bodyweight, represents a more complete osteotomy planning approach, the third dimension is missing to make the simulation perfect.
The simulation is based on a static analysis and is only valid if force distribution is the same in standing posture as well as in dynamic performance of the knee.

[1] http://www.voyanthealth.com/traumacad.jsp (accessed 13-08-2010)

An Intraoperative Planning and Navigation System for High Tibial Dome Osteotomy

Wang et al. [41] presented a 2D intraoperative planning and navigation system for high tibial dome osteotomy[2]. In contrast to preoperative planning, intraoperative planning is done with the patient lying in the surgery block.
The system is based on static fluoroscopic x-ray imaging of hip, knee and ankle articulations that are acquired at the beginning of the surgery. Following registration of anatomic landmarks, a patient specific coordinate system is established. This provides a basis for the measurement of deformity, parameter calculation and the surgical procedure. The marked instruments are tracked by a camera system and its position is then superimposed onto the fluoroscopic images in multiple planes and in real time. A navigational guidance based on schemes and preliminary taken radiographs is provided. Abandoning continuous fluoroscopy, this system reduces the x-ray exposure for patient and surgical team.
A drawbacks of this system is the 2D representation and the limit to high tibial dome osteotomy. In addition, fluoroscopic guidance with its limited view was found to be less accurate than navigation based on 3D bone models [13].

4.2 3D Tools

In 3D, one can rather find navigation focussed systems, than pure preoperative planning tools.
There are more and more computer aided surgery (CAS) systems based on 3D bone models, coming either from CT acquisition[42] or generic models. Generic bone models do not require additional irradiation and can be more or less patient specific.

A Surgical Planning and Guidance System for High Tibial Osteotomy

Ellis et al. [16] developed a three-dimensional surgical planning and guidance system for high tibial osteotomy.
Based on CT data a bone model is extracted; a three-dimensional surgery plan is arranged preoperatively and then executed in an image-based guidance system during the intervention.
They evaluated the tool with pilot studies on knee arthritis patients, but apparently it has never been commercialized.
Drawbacks are the high costs and time for the data acquisition and preparation. In addition, this tool is limited to only high tibial closing wedge osteotomies and is thus not universally applicable.
The visualization, including the transfer between CT scanner and UNIX workstation and iso-surface extraction, required approximately 30 minutes, the preoperative planning of the user about 10 minutes, and the rendering of the surgery simulation results, using OpenGL, took 1-2 seconds.

VectorVision®osteotomy - an Intraoperative Planning and Navigation System for High Tibial Osteotomy

The Brainlab company provides numerous tools for computer-aided surgery and as well one solution for intraoperative osteotomy planning and navigation.
VectorVision ®osteotomy[3] allows femur and tibia 3D visualization as models that provide information of the patients lower limb anatomy, based on important landmarks.
Anatomical parameters (angles and lengths) are calculated intraoperatively. During navigation, surgical instruments are tracked and displayed in real-time, as well as the changing parameters describing the surgical outcome.

[2]Dome osteotomy is characterized by a curved cut [30] and not further discussed in this work.
[3]http://www.brainlab.com/scripts/website_english.asp?menuDeactivate=0&articleID=2016&articleTypeID=140&pageTypeID=4&article_short_headline=VectorVision%AE%20osteotomy (accessed 21-09-2010)

Cheung et al. [13] tested the Brainlab VectorVision 1.0 system and used the arthroscopic assisted, image guided method. Marker were fixed minimal-invasively at anatomical features, e.g. the tibial plate, for registration with the bone model.
Even if there is the risk of infection and of cartilage damage caused by implanted markers, they drew the conclusion, that arthroscopic assisted computer navigation in medial open wedge high tibial osteotomy is more advantageous than conventional and non-arthroscopic assisted HTO. The correction of the limb alignment was more accurate.
An advantage is, that there is no need for any radiation exposure to patient and surgeon.
Apparently, the used bone model can only represent a rather limited number of patient specific landmarks. This could lead to wrong evaluation if, for instance, existing bone deformities are not visible in the model.

In [24], Peter Keppler of the university hospital Ulm gives a short overview over the osteotomy navigation system *VectorVision*, as well as over *Medivision* and *Orthopilot*. He emphasizes, that navigation systems can not replace preoperative planning.

Chapter 5

OstEOS - A New Preoperative Planning Tool for Osteotomy

The main contribution of this work was the development of a software tool for lower limb osteotomy planning based on 3D models of the bones. The prototype, named *OstEOS*, was designed as an extension of SterEOS, the tool for radiograph reviewing and 3D skeletal reconstruction.
This software tool is a prototype and was developed in order to identify the clinical needs of surgeons, to provide a base for discussions with them, and to assemble software requirements.
In opposite to the presented 3D tools, OstEOS is not limited to one type of osteotomy, but allows the planning of femoral and tibial opening, closing and derotation osteotomy. It is based on very patient specific bone models and gives a reliable presentation of the anatomy.
This chapter starts with an overview over the OstEOS components and functionalities, and the program flow. A description of the input data is provided. Following, technical details concerning the bone coordinate systems, the cutting process and the parameter calculation are presented. Finally, important use cases are discussed.

5.1 Overview Components & Functionalities

The following list gives an overview of characteristics and functionalities of OstEOS. In further sections of this chapter they are explained in detail.

- **Osteotomy modes.** OstEOS provides support for the planning of opening, closing, and derotation osteotomies.
- **Bone coordinate systems.** The bone to operate determines the coordinate system which is used to represent the bone model. Femur and tibia coordinate systems are defined at the base of the anatomical characteristics of the bones.
- **Cutting plane.** The bone is cut with a cutting plane which is represented by a rectangle. It can be positioned by means of translation and rotation. Furthermore its size can be adapted to the bone surface at a certain level.
- **Cut of the bone model**. The 3D model of the bone is cut in an upper and a lower part.
- **Bone alignment.** After the cut, the lower bone part can be moved using translation and rotation or by entering desired surgical or clinical parameters.
- **Calculation of parameters.** Preoperative clinical parameters are calculated and by cutting and aligning, the bone shape changes and a simulation of the postoperative parameters is provided in real-time. Surgical parameters are calculated as well.
- **Saving of the cutting result.** At the end of the surgery planning the results can be saved.

5.2 Program Flow

The program's work and control flows are illustrated in the activity diagram in figure 5.1.
The layout of the graphical user interface (GUI) and the system behavior change according to the four following program states:

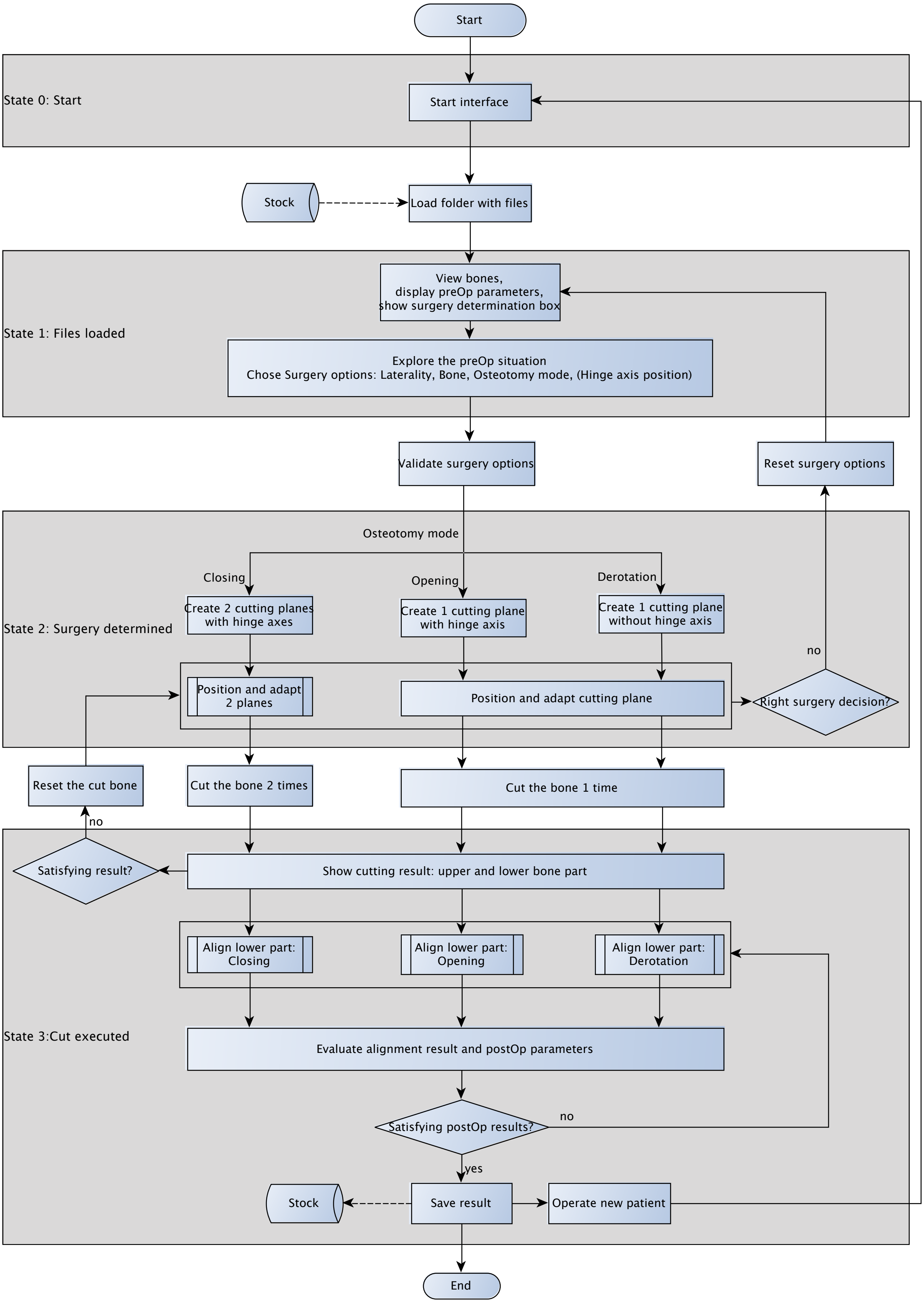
- 0 Start
- 1 File load → Visualization of the 3D bone models
- 2 Surgery determination → Display of cutting planes
- 3 Cut → Visualization of the cutting result

In the first step, the user selects via file dialogue a directory. If the directory contains the required input data, the program passes from state 0 to 1. At this point, the 3D bone models and the mechanical bones axes are displayed and the patient's anatomy can be evaluated by exploring the bones and by consulting the preoperative parameters.
Next, the user has to determine the surgery by choosing the leg and bone to operate, the osteotomy mode and, for opening or closing, the hinge axis position. After the validation of these surgery specifications, the program transitions into state 2. Now, the view changes according to the bone coordinate system and the cutting planes are displayed and can be adjusted. According to the chosen osteotomy mode the program behavior changes: the number of cutting planes and hinge axes and the plane transformation possibilities differ.
The surgery determination can be reset and the user can change the specifications.
By clicking on the *Cut* button, the cutting process starts. When the calculations are finished, the program passes to state 3. The two bone parts are viewed and the lower one can be moved.
The user moves the lower part until the result and the postoperative parameters are satisfying. The cut can be undone.
At the end of the planning the surgery results can be saved. A .wrl file with the postoperative 3D model of the operated bone and a .txt file with the new positions of the limb feature points are created.

During the program flow, one correction can be carried out. In order to execute a second correction on the same or the opposite leg, the cutting results have to be saved and the patient data have to be reloaded.

Section 5.6 describes important use cases in detail.

Figure 5.1: Flow chart of OstEOS.



5.3 Input Data

The main input to OstEOS is the 3D model of the bones: right and left femur and tibia. It is provided via four .wrl files[1] and one text file.
The .wrl files contain the 3D models of the bones. The three-dimensional objects are represented by vertices with x, y and z coordinates and by an index, a list containing point index triples which represent triangles of the mesh.
In addition, since the VRML file format does not allow to store supplementary information, a text file is used to provide anatomical point coordinates and their names. This text file contains important anatomical points for both legs such as the centre of the femoral head (cf. table 2.1). They are only one part of the points of the generic bone model, generated by the SterEOS.

The input data generating process is illustrated in figure 5.2 and contains the following steps:

- Acquisition of frontal and profile standing lower limb radiographs with the EOS system
- Review of the radiographs (DICOM files) with SterEOS
- Reconstruction of the femur and tibia in SterEOS 3D
- Export of the 3D models and the text file

The acquisition takes less than 4 minutes and the 3D reconstruction of femur and tibia takes 2-3 minutes. The reconstruction is a half-manual registration of the frontal and lateral radiograph with the contours and feature points of the generic bone model.

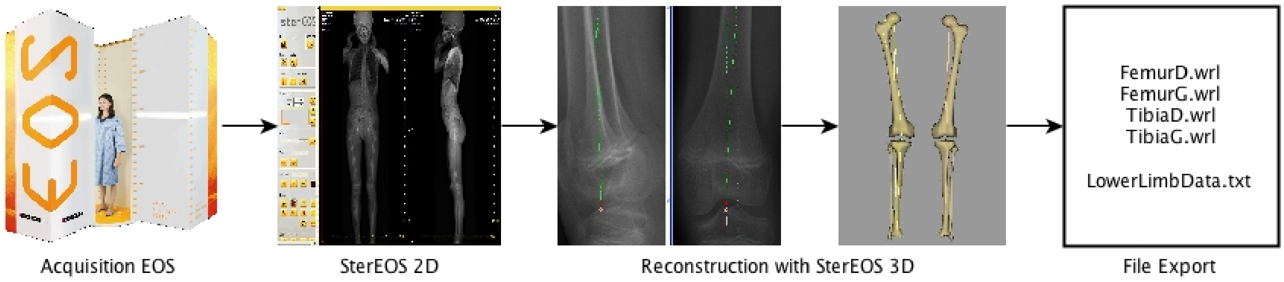


Figure 5.2: Steps to attain the required input data.

The points stored in the text file do not reference the vertices in the .wrl files. Thus the files are completely independent of each other. Appendix A.1 shows .wrl and text file examples.
Having no reference between the visual data (coming from .wrl files) and the anatomical data (coming from text file), they are handled separately.
The **visual data** of one bone is stored in two matrices: a vertex matrix and an index matrix.
The **anatomical data** for both legs is stored in one matrix (`limb_points`) in a certain order. Containing each point one time for the right and one time for the left leg, this matrix is of size `n = 2 * number_of_feature_points`. The point coordinates concerning the right leg are listed in the first `n` rows and those concerning the left leg are listed from `n+1` to `n+n`.

[1].wrl is the filename extension of the text file format VRML (Virtual Reality Modelling Language) representing 3D interactive vector graphics

5.4 Technical Details

At the beginning of this section, the representation of the visual data is discussed and the bone coordinate systems are defined. The clinical parameter calculation, and following, conceptual choices for cutting planes and hinge axes are explained. Finally, after the definition of the surgical parameters, the cutting process is presented.

5.4.1 Visualization

The choice of the representation of the visual objects (bones and cutting planes) was based on three components of the tool:

(a) the view of the bones,

(b) the interaction with the objects, like cutting plane positioning and bone alignment, and

(c) the calculation of the clinical parameters.

Another consideration are the two main steps of the workflow. The first one is the exploration step where the user evaluates the anatomical situation of the lower limb bones. This corresponds to state 1 in the program flow (cf. section 5.2). When the surgery was determined and one of the four bones was chosen, one gets to the second step: the surgery, which corresponds to state 2 and 3. In this case a straight frontal view of the chosen bone should be displayed.

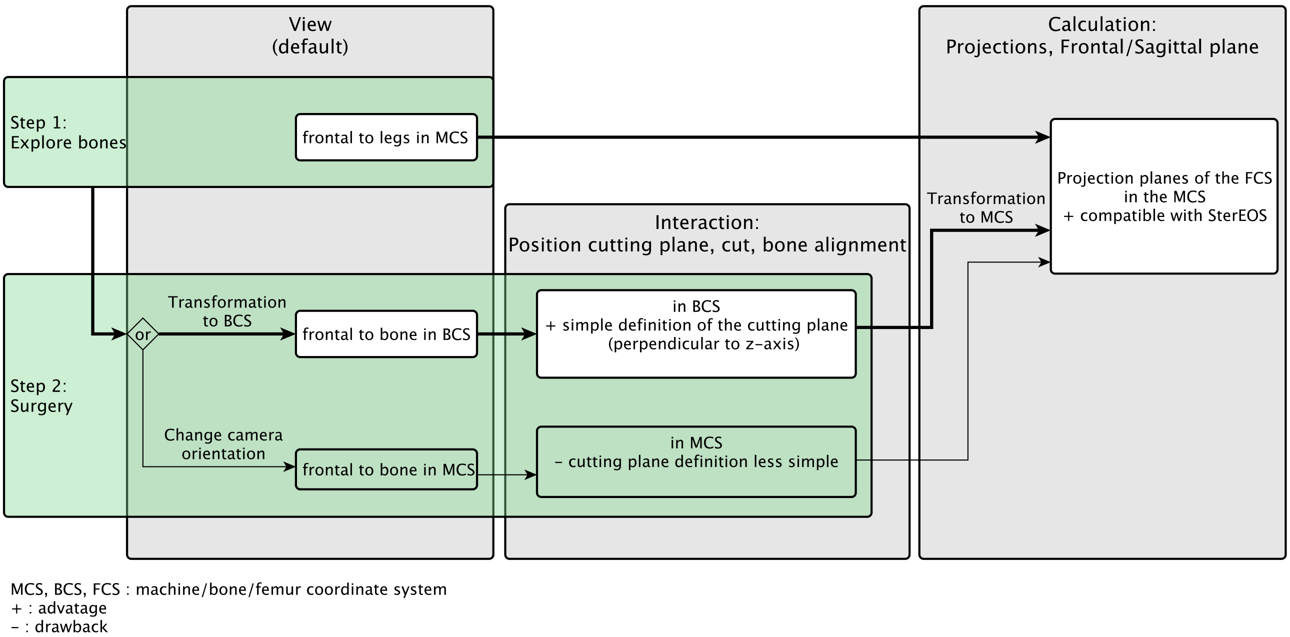


Figure 5.3: View Interaction Calculation.

The scheme in figure 5.3 compares different possibilities of object representation in various coordinate systems. The white boxes, connected with the bold edges, represent the choice that was made in OstEOS. The alternative represented in green nodes was rejected.
The vertices coming from the input data are represented in the machine coordinate system (MCS) of the acquisition modality EOS. The representation in this coordinate system is adequate for the exploring step. But for the surgery step it is better to provide a straight view of the focussed bone.
At this point there were two options: transforming the bone, right or left femur or tibia, in its proper coordinate system (bone coordinate system or BCS) or just changing the view point parameters in order to centre the bone on the screen. These alternatives do not make any difference for the user; the appearance is the same.
The interaction component makes the difference; not for the user, but for the complexity of calculations. Geometrical transformations, such as the positioning of the cutting plane relatively to the focussed bone, and the user's plane manipulations, are less complicated if they are done in the BCS. In tibial opening osteotomy, the bone is usually cut parallel to the tibial plate. Being in the BCS, it is easy to place the cutting plane this way, just put it in the x-y-plane. A translation along the bone axis can be done simply by changing the z value.
Therefore the first solution was chosen: view and interaction are done in the BCS and in order to calculate the postoperative parameters the limb points are transformed back to the MCS.
Thus parameter calculation is done in MCS representation for pre and postoperative data.

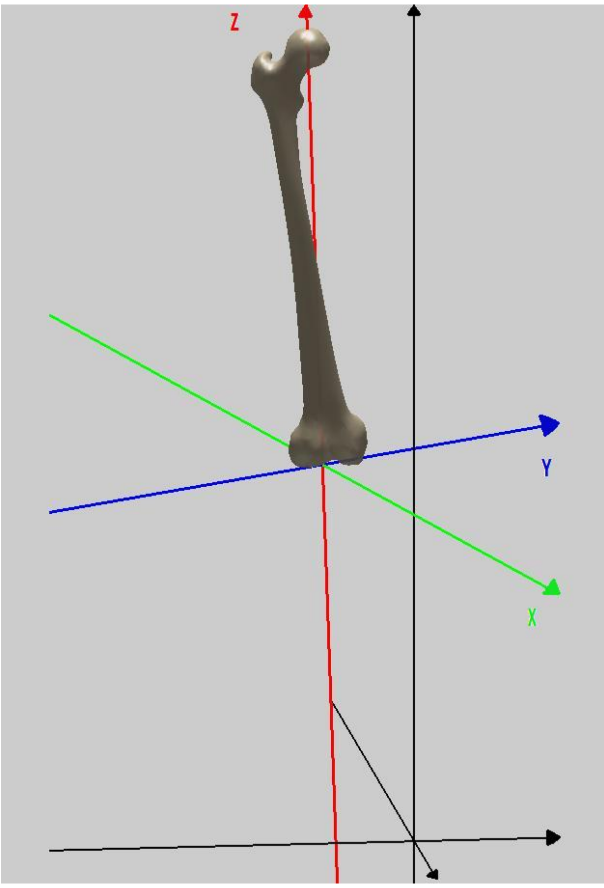


Figure 5.4: Machine and femur coordinate system.

5.4.2 Bone Coordinate Systems

The angle calculation and the straight femur view require the definition of a femur coordinate system, FCS (cf. figure 5.4). The SterEOS developers fixed a mathematical definition of the FCS, which was reimplemented in OstEOS.
A tibia coordinate system (TCS) definition did not exist in SterEOS, but was necessary in our tool for the straight tibia view.
The straight view on a certain bone is provided as soon as the user chooses one bone to operate. The bone model coordinates of all four bones are transformed to the coordinate system of the chosen bone. For the user the view changes since the bone models are set in the frame of the chosen one.

The coordinate system, from the machine coordinate system (B) to the bone coordinate system (B'), is changed through the transformation f. It represents a change of basis.

$$f : B \rightarrow B' \tag{5.1}$$

The rotation matrix $M_{B'}^{B}$ (5.2) contains the mapping of the standard basis vectors and is in non homogeneous coordinates of size 3×3.

$$M_{B'}^{B} = \begin{pmatrix} f(\overrightarrow{b_x}) \\ f(\overrightarrow{b_y}) \\ f(\overrightarrow{b_z}) \end{pmatrix} \tag{5.2}$$

Applying this rotation and additionally a translation to the new origin, the vertices are transformed to the target coordinate system.

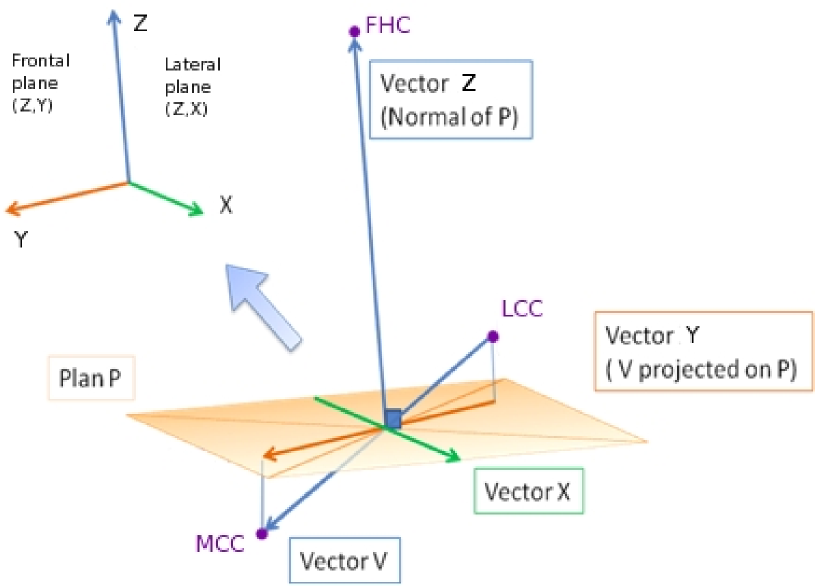


Figure 5.5: Definition of the femur coordinate system (adapted from [17]).

The Femur Coordinate System

Figure 5.5 illustrates the definition of the femur coordinate system (FCS).
The origin of the FCS is the middle of the segment connecting the two condyle centres MCC and LCC. The z axis (pointing to the top) is defined by the origin and the centre of the femoral head FHC.
There is a plane P defined by the z axis as normal and passing through the origin. The y axis (pointing from lateral to the medial condyle) is defined by the projection of the condyle segment to the plane P. The x axis (pointing from posterior to anterior) is the result of the cross product of z and y axis.

The Tibia Coordinate System

The definition of the tibia coordinate system (TCS) was determined by constraints: it should be defined based on the given anatomical feature points, and the tibial plate, determined by the two plateaus, should define the transverse plane, since it is the most important reference in tibia osteotomy.
Due to these constraints, TCS definitions available in the literature were inappropriate. Fitzpatrick et al. presented a TCS definition based on the tibial anatomical axis as axial axis [19]. Since the tibial plate is not perpendicular to the anatomical tibial axis it could not be used in OstEOS.

The SterEOS tibia bone model includes five points characterizing the proximal end of the tibia (cf. figure 5.6) :

- most posterior point of the medial plateau (MP)
- most posterior point of the lateral plateau (LP)
- central point of the medial plateau (MC)
- central point of the lateral plateau (LC)
- intercondylar eminence centre (IE)

Finding a reliable mathematical definition of the tibial plate with these points is difficult, because only two of the five points are lying on the wanted plane. A third point on the tibial plate would be necessary to define a correct plane.
The following definition is a good approximation if there is no big posterior or anterior tilt of the tibial plate.
The basis of the calculation are the centre and posterior points of the plateaus. The points in the middle of the centre segment and the posterior segment are calculated by linear interpolation.
The origin of the TCS is the point between LC and MC. The x axis is the vector from point P to the origin. The y axis passes through the plate centers and points from LC to MC. The z axis (pointing to the top) is the result of the cross product of x and y axis.
The black plane in figure 5.6 represents the x-y-plane.

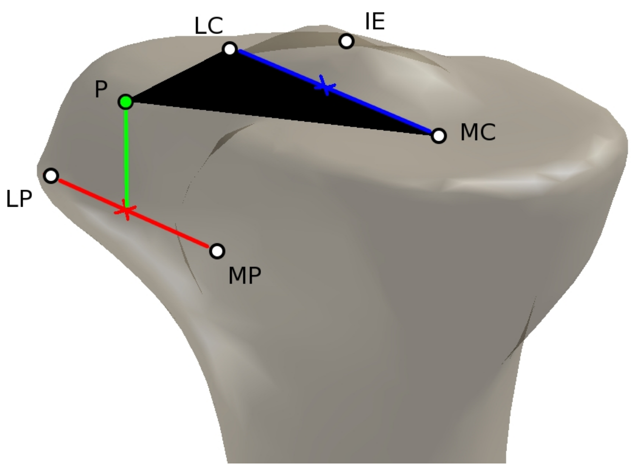


Figure 5.6: Angular back view on the proximal end of the tibia with the five given points. The black triangle defines the x-y-plane of the tibia coordinate system.

5.4.3 Calculation of the Clinical Parameters

The clinical parameters can be classified in two groups. Those who are calculated in 3D and those who are calculated in 2D with prior projections.
The 3D-parameters are distances between points, like the lengths of femur, tibia and the leg as they are shown in table 2.4.
The 2D-parameters are defined on a certain projection plane. Angles like FTMA, FMA and TMA are calculated on the frontal plane. The tibial slope is calculated on the sagittal plane.
The frontal and sagittal planes used for these projections, are the planes of the left or right femur coordinate system (see section 5.4.2). The planes of the tibia coordinate system are not used for projection, because they are not used in SterEOS either.
Tibial and femoral torsion are calculated on the plane perpendicular to the mechanical bone axis. All calculations, both 2D and 3D, are based on the limb points in the machine coordinate system.
The user is not able to consult all angles listed in table 2.2 but a limited choice. Some parameter calculations that had not been validated yet (e.g. the tibial slope), are not displayed (see section 7.2).
In the GUI, the following preoperative parameters for both legs and postoperative parameters for the operated leg are shown:

- FTMA
- FMA
- TMA
- Femur length
- Tibia length
- Leg length
- Femoral torsion
- Tibial torsion

5.4.4 Cutting Planes and Hinge Axes

A cutting plane is represented by a rectangle, whose vertices define the plane.

Default Position

The cutting plane is defined at the base of the bone coordinate system of the operated bone. It is placed by default in its x-y-plane. For the tibia, the plane is parallel to the tibial plate.
The cutting level in osteotomy is often near the knee articulation. Thus a default plane position at a certain minimal distance to the articulation is suggested.
Subsection 3.1 discusses the minimal distances for tibia and femur. By default, the plane is perpendicular to the frontal and sagittal plane of the bone coordinate system. In the closing mode, one of the two planes is in the default position and the second plane one is defined based on the first one, taking it and rotating it in a certain angle around its hinge axis.
The hinge axis can, according to the user's choice, be the medial or lateral segment of the cutting plane (see figure 5.7).
In the opening and closing mode, the user can rotate the cutting plane(s) around the hinge axis, and after the cut, the lower bone part as well.

Degrees of Freedom

The planes can be translated in the z direction. A translation in x and y is not meaningful. Even if in reality the surgeon may leave a few millimeters of connection at the bone surface, it is of minor impact. In the closing mode, the two planes are translated together in order to preserve the hinge axis position.
In the opening and closing mode, there is another degree of freedom: the cutting plane(s) can be rotated around its hinge axis which is one of the edges perpendicular to the frontal plane. Figure 5.7 shows the possible hinge axes as blue edges lying lateral and medial to the bone. Thus when rotating the plane it stays perpendicular to the frontal plane.

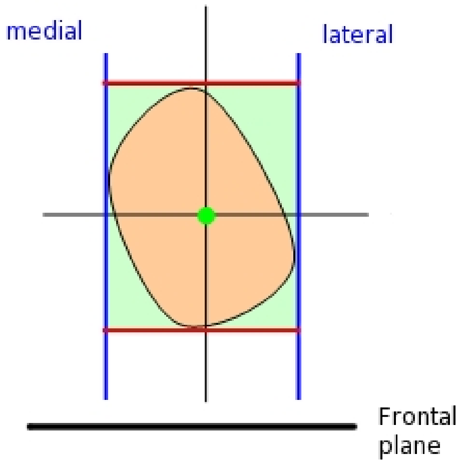


Figure 5.7: Scheme shows a bone at a certain level in above view. The blue lines represent the hinge axes.

The prototype limits the possibilities of rotation for reasons of pertinence and simplicity of manipulation. In osteotomies which tend to correct an angulation it is considered better not to incline the cutting plane back or forwards - this is avoided with the limited rotation.
One can imagine more complex surgeries where a correction of angulation and rotation at the same time is necessary. In this case, an inclination, the rotation around any axis, would be useful.
In order to move the hinge axis directly to the bone surface, we implemented a function that adapts the rectangle borders to the bone surface at the current level. Figure 5.7 shows the cutting plane adapted to the bone surface in above view.
In the derotation mode, a translation in z direction is the only degree of freedom and the cutting plane has no hinge axis. The transformation is limited to translation because a big inclination of the cutting plane in derotation is rather avoided. We decided to place the cutting plane in the x-y-plane of the bone coordinate system.
Extensions to allow the user wider influence are imaginable, because the opinions differ according to which axis the cutting plane should be perpendicular (mechanical, anatomical bone axis or any other). It should be placed in a way that by rotating the lower part, the ankle centre does not move and the two bone surface fit on each other. The ankle centre should be kept unchanged in order not to disrupt the ankle articulation surfaces. For a better healing, it is beneficial to maximize the contact surface. Unfortunately, these objectives are often opposed.

Figure 5.8: In closing mode osteotomy, the bone model is cut two times. Result: upper part, wedge and lower part.

5.4.5 Cutting Process

The cut of the bone is done with an infinite plane, defined by the cutting rectangle vertices.
The bone object, represented in bone coordinate system, is cut with the help of the cutting plane and divided in two parts: the upper and lower bone part.
In the closing mode, a second cut is done on one of the resulting parts of the first cut. In this case, three objects result from the cut: the upper part, the middle part (wedge) and the lower part (see figure 5.8).
As described in section 5.3, the visual data are stored separately from the anatomical data. Therefore, the cutting process consists of two parts: cutting the 3D bone model and dividing the `limb_points` matrix.

Cutting the 3D Bone Model

The cut splits the vertices and edges of the 3D model in two parts. Whereas the vertices can be divided clearly by means of an orientation test, the intersected edges have to be rearranged. Figure 5.9 shows a triangle strip which represents an unfolded part of the bone mesh being intersected by the cutting plane.
If the cutting plane intersects two edges of a triangle, the intersected triangle is divided into a triangle and a quadrangle. The cutting algorithm in appendix A.3.1 takes this most frequent intersection case into account. In order to recover the mesh characteristics, the quadrangle is divided into two triangles (see figure 5.9). Thus there is the upper or lower part which obtains one new triangle and the respectively other part which obtains two new triangles. These two possibilities are highlighted in figure 5.9. The intersection points of edges and cutting plane become new vertices of the model and define the cut surface.
Special cutting cases like ‘plane intersects one edge and one vertex’, ‘plane intersects one vertex’, ‘one edge is lying on the plane’ were not addressed because they appear rarely.
After the reparation of the border, there is still the polygon shaped hole in each part to triangulate. The vertices of this polygon are the intersection points.
The bone part which is cut during an osteotomy is usually meta- or epiphysis. Due to the fact that these bone parts are convex bodies, a trivial triangulation algorithm for convex polygons was used to close the holes: one vertex is connected to all other vertices. The resulting bone parts are then stored as proper 3D models.

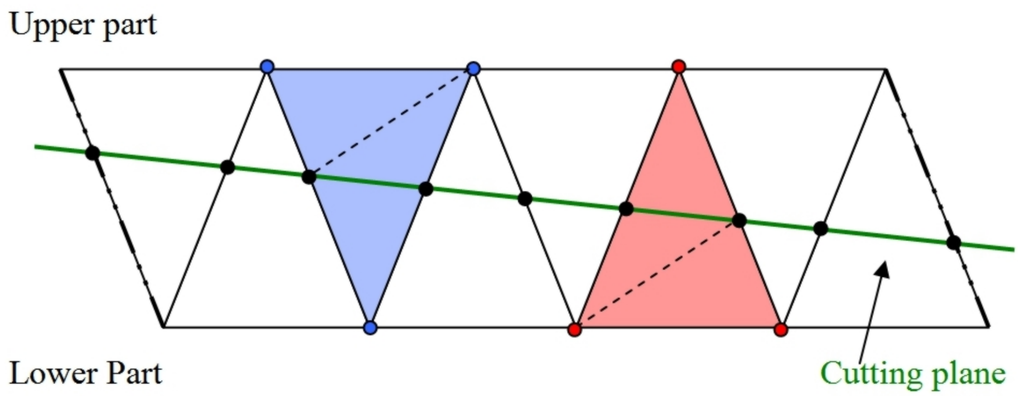


Figure 5.9: Part of an opened bone triangle mesh and the cutting plane, that divides vertices and edges in two parts.

Dividing the Lower Limb Points

The assignment of limb points either to the upper or lower part happens in the same way as the bone model vertices: with the help of a 3D orientation test.
The `limb_points` matrix is split into two matrices. For a left leg cut, the upper limb point matrix contains all vertices of the right leg points and the vertices of the left leg above the cutting plane. Rows in the matrix that contain vertices lying below the plane are stored as NaN (Not-a-Number) values. The lower limb point matrix is constructed vice versa. The matrix scheme 5.3 illustrates the algorithm.
The goal of the limb point division is to allow an independent geometrical transformation for the two parts. When both parts are represented in form of matrices remerging them is simple.
After each user manipulation of the lower part the two matrices are merged. The resulting matrix is used to compute postoperative parameters in real-time.
In closing osteotomy, lower limb points could be in the wedge part. In this case, clinical parameters based on this point are not computed.

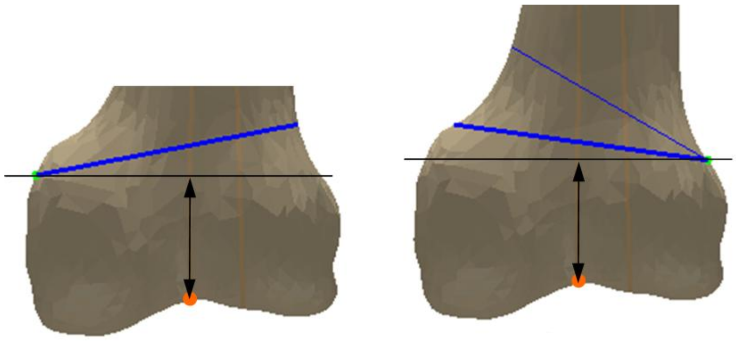
$$
\begin{array}{c}
\textbf{Limb points}\\
\begin{pmatrix}
R_{1,1} & R_{1,2} & R_{1,3}\\
R_{2,1} & R_{2,2} & R_{2,3}\\
\vdots & \vdots & \vdots\\
R_{n,1} & R_{n,2} & R_{n,3}\\
 & & \\
L_{n+1,1} & L_{n+1,2} & L_{n+1,3}\\
L_{n+2,1} & L_{n+2,2} & L_{n+2,3}\\
\vdots & \vdots & \vdots\\
L_{n+n,1} & L_{n+n,2} & L_{n+n,3}
\end{pmatrix}\\
\swarrow \qquad\qquad\qquad \searrow\\
\begin{array}{cc}
\textbf{Upper part points} & \textbf{Lower part points}\\
\begin{pmatrix}
R_{1,1} & R_{1,2} & R_{1,3}\\
R_{2,1} & R_{2,2} & R_{2,3}\\
\vdots & \vdots & \vdots\\
R_{n,1} & R_{n,2} & R_{n,3}\\
 & & \\
L_{n+1,1} & L_{n+1,2} & L_{n+1,3}\\
NaN & NaN & NaN\\
\vdots & \vdots & \vdots\\
L_{n+n,1} & L_{n+n,2} & L_{n+n,3}
\end{pmatrix}
&
\begin{pmatrix}
R_{1,1} & R_{1,2} & R_{1,3}\\
R_{2,1} & R_{2,2} & R_{2,3}\\
\vdots & \vdots & \vdots\\
R_{n,1} & R_{n,2} & R_{n,3}\\
 & & \\
NaN & NaN & NaN\\
L_{n+2,1} & L_{n+2,2} & L_{n+2,3}\\
\vdots & \vdots & \vdots\\
NaN & NaN & NaN
\end{pmatrix}
\end{array}\\
\searrow \qquad\qquad\qquad \swarrow\\
\textbf{Limb points}
\end{array}
\tag{5.3}
$$

5.5 Surgical Parameters

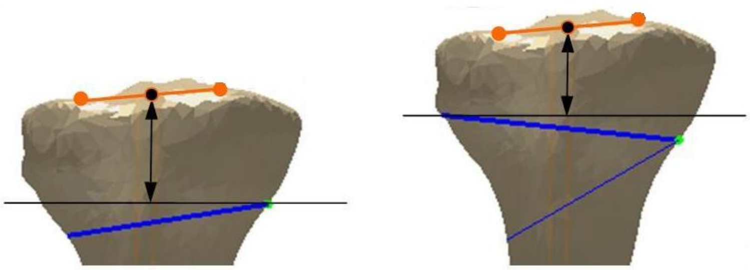
This section describes the surgical parameters that are computed in OstEOS including the distance between cutting plane and articulation, the correction angle, the wedge base height, which were mentioned earlier in section 3.4, and additionally the gap angle.

5.5.1 Distance between Cutting Plane and Knee Articulation

A certain minimal distance between cutting plane and knee articulation should be kept, in order to avoid bone fractures in femur condyles or tibial plateaus.
This distance is measured between a bone reference point and the highest plane point for the tibia and respectively the lowest plane point for the femur. The way this distance is defined is shown in figure 5.10.
For the tibia, the bone reference point is the point between internal and external tibial plate centers. The minimal distance to the cutting plane should be at least 15mm [39].
For the femur, the bone reference point is the trochlea. The cutting plane should be positioned at least above the condyles.
In the closing mode, the plane with the highest (respectively lowest) z value is chosen.
The distance is the difference in z direction.



(a) Distal end of the femur. Distance to the trochlea is calculated. Left: Opening mode. Right: Closing mode.



(b) Proximal end of the tibia. Distance to a point between the plateau centers is calculated. Left: Opening mode. Right: Closing mode.

Figure 5.10: Minimal distance between cutting plane and anatomical points near the knee joint.

5.5.2 Correction Angle

The definition of the correction angle is different in the three osteotomy modes. They are listed in the following table.

Osteotomy Mode	Definition Correction Angle
Closing	Angle between the cutting planes (n°after the cut)
Opening	Angle between the cut bone surfaces (0°after the cut)
Derotation	Angle of rotation (0°after the cut)

Correction Angle Determination

One of the most important questions in varus/valgus osteotomy planning is, how many degrees the bone has to be opened or closed to obtain optimal surgery results.
Computer support in calculating the needed correction angle can replace pencil-and-ruler techniques and be a useful help to the surgeon.
There are several planning methods which differ mainly in the clinical parameter chosen to be optimized: the FTMA angle or the joint centre distance (JCD).
Since the SterEOS generic bone model does not provide some of the necessary anatomical points to optimize the JCD, an algorithm based on the FTMA angle, inspired by the approach of Coventry[14], was implemented.
He proposed a first method for finding the ideal correction angle in 1973 [14]. His approach based on the anatomical (FTAA), and in later works, on the mechanical (FTMA) angle, became very popular. He applied the following formula on a 2D frontal radiograph:

$$\begin{gathered} CorrectionAngle = PostOpFTMA - PreOpFTMA \\ \beta = a' - a \end{gathered} \tag{5.4}$$

Mathematically, this formula can only be correct if the centre of rotation is equal to the knee centre. Since this condition never occurs, the formula is only an approximation.
By projecting the points on a plane perpendicular to the hinge axis, this problem can be solved using trigonometrical laws.
Figure 5.11 shows a right leg in frontal view with a valgus deformity. The FTMA value a is higher than the ideal value. A varus osteotomy with lateral opening can be performed in order to correct the malalignment.
When the lower part is rotated, the ankle centre (point B in figure 5.11) moves laterally. The postoperative position of point B will be A. According to Coventry, the tibia should be opened at an $a' - a$ angle. Observable in the figure 5.11, this correction angle $\widehat{ADB}$ will not lead to the desired FTMA angle. The bone must in fact be opened at an $\widehat{ACB}$ angle.
The following points are necessary to calculate the correction angle:

D	fix bone point
C	projected hinge axis
B	bone point to move

The condition for the reliability of this method is, that the hinge axis (projected to point C) is perpendicular to the plane on which the calculation is done.
This condition is not necessarily fulfilled for the tibia, because for angle calculations, the femur frontal plane is used as projection plane. In a tibial osteotomy, the projection result of the hinge axis on the frontal plane is not the required point but a line segment.
We tried to address the problem by projecting the point in the middle of the two hinge axis points on

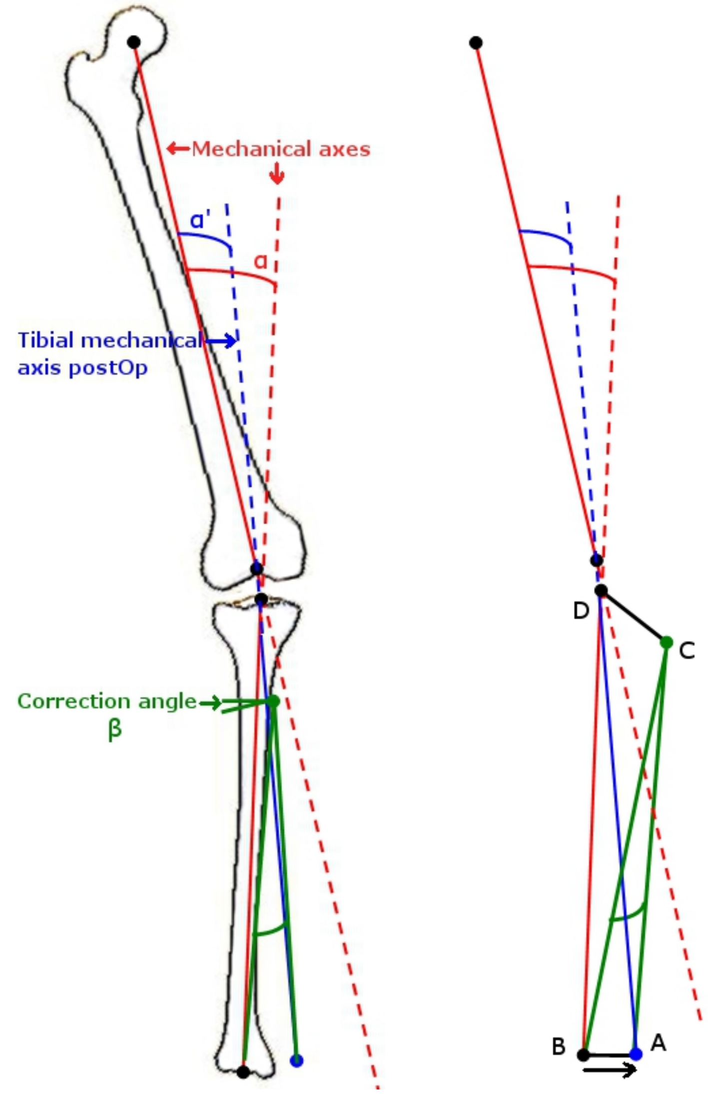


Figure 5.11: Scheme of a right leg in frontal view in order to determine the correction angle.

the frontal plane. However, the results remain unsatisfactory if the patients leg is flexed.
For now, in tibial osteotomy, the calculation is done with errors of some degree depending on the leg posture of the patient during acquisition. Future work should be done in order to find a solution for this problem.
The calculation steps in OstEOS are shown in the pseudo code below. For a femoral cut, the input parameters should be the following:

$$fix\_bone\_point = TrochleaCenter$$

$$bone\_point\_to\_move = FemoralHeadCenter$$

If the algorithm existed for the tibia, the following input parameters would be passed:

$$fix\_bone\_point = KneeCenter$$

$$bone\_point\_to\_move = AnkleCenter$$

```
Function: calculate_correction_angle()
/* calculate the required correction angle to achieve the desired ftma angle */
Input parameters:
     fix_bone_point, bone_point_to_move
     rotation_axis /* projection point of the rotation axis */
     preop_ftma, desired_ftma /* angles in degree */
Output parameter: corr_angle in degree
Procedure:

B = bone_point_to_move
C = rotation_axis
D = bone_point_fix
a = preop_ftma
a' = desired_ftma

/* lengths of the triangle edges */
CD = distance(C,D)
BD = distance(B,D)
BC = distance(B,C)
AC = BC

/* triangle edge vectors */
vDC
vDB

/* angles */
CDB = angle(vDC, vDB)
CDA = CDB - (a' - a)
CAD = arcsin(CD*sin(CDA)/AC)
ACD = 180 - CAD - CDA;

/* calculate the unknown distances AD and AB */
AD = square_root(AC^2 + CD^2 - 2*AC*CD*cos(ACD))
AB = square_root(AD^2 + BD^2 - 2*AD*BD*cos(a' - a))

/* calculate the correction angle */
corr_angle = arccos(1-((AB^2)/(2*(AC^2))))
```

5.5.3 Gap Angle

The gap angle only exists in the closing mode. It is the angle between the cut bone surfaces; after the cut it is equal to the correction angle. When the bone is closed completely, the two surfaces are put on each other and the gap angle is 0°.

5.5.4 Wedge Base Height

The wedge base height parameter is important in opening and closing osteotomy.
In the opening mode, it defines a fitting artificial or natural bone wedge. In the closing mode, besides the correction angle, is it used to find the correct cut position in the real surgery procedure. It also helps to assess the loss of natural bone matter.
The wedge base height is the difference in z direction between one point U from the upper cutting face and one point L from the lower cutting face. U and L are the pair of vertices that have the biggest of the minimal euclidian distances between upper and lower points. Appendix A.3.2 shows the algorithm for the wedge base height calculation.

5.6 Important Use Cases

5.6.1 Cutting Plane Positioning

This section describes the subroutine of cutting plane positioning and the characteristics for the three osteotomy modes. This subroutine can be found in the activity diagram in figure 5.1 in the dashed box in state 2.
The GUI provides buttons which translate the plane about 1mm or rotate it about 1°in support of placing of the cutting plane. In all three modes, a button allows the fitting of the cutting rectangle size to the bone amplitude at the certain level.
This is useful in opening and closing mode in order to fit the hinge axis on the bone surface. Figure 5.12 shows the adaptation result.
If the plane is moved too near to the articulation, it is highlighted in red to warn the user that the minimal distance is exceeded. The distance is continuously displayed in millimeters through the GUI.

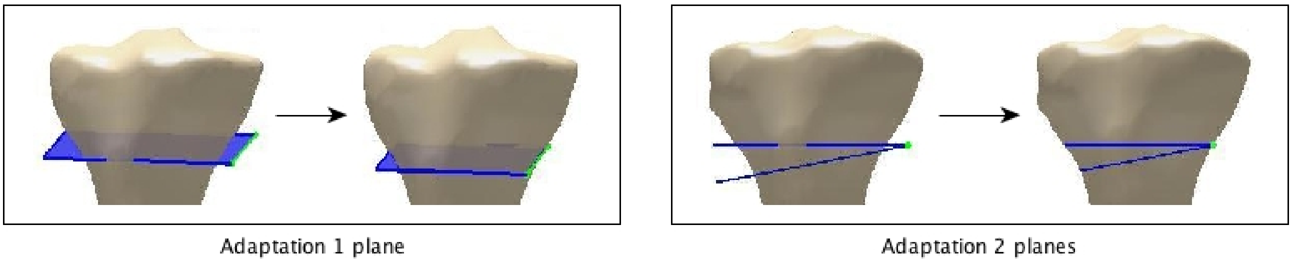


Figure 5.12: Adaptation of the cutting plane(s).

Opening. In the opening mode, there is one cutting plane, which can be translated up and down along the z axis and rotated about its hinge axis.

Derotation. In the derotation mode, there is one plane without hinge axis. The plane can be translated along the z axis. The plane rotation buttons are not activated.

Closing. In the closing mode, there are two planes, which can be translated along the z axis and rotated about the plane's hinge axis.
The two cutting rectangles have one common edge which represents the hinge axis. In order to preserve this axis the planes should not disperse. Therefore a translation always applies on the two planes.
In contrast, the planes are rotated individually by focussing one of them.
Additionally to the transformation buttons, the orientation of the planes can be changed by typing the desired angle between the cutting planes into an input field in the GUI. The desired correction angle is achieved by leaving the focussed plane unchanged and orientating the other one relatively to it.

Another possibility to manipulate the planes's orientation is to type the value of the desired FTMA angle in a destined field in the GUI. Doing so, an algorithm to determine the required correction angle is run (cf. section 5.5.2). The cutting planes are orientated accordingly.
The closing mode also provides a preview of the postoperative parameters. They are computed by simulating the cut and closing the current angle between the cutting planes. In this process, the cut and alignment is only executed on the data the parameter calculation is based on: the `lower_limb` matrix. The visualized 3D model does not change. This allows the user to have a quick postoperative preview without executing the cut on the 3D model.

5.6.2 Lower Part Alignment

After the cut, the lower part can be moved in order to align the axes. Whenever the lower bone part is moved, both visual and anatomical information are updated and postoperative parameters are computed and displayed next to the preoperative parameters in the GUI.
Right after the cut, the pre and postoperative parameters for the operated leg are identical. But when the lower bone part is moved, the postoperative parameters change. There are updates in the GUI parameter table; and a parameter that changes in comparison to its preoperative one is highlighted. If the femur is cut, the tibia moves with the lower part.

This section describes the subroutine of aligning the lower bone part and the characteristics for the three osteotomy modes. The position of this subroutine in the entire workflow is illustrated by the dashed box in state 3.
The lower bone part can be manipulated in different ways. Amongst others, the user can click on buttons which rotate it about 1°or translate it about 1mm. In all three modes the lower part can be translated via click buttons in x and y direction; thereby moved from left to right and from front to back.

Opening In the opening mode, the rotation of the lower bone part around the hinge axis can be attained stepwise, clicking on buttons, or by typing the desired correction angle into an input GUI element. Furthermore the desired FTMA angle can be typed in a destined field in the GUI. The lower part is rotated accordingly to the computed correction angle.

Closing In the closing mode, it is usually desired to close the formed gap completely. With a click on a special button this alignment is done: the lower bone part is rotated through the correction angle around the hinge axis. The rotation can be done stepwise as well.

Derotation In the derotation mode, the lower bone part can be rotated around an axis defined by the normal of the cutting plane and the rectangle centre point illustrated in green in figure 5.7.
The lower part can be rotated and translated stepwise, clicking on buttons.

5.7 GUI Layout

The GUI has been realized in one figure window which is filled step by step with elements. This choice has been made for reasons for simplicity in the GUI handling and its implementation. The GUI layout is determined by the current program state.
Appendix A.4 shows screenshots of the four interface states. The buttons which provoke the principal callback functions and stimulate the transition to the next state, are emphasized.

Chapter 6

Implementation

This chapter describes the prototype characteristics and the used software tools.
Finally, the architecture of OstEOS is presented.

6.1 Prototype Characteristics

The prototyping of a 3D osteotomy planning software was necessary because the software requirements could not be completely assembled a priory. To accomplish this task it was very helpful to have a prototype as a basis for discussions with surgeons and as well with colleagues.
In order to develop an effective application, the cooperation and early feedback of the prospective users was essential and helped to correct functional errors quickly.
The analysis of the clinical needs, the assembly of software requirements and the development of a functional prototype received priority during this work.
The developed software tool is a so called *Throw-away prototype*[1] helping to discover requirements and problems and discard them.
At the base of the validated system requirements, the application will be integrated later on in the global SterEOS system, using some other development process. All these conditions motivated the choice of the used tools.

6.2 Used Tools

The application development was carried out under the operating system Windows XP.
The prototype has been implemented in MATLAB, a high-level programming language and interactive development environment. MATLAB comes with mathematical functions, graphics functions for data visualization and a tool for building graphical user interfaces (GUIDE).
We had the Version R2007a[2] and toolboxes for the handling of DICOM images and image processing for our disposal.
Providing lots of functions, MATLAB is an established programming language for prototypes.

[1] http://www.comp.lancs.ac.uk/computing/resources/IanS/SE6/Slides/PPT/ch8.ppt (accessed 16-08-2010)
[2] http://www.mathworks.com/access/helpdesk/help/toolbox/compiler/rn/bq249ht.html (accessed 16-08-2010)

6.3 Prototype Architecture

The prototype was implemented through MATLAB script files (.m files). The graphical user interface was designed with the GUIDE feature of MATLAB.
Scheme 6.1 shows an overview over the architecture of OstEOS with its principal functional methods and their interactions. Functions concerning the GUI layout are not mentioned.

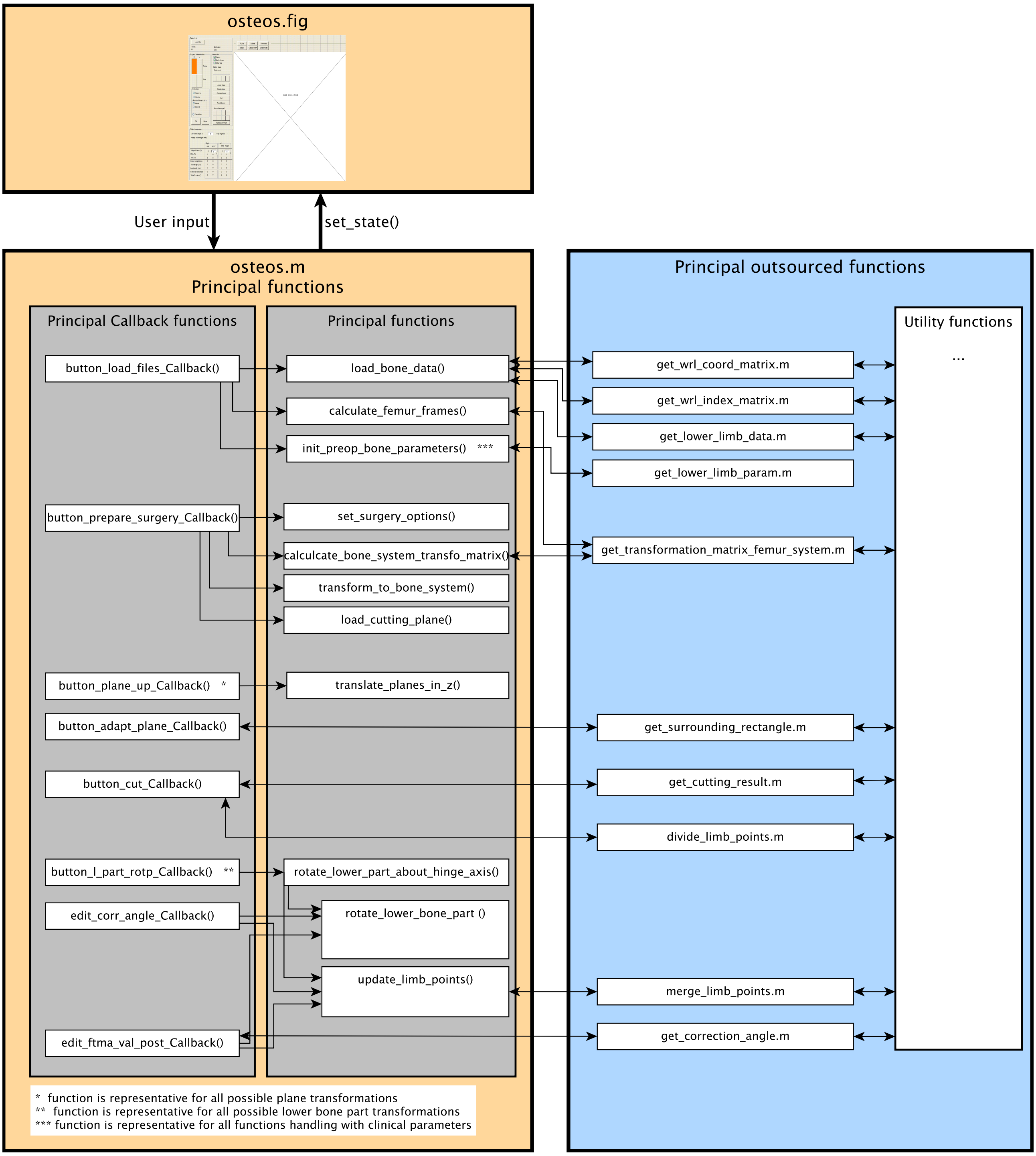
A .fig file for the GUI window and an associated .m were created. All functions which directly or indirectly interact with the GUI are situated in the .m file. These are the call-back functions and functions that access and manipulate the handles structure[3]. This structure was automatically generated and contains all the GUI components (buttons, axes, panels, etc.). Due to the fact that it is passed to each callback function, the handles structure is useful in order to store any global data. The **handles structure** was used to save:

- vertices and indexes of bones
- vertices of bones in BCS
- anatomical limb points
- handles to graphical objects (bones, planes, axes, upper and lower part)
- transformation matrix from machine to bone coordinate system
- user's choice of the surgery
- values of surgical parameters

The call-back functions are executed as response to button click or to an edit entry. The process which is executed thereupon, is subdivided in steps which are represented in proper functions.
All functions which do not access or manipulate the handles structure, were implemented in proper .m files.

[3]http://www.mathworks.com/support/tech-notes/1200/1205.html#handles%20structure (accessed 20-09-2010)

Figure 6.1: OstEOS system architecture.



Chapter 7

Verification and Validation

The aim of verification and validation is to demonstrate that the application OstEOS meets the practical demands of surgeons and serves a purpose as prototype.
User feedback was sought not only at the end of the development process, but also during the intermediate states. Prototyping OstEOS was an iterative process: current versions have been presented to surgeons and colleagues, new aims were defined, and afterwards the application was improved and corrected.
Intermediate tests and evaluations were done, but are not the focus of this chapter. Instead, the chapter discusses the final verification and validation and whether OstEOS as a prototype brought the desired effects.

7.1 Motivation for the Prototype

The aims of the prototype were completely achieved. The clinical needs for osteotomy planning could be clarified and a technical solution was implemented.
The software requirements could be assembled. The components and functionalities of OstEOS (cf. section 5.1) are the basic and most important features that an osteotomy planning tool should provide. There are more advanced features imaginable to allow the planning of more complex osteotomies. Those future prospects are explained in section 8.2.
OstEOS was a good base for discussions with surgeons and colleagues during advancement presentations to future clients as well as firm intern meetings. The presentation to expert surgeons allowed the collection of early feedback and to correct functional errors quickly. We stayed in contact with a French and a Canadian surgeon and let them test the application intermediately. It was interesting to compare their often opposite opinions. This showed us that it is important to design a multifunctional software to reach a large client spectrum.

7.2 Success Criteria

The following success criteria were governing the implementation process and were validated by means of final user tests. Effectiveness, efficiency and satisfaction originate from the ISO standard for usability[1] and were presented in a lecture of Marcus Nitsche [29].

[1]ISO Standard 9241-110: Ergonomics of human-system interaction

Effectiveness

An application is effective if it fulfills its intended purpose and if the user is able to achieve certain goals with it. The effectiveness can be scaled by measuring the accuracy and completeness with which the tasks are realized.
The user should be able to plan a real patients case with the application. OstEOS should answer questions concerning the surgery type as well as the cut position and the correction angle.

Efficiency

Efficiency is the relation between effectiveness and the resources (time, memory) needed for achieving a certain goal. An application is efficient if the effectiveness is high using little resources.
The purpose of the application is to enable the user to do an osteotomy planning in less than five minutes. This is the minimal time surgeons need to plan their operation manually with a pencil and a ruler on a 2D radiography. Depending on the number of clinical parameters that are needed, a manual planning can take up to 15 minutes. The calculation of angles is the time limiting factor.

Satisfaction

The users satisfaction with a system is achieved if the user feels comfortable during the employment of the software and if he adopts a positive attitude towards it.

Correctness of Parameter Calculation

The correctness of parameter calculation is a success criterion which should not be neglected, but which is not crucial for this prototype. Nevertheless this section gives an evaluation for the clinical and surgical parameters used in OstEOS.

Clinical Parameters. The calculation rules for clinical parameters were adopted from SterEOS. There are parameters that are not calculated in SterEOS because either the needed reference points are not present in the generic bone model or the calculation with 3D points is not yet validated.
The acceptance of a calculation rule for a clinical parameter precedes a long, clinical accepted and reliable test and validation period. This is the reason why the pertinence and correctness of specifications for new parameters, developed in the framework of this prototype, were not validated.
This is the case for the definition of the tibial plate and the tibial slope. The mathematical definitions for these parameters can only be considered as primary, unvalidated concepts. For this reason the tibial slope does not appear in the OstEOS GUI. Regardless, the definition of the tibial plate is used as the basis for the used tibia coordinate system.

Surgical Parameters. The calculation rule of the correction angle as the angle of opening and closing is widely accepted. The transition from traditional 2D planning to 3D did not cause any problems, because this angle is defined as the angle between the cut bone surfaces respectively between the cutting planes.
For derotation osteotomy it is straight forward to measure the angle by which the lower bone part is rotated.
The algorithm of the wedge base height was defined with respect to inserting a filling wedge in the opened bone.
The distance between the cutting plane and the knee articulation in 3D was inspired by the 2D definition and its validity was confirmed during an expert talk with Eric Stindel [38].

7.3 Clinical Validation

In order to validate the prototype in the clinical sense, the usability in terms of efficiency, efficacy and satisfaction has been tested via user tests.

User Dest Design

The test was carried out with two surgeons. They were asked to plan and virtually execute three osteotomies using OstEOS, performing one opening, one closing and one derotation on pathologic bone models.
In order to allow a comparison of the 3D planning with traditional planning on 2D radiographies, the test users were already familiar with osteotomies.

Person 1 is a surgeon interested in computer support for surgery who helped in earlier states of the prototype to improve it. He typically plans osteotomies on 2D radiographs.
Person 2 is a pediatric surgeon who was not familiar with software tools for osteotomy planning. She had a brief introduction and demonstration of OstEOS before trying it herself. This surgeon does approximate planning and uses rarely planning sketches, because there is always unstableness in further anatomical development due to the growing of children.

User Test Results

The time taken for the planning of one surgery by person 1 was 3-4 minutes. The satisfaction was high and the feedback was mainly very positive.
There were no barriers performing the planning with OstEOS; wrong decisions could be easily undone with the help of reset buttons. The main driver for incorrect inputs were unintuitive button labels, which were changed afterwards.
The approach to the osteotomy simulation and the steps to attain a cut and axis alignment were clear. Person 1 was able to get the answers on his questions; for example where to place the cutting plane, how many degrees to open the bone and which size of wedge to use to fill the resulting gap.
The only negative feedback was in regard of the interaction with the 3D scene using the standard MATLAB functions for panning, zooming and rotation.
However, the three-dimensional aspect helped significantly with the comprehension of the shape of bone and wedge. The possibility to navigate in a 3D space also allowed the surgeon to better understand the patients anatomy. The pre and postoperative parameters, updated and displayed in real time, were received with enthusiasm.
Person 1 was satisfied with the application. He enjoyed testing the prototype and even asked for a version to show it to colleagues.
Person 2 took 5-10 minutes and had been helped when she was stuck. She found the tool very useful but in her opinion, one function was missing: the possibility to locate the centre of deformity (CORA). This interest arises from her patient category. Children usually do not suffer from osteoarthritis; but the motivation for osteotomy is rather a deformity in the bone itself.
She identified another clinical need: the ability to plan osteotomies on the two legs at the same time. A surgery at both legs is rarely performed on adults because of the long, postoperative period of disability. Nevertheless on children it is done quite often.

User Test Conclusion

Effectiveness could be validated partially. Person 1 was able to carry out a complete osteotomy planning. On the other hand, the test of person 2 showed that further functionalities need to be implemented, in order to enlarge the spectrum of supported patient cases.
The test showed that osteotomy planning can be done in three minutes by experienced surgeons that are familiar with OstEOS.
The computed clinical preoperative and postoperative parameters contributed a lot to the shortening of the planning time compared to the traditional planning without OstEOS.
Besides from the surgeon is demanded less mental effort. As a conclusion, the efficiency has been validated.
The satisfaction was high. Both test persons were interested in using a tool like OstEOS in clinical every day life. The predominant reaction was very position and the three-dimensional representation was a major motivating factor.
Nevertheless both test persons gave ideas for enhancements. In order to provide a better and more precise navigation in the 3D bone scene, special functions for panning, zooming and rotation should be implemented.
The MATLAB panning function does only work, if the user drags an object. The panning function should work in all cases. The behavior of the MATLAB zooming function is not clear if the user clicks and moves the mouse, holding the mouse button down. It is not predictable if a smooth zooming takes place, or if a rectangle is spanned, which will be expanded on the whole windows when the mouse button is released. The zooming function should be clear. Using the MATLAB rotation function the rotational effect is hard to control. Additionally to this free rotation, functions could be provided to allow limited rotations about certain axes, e.g. the axes of the bone coordinate system. A button, allowing the user to get back to the initial global view, should be provided as well.
The success criteria were met even though there should be implemented supplementary functions in order to satisfy a larger user group.

Chapter 8

Conclusion and Future Work

8.1 Conclusion

The goal of this work was the development of a software prototype for the planning of lower limb osteotomy. It included the analysis of anatomical background and clinical needs. All specifications and requirements for a 3D planning tool have been explored and realized for the most part.
The implemented prototype OstEOS met all demands and is a valuable base for further developments. During tests, surgeons evaluated the usability of OstEOS and adjudged it very positive.
OstEOS allows the planning of many types of osteotomy and thus stands out from other 3D planning tools which are often limited to high tibial osteotomy.
We can conclude, that the three-dimensional aspect enriches the planning in comparison to 2D tools, but that it holds further challenges. Most notably it is the interaction with the 3D scene that requires practice. Ideally, a planning tool should allow a realistic simulation of all manipulations that can be done during the surgery in the operating block. However, the realization on a screen with a good control through the user is challenging.

8.2 Future Work and Directions

There are many directions for future improvements of OstEOS. The three main categories are: increasing the number of features, the automation of processes, and the improvement of the user interface.
A future version of this tool should allow the planning of more advanced osteotomies. One should be able to plan combined opening and derotation osteotomies, to simulate a non planar cut or any alignment, and to plan double level osteotomies, allowing more than one cut, on femur and tibia at the same time.
In order to augment the possibilities of osteotomies, the degrees of freedom for the cutting plane, and thus for the lower bone part, should be increased. This will make it necessary improve the GUI structure to allow a better user control. There are also simple ideas for improving the GUI, as the visualization of clinical and surgical parameters in the bone scene, additionally to the display in a table.
Advanced planning software should provide functions to find the centre of rotation of angulation (CORA). Paley and Pfeil presented this quite geometrical planning approach which is determined with osteotomy rules [30]. By putting those osteotomy rules into algorithms, the ideal cutting position and alignment could be calculated automatically.
Furthermore, it seems possible to extend the two dimensional approach of OASIS modeling the forces to 3D and integrate it (cf. section 4.1).

Appendix A

Appendix

A.1 OstEOS input data

File structure FemurG.wrl

```
FemurG.wrl:
#VRML V2.0 utf8
Group {
children [
Shape {
appearance Appearance {
 material Material {
  diffuseColor 1 1 1
 }
}
geometry IndexedFaceSet {
creaseAngle 3.14159
solid FALSE
coord Coordinate {
point [
11.417047  45.012168  657.886066,
...
]
}
coordIndex [
4, 0, 11, -1,
...

 ]
}
}
]
}
```

File example LowerLimbData.txt

```
Computation date: 26/07/2010, time: 17h07min51s
Patient Name: TEST
Lower limb Laterality: GAUCHE

Femur data
Trochlea center: (x = -47.76886182, y =  91.02407224, z =  744.64610817)
Medial condyle center: (x = -70.28137029, y =  67.29741416, z =  735.27265340)
Lateral condyle center: (x = -62.79916203, y =  123.05203101, z =  739.16668920)
Femoral head center: (x = -74.43308155, y =  106.64631249, z =  1156.73202665)
Femoral neck inferior base center: (x = -77.27306416, y =  131.44879899, z =  1127.70161989)
Medial condyle posterior point: (x = -90.27494493, y =  70.47293674, z =  756.56906974)
Lateral condyle posterior point: (x = -83.50853092, y =  120.52810005, z =  756.27785596)
Great trochanter center: (x = -96.92385929, y =  148.61007812, z =  1144.12529089)
Center of femur proximal inferior neck section: (x = -77.27306416, y =  131.44879899, z =  1127.70161989)
Femur proximal superior diaphysis superior point: (x = -83.53378429, y =  139.82028531, z =  1111.57195449)
Femur proximal superior diaphysis inferior point: (x = -65.97810722, y =  129.15863299, z =  1031.52118740)
Femur distal inferior diaphysis superior point: (x = -53.12039384, y =  110.98131546, z =  886.73086336)

Tibia data
Knee center (center of proximal tibia): (x = -57.88057861, y =  91.56647269, z =  731.07762097)
Ankle center (center of distal tibia): (x = -88.79071617, y =  92.34077160, z =  388.44530976)
Center of external tibial plate: (x = -59.77211817, y =  111.99183929, z =  726.86634095)
Center of internal tibial plate: (x = -57.54593149, y =  71.28193940, z =  723.91360337)
Center of external posterior tibial plate: (x = -78.32826317, y =  118.34928522, z =  714.41618971)
Center of internal posterior tibial plate: (x = -78.70498141, y =  79.36443011, z =  712.55145912)
Distal point of external malleolus: (x = -105.36178539, y =  115.66043433, z =  370.06108435)
Distal point of internal malleolus: (x = -74.43323289, y =  78.67327235, z =  382.08451504)
Center of external malleolus: (x = -110.14049028, y =  117.84966436, z =  376.22296643)
Center of internal malleolus: (x = -75.74436854, y =  73.85174173, z =  389.84591935)
-------------------------------------------------------------
```

A.2 Specification of osteotomy

Surgery goal

Correction sense	Parameter to correct	Projection plane
Valgus	FTMA	Frontal
Varus		
(Flessum)		(Lateral)
(Recurvatum)		
Internal	Femoral torsion	Plane ⊥ to femoral mechanical axis
External		
Internal	Tibial torsion	Plane ⊥ to tibial mechanical axis
External		

Realisation

Mode	Number of cuts	Position of the wedge	Bone transformation	Rotation axis
Opening	1	medial	Rotation +Translation	⊥ to the frontal plane
		lateral		
Closing	2	medial		
		lateral		
Derotation	1	no wedge		defined by normal and centre point of the cutting plane

Bone to cut

Femur
Tibia
(Fibula)

Cut level

Proximal	Near to the torso
Distal	Away from the torso
Any	

Cut character

Cut	Form
planar	Approximates a plane, cut direction does not change
(biplanar)	Cut direction changes one time
(curvilinear)	Cut direction changes constantly, shape of the cutting face is curved
(other)	

Table A.1: Osteotomy specifications. All osteotomies, besides the ones in brackets, can be simulated with OstEOS.

A.3 Algorithms

A.3.1 Mesh Cutting

```
Function: get_cutting_result()
Input parameters: coords, index, plane
Output parameters: lower_part_coords, upper_part_coords,
     lower_part_index, upper_part_index
Procedure:

/* 1: Divide the vertices in lower and upper part */

Allocate matrices for upper and lower part vertices, with 4 columns:
     x, y, z coordinates and old index position
lower_part_coords
upper_part_coords

Allocate matrices for the upper and lower part index, with 3 columns:
     indexes of the 3 points
lower_part_index
upper_part_index

Allocate a matrix that will contain for each vertex the index in the upper part
     and the index in the lower
index_map

For i=1 to number of vertices
     if point coords(i) is on the right side of the plane then
          Add coords(i) to lower_part_coords (stock old index and coordinates)
     else
          Add coords(i) to upper_part_coords (stock old index and coordinates)
     end if
end for

/* 2: Divide the index in lower and upper part */

Allocate matrix that will contain the triangles that are cut, with 5 columns:
     indexes of the 3 triangle forming points and indexes of the 2 intersection points
intersected_triangles

Allocate matrix that will contain intersection points, with 3 columns:
     x, y, z coordinate
intersection_points

For i=1 to number of indexes
        if all 3 points are lying below the plane then
                stock them in the lower_part_index matrix
        else if all 3 points lying above the plane then
                stock them in the upper_part_index matrix
        else
                find the two edges of the triangle that are cut
```

```
                stock the intersection points in the intersection_points matrix
                stock the intersected triangle in the intersected_triangles matrix
        end if
end for

/* 3: Add intersection points and edges between them to the lower and upper part */

Allocate matrices for stocking edges between two intersection points with 2 columns:
     indexes of the two intersection points coming from the same triangle
ispoint_index_u
ispoint_index_l

Allocate matrix for stocking information about the position of an intersection point
     in coords matrices with 2 columns:
     index in upper_part_coords, index in lower_part_coords
position_map

For i=1 to number of intersected triangles
     Get the two corresponding intersection points of the triangle with the help of
          intersected_triangles and intersection_points matrices

     Add them to lower_part_coords
     Add the indexes of the 2 intersection points to ispoint_index_l
     Add them to upper_part_coords
     Add the indexes of the 2 intersection points to ispoint_index_u

     Add their indexes in the position_map

     if one triangle point below and two triangle points above the plane then
          add one triangle to lower_part_index
          add two triangles to upper_part_index
     else
          add one triangle to upper_part_index
          add two triangles to lower_part_index
     end if
end for

/* 4: Triangulate the polygon of intersection points to close the hole */

Matrix cutting_face_triangles_u = Convex Polygone Triangulation of ispoint_index_u
Matrix cutting_face_triangles_l = Convex Polygone Triangulation of ispoint_index_l

Make sure that the triangle normals are pointing outside

Add cutting_face_triangles_u to upper_part_index matrix
Add cutting_face_triangles_l to lower_part_index matrix
```

A.3.2 Wedge Base Height Calculation

```
Function: calculate_wedge_base_height()
Input parameters: upper_face and lower_face
     (two matrices with the vertices of the upper/lower face of the wedge)
Output parameter: height
Procedure:

/* 1: Find for each point of the upper_face matrix the point with the
     smallest distance in the lower_face matrix:
     stock the point index and the distance */

n = number of points in upper_face matrix
Allocate n*2 matrix min_dist_points

For i=1 to n
     min_distance = 1000000
     index_of_point_with_min_distance = 0

     For j=1 to number of points in lower_face matrix
          dist = Euclidian distance between points upper_face(i) and lower_face(j)
          if dist < min_distance then
               min_distance = dist
               index_of_point_with_min_distance = j
          End if
     End for

     min_dist_points(i) = index_of_point_with_min_distance, min_distance

End for

/* 2: Get the biggest of the minimal distances and the associated point pair */

Max_distance point_index = maximum(min_dist_points(:,2))
upper_point = upper_face(point_index)
lower_point = lower_face(min_dist_points(point_index))

/* 3: Calculate the distance between the two points in z direction*/

height = abs(upper_point(3)-lower_point(3))
```

A.4 GUI States

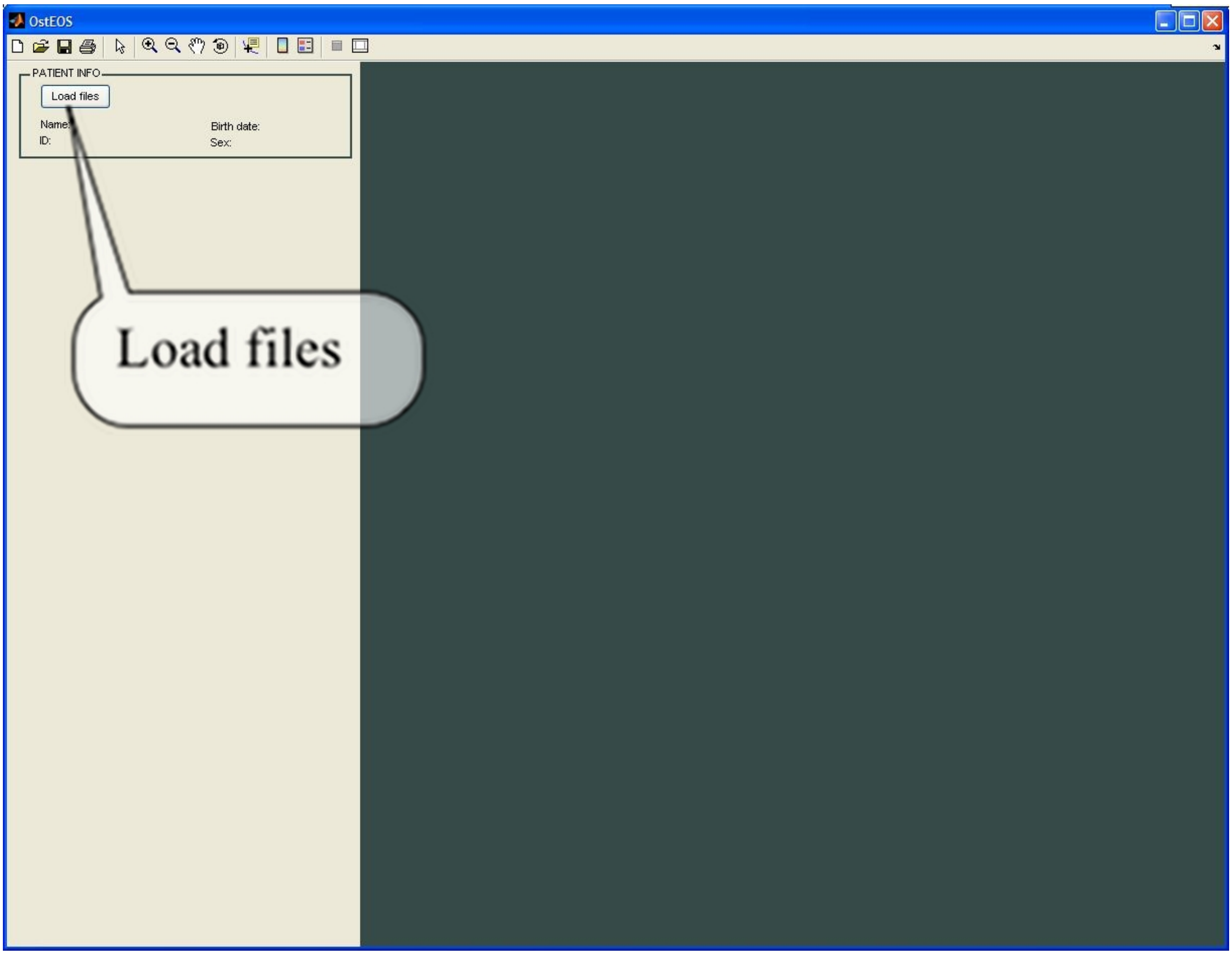


Figure A.1: GUI in state 0.

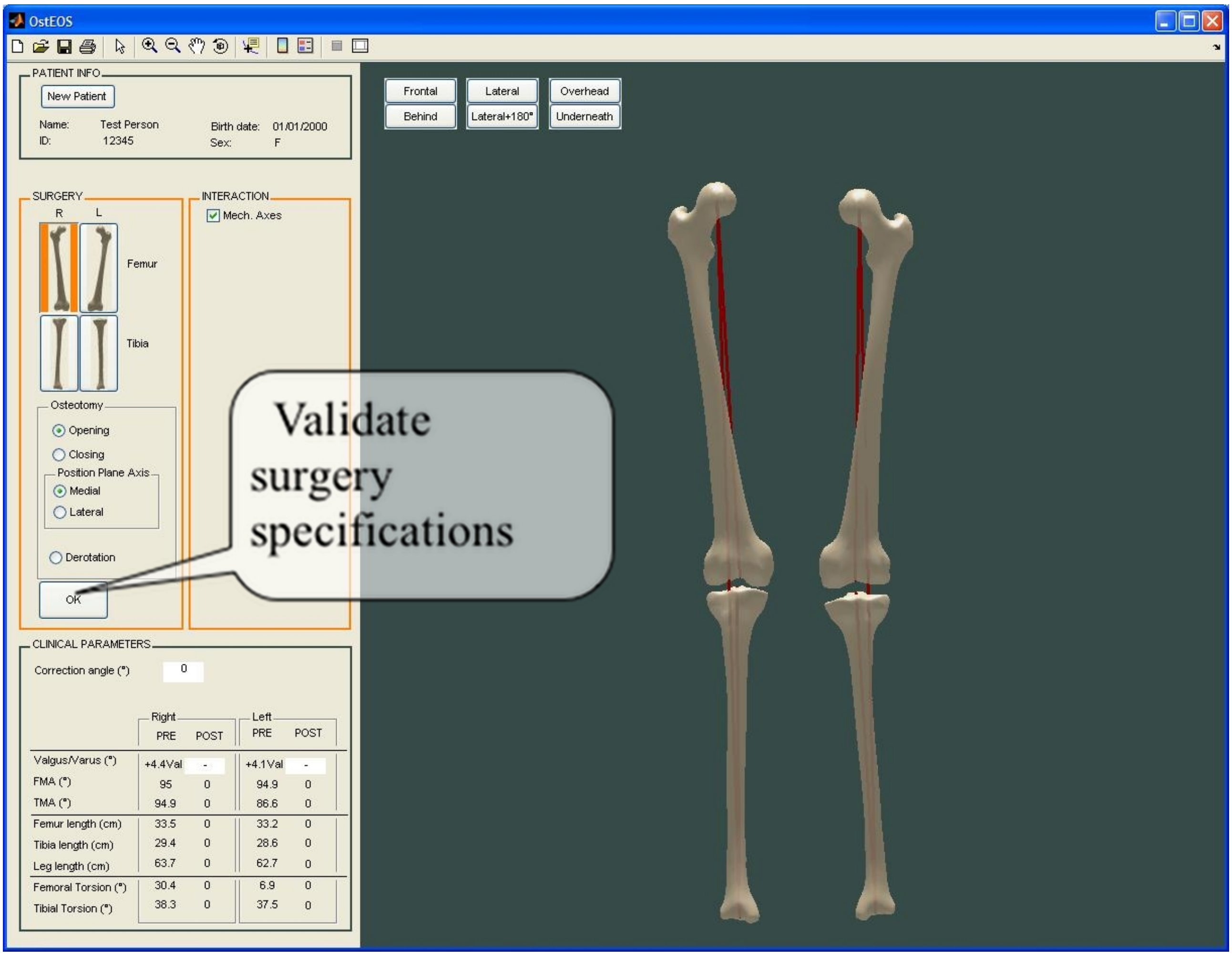


Figure A.2: GUI in state 1.

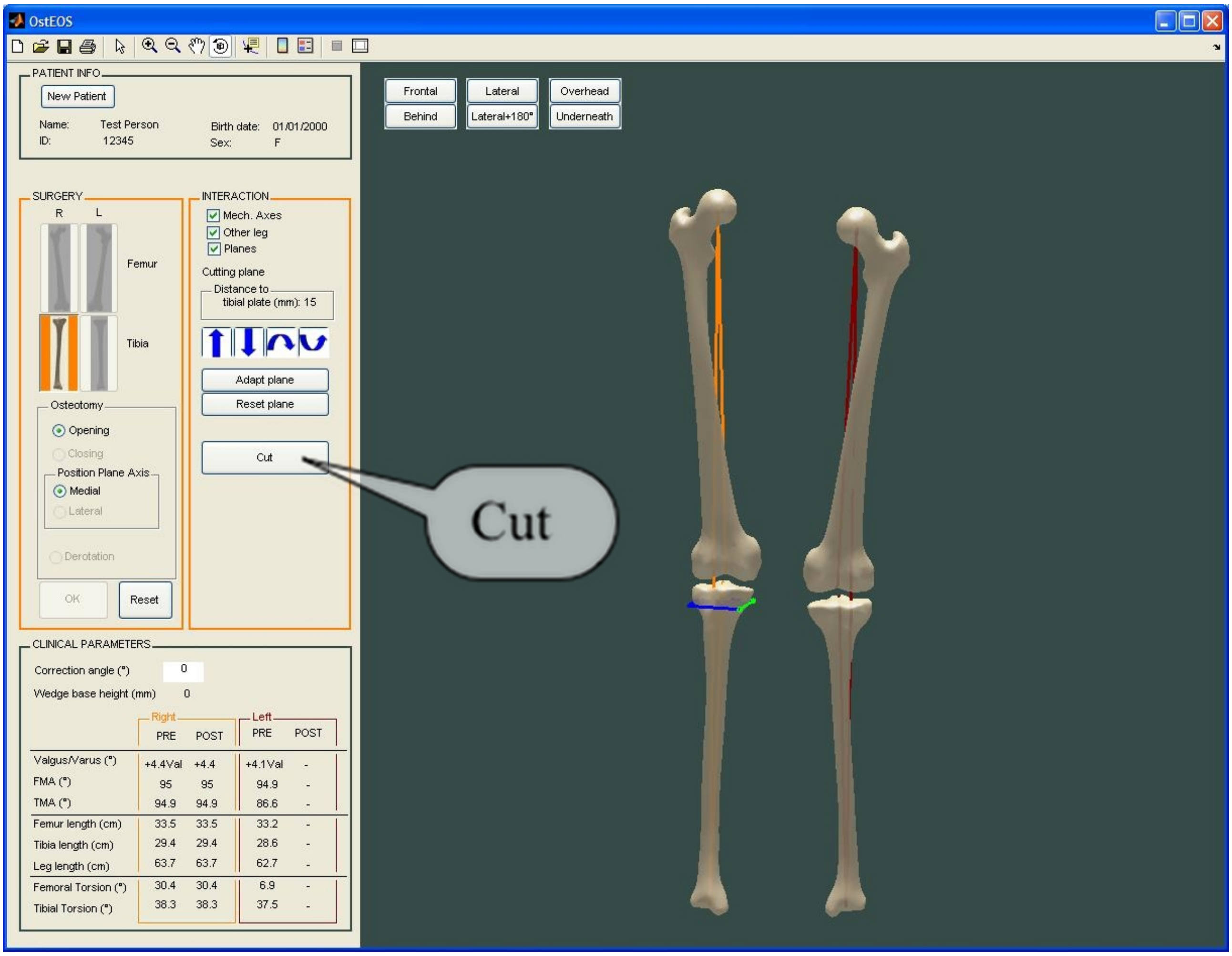


Figure A.3: GUI in state 2.

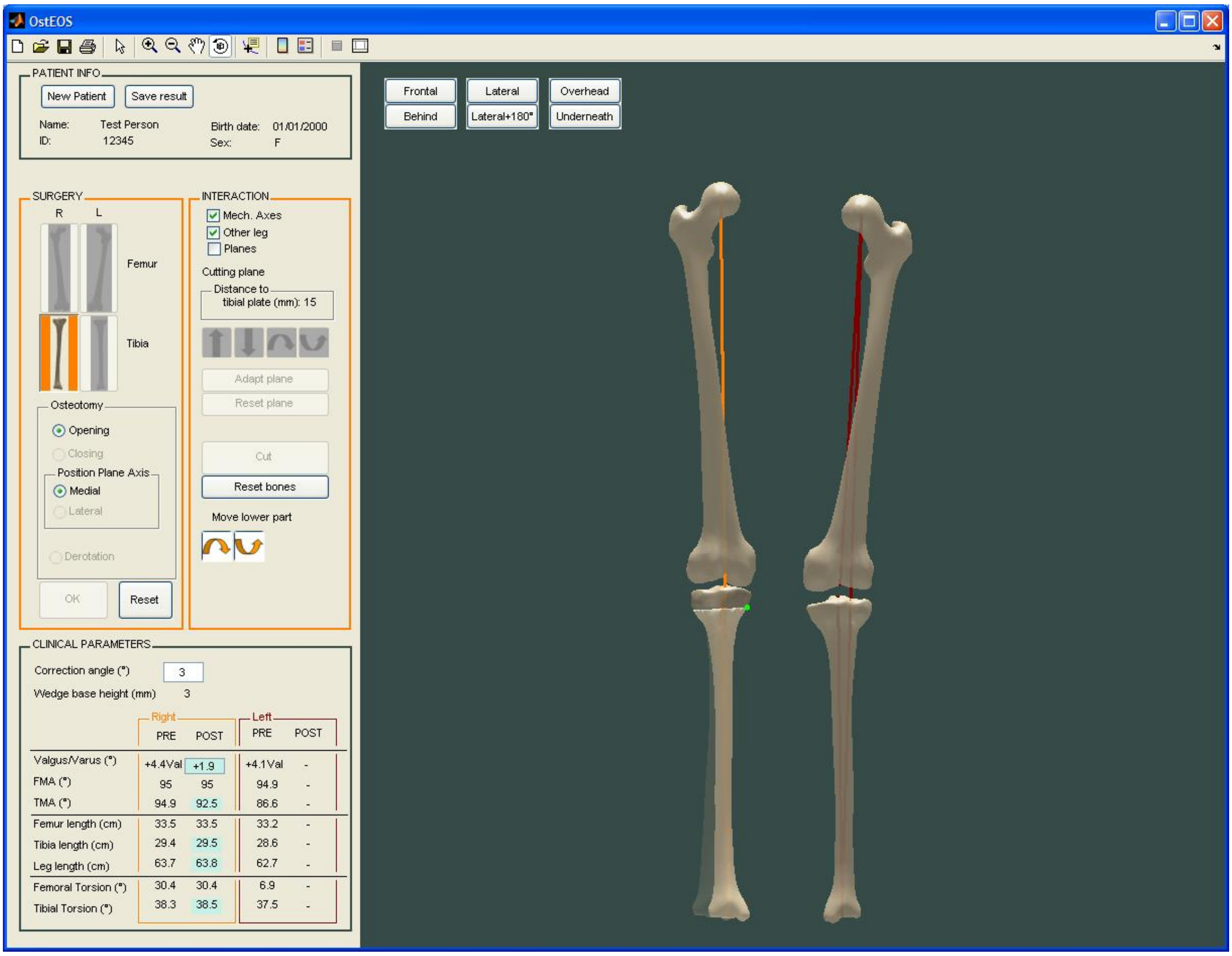


Figure A.4: GUI in state 3.

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List of Abbreviations

MRI	magnetic resonance imaging
CT	computed tomography
CAS	computer-aided surgery
GUI	graphical user interface
HCI	human Computer Interaction
AP	anterior Posterior
LAT	lateral
M	medial
L	lateral

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