Chapter 37: Image-Based Surgery Planning

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Abstract

This Chapter presents the general concepts and technical aspects of image-based surgery planning. It starts with a brief historical account of image-based surgery planning, its evolution, and its current use today. It then presents a brief overview of the general concepts of image-guided surgical planning and present two types of applications: 1) surgery planning for bone fracture surgery in orthopaedics; 2) surgery planning for keyhole neurosurgery and percutaneous ablations. It then concludes with a brief discussion on trends and perspectives in image-guided surgery planning.

Keywords

Image-guided surgery; preoperative planning; computer-assisted surgery; decision-making processes; medical imaging

1. Background and motivation

The planning of surgeries based on preoperative images has a long history, starting with the first film X-ray images at the beginning of the 20th century. With the proliferation of clinical imaging modalities in the recent past, including X-rays, ultrasound (US), computed tomography (CT) and Magnetic Resonance Imaging (MRI), it is now possible to assess the patient condition, make a diagnosis, explore the treatment options, and plan the surgery ahead of time. Image-based surgery planning allows the surgeon to consider a variety of approaches, evaluate their feasibility, foresee possible complications, and optimize the treatment so as to reduce the risk of injury and improve the surgical outcome. The preoperative images allow the surgeon to visualize and locate the surgical access area, to plan the position of surgical instruments and implants with respect to the patient anatomical structures, and to assess the safety of their location and of the surgery execution. Preoperative images allow building patient-specific anatomy and pathology models which can then be used for advanced planning based on optimization and simulation. Preoperative planning based on these models allows the customization of the surgery to the specific characteristics of the patient. The rise of minimally invasive surgery, and more recently of image-based intraoperative navigation and medical robotics, has further increased the need for image-based surgery planning.

The types of surgeries for which image-based planning is used spans a very wide range across surgical procedures and specialties, e.g. orthopaedics, neurosurgery, abdominal surgery, and urology, to name only a few. By their very nature, each type of surgical procedure has its own characteristics, constraints, and requirements. For example, in orthopaedic surgery, preoperative planning systems are used for the selection and sizing of joint replacement

implants and fracture fixation hardware and for their optimal positioning based on the patient bone geometry and bone quality derived from the patient preoperative CT scan. Advanced biomechanical analysis includes patient-specific kinematic and dynamic simulations of knee and hip joints, bone loading analysis, and fracture risk analysis. In stereotactic neurosurgery, the planning consists of determining an appropriate access location on the patient skull and defining a safe insertion trajectory to reach a brain tumor, perform a biopsy, and deliver therapy as needed.

Over the past 30 years, many preoperative planning systems have been developed, and some of them are in routine clinical use. In fact, some surgeries, e.g. radiation surgery and stereotactic neurosurgery, cannot be performed without accurate image-based preoperative planning. More broadly, the availability of Computer Assisted Surgery (CAS) technology, of which image-based preoperative planning is a key component, allows clinicians to explore more treatment options and surgical scenarios and execute them more precisely and reliably.

A detailed survey of image-based surgery planning is outside the scope of this Chapter. In the following, we will briefly outline the general concept of image-guided surgical planning and present two applications: 1) reduction and fixation planning for orthopaedic bone fracture surgery, and 2) trajectory planning for keyhole neurosurgery and percutaneous ablations. We chose to include these case studies because they cover a variety of anatomies, types of organs, and types of planning. In particular, they include three types of surgery planning (neurosurgery, orthopaedic surgery and abdominal surgery) of three anatomies (brain, liver and kidneys, bones) with both hard and soft tissue, and involve both linear trajectories of simple and complex surgical instruments (needles) and implants (fracture fixation plate). We will then conclude with a brief discussion on trends and perspectives in image-guided surgery planning.

2. General concepts

The main components of preoperative planning systems are visualization, modeling, analysis, and plan generation. Visualization consists of showing the original images, structures of interest, implants and/or surgical tools in a way that is intuitive and useful for the clinician. Modeling consists of creating mathematical representations of the structures of interest, the surgical tasks and their constraints, and the physiological phenomena that are taken into account for the planning. Analysis consists of exploring the solution space of the planning problem by manual exploration, simulation, and/or optimization. Plan generation consists of selecting the solution that is most appropriate for the intervention based on the results of the visualization and the analysis.

The major types of surgical planning tasks are:

- **Surgical target identification:** determine the surgical target and its location in the preoperative patient images and identify the relevant surrounding structures.
- **Surgical access planning:** plan the surgical access point/location and path to the predefined target structure that causes minimal or no damage to the relevant surrounding structures.

- **Surgical tools and implant positioning:** determine the position of surgical tools and probes for the delivery of treatment and/or the location of implants.
- **Assessment of the selected plan:** predict and evaluate the expected effect of a treatment, e.g., radiotherapy, cryoablation, brachytherapy, the placement of a stent, a brain stimulation electrode, or an orthopaedic implant.

Advanced image-based planning also includes: 1) the design of patient-specific surgical aids and implants, such as 3D printed custom surgical guides and jigs, 2) positioning and plan design for intraoperative navigation and surgical robots, and 3) surgical workflow planning and optimization. We will not discuss these further in this Chapter.

The main technical elements of image-based preoperative planning are:

- **Pre-treatment image processing:** image enhancement, region of interest selection, registration between multiple scans (when available), volumetric visualization of images.
- **Segmentation and model construction:** segmentation of the structures of interest, geometric modeling of these structures, biomechanical modeling, physiological modeling, and/or treatment delivery modeling for simulation.
- **Definition of task-specific goals and constraints:** when applicable, mathematical formulation of the task goals and constraints as a multi-objective constrained optimization problem.
- **Visual exploration of the anatomy:** interactive visualization of the anatomy of the patient in the context of the preoperative images.
- **Plan elaboration:** manual plan elaboration based on visualization of the anatomy and analysis of the constraints using a trial and error process, or automatic plan computation by simulation or by optimization of the defined multi-objective constrained optimization problem.

The advantages of image-based preoperative planning include the ability to explore treatment alternatives, e.g., various access points, surgical tools access points, paths, locations, and the selection of implants. It also allows to increase the precision of the surgery, increase its robustness, and reduce its risks. In difficult cases, image-based preoperative planning helps to find a feasible strategy, and allows the access to surgery for the patient.

In the operating theater, the preoperative plan is imported and implemented. The implementation can be qualitative, i.e., by serving as a visual guide to the surgeon, or quantitative, following the registration of the preoperative plan to the intraoperative situation. The plan can then be used for visual guidance, for image-based navigation, or for robotics-based assistance. In some cases, the plan may be modified intraoperatively based on new images acquired in the operating room. minimally invasive surgery, laparoscopic and endoscopic surgery for the purpose of observation, biopsy, brachytherapy, treatment delivery.

3. Treatment planning for bone fracture in orthopaedics¹

3.1 Background

Computer-based treatment planning for orthopaedic surgery, also termed Computer Aided Orthopaedic Surgery (CAOS) dates back to the early 1990's [1]. It is, together with neurosurgery, the first clinical specialty for which treatment planning, image guided navigation and robotic systems were developed. CAOS planning methods and systems have been developed for most of the main orthopaedic surgery procedures, e.g., knee and hip joint replacement, cruciate ligament surgery, spine surgery, osteotomy, bone tumor surgery, and trauma surgery, among others. Commercial systems for some of these procedures have been in clinical use for over a decade. FRACAS, the first system for computer integrated orthopedic system for closed femoral medullary nailing fixation, dates back to the 90's [2].

The treatment for bone fractures is a routine procedure in orthopedic trauma surgery. Bone fractures can be intra-/extra-articular, on load-bearing bones, and range from a simple, non-displaced fissure of a single bone to complex, multi-fragment, comminuted, dislocated fractures across several bones. The main goal of orthopedic trauma surgery is to restore the anatomy of the bone fragments and their function in support of the bone healing process. The two main steps of the surgery are fracture reduction, to bring the bone fragments to their original anatomical locations, and fracture fixation to keep the bone fragments in place with fixation hardware including screws, nails, and plates. Surgery planning consists of determining the surgical approach, the bone fracture reduction, and the type, number, and locations of the fixation hardware [3].

For simple fractures, the planning is performed on X-ray images of the fracture site with software packages that support the overlay of translucent 2D digital templates of the fixation hardware on the digital X-ray images. For more complex cases, e.g., pelvic bone fractures and multi-fragment femoral neck/distal radius fractures, the planning is performed on CT scans with 3D bone fragment models [3]. These fracture cases have a higher incidence of complications, including bone and/or fixation hardware misplacement and inaccurate fracture reduction resulting from bones fragment misalignment. Complications result in reduced functionality, higher risk of recurrent fractures, fracture reduction failure, and fracture osteosynthesis failure and require revision surgery in 10–15% of all cases [4]. Various preoperative planning systems for fracture surgery based on 3D bone and implant models from CT scans are reported in the literature [5-10]. They include systems for maxillofacial surgery, for hip fracture surgery simulation, for proximal humerus fractures, and for pelvic and acetabular fractures surgery.

¹ This section is based on the paper "Haptic computer-assisted patient specific preoperative planning for orthopaedic fracture surgery", Kovler I, Joskowicz L, Kronman A, Weill Y, Salavarieta J. *Int. J. of Computer-Aided Radiology and Surgery* 10(10), 1535–1546, 2015.

Fig. 1: (a) Two-hand haptic system and screen view of (b) a 3D model of a pelvic fracture, (c) a custom fixation plate.

The main drawbacks of these systems are that they do not support two-hand manipulation, that they do not account for ligaments, and that the custom hardware creation is not automated. Since bone fracture reduction is a time-consuming and challenging aspect of the planning, various methods have been proposed for this task [11-19].

3.2 System overview

We have developed a 3D two-hand haptic-based system that provides the surgeon with an interactive, intuitive, and comprehensive, planning tool that includes 3D stereoscopic visualization and supports bone fragments model creation, manipulation, fracture reduction and fixation, and interactive custom fixation plate creation to fit the bone morphology (Fig. 1). We describe next the planning workflow, system architecture, and the fracture reduction method based on [20,21].

3.3 Planning workflow

The inputs to the planning system are a CT scan of the fracture site and geometric models of the standard fixation hardware, e.g., screws and plates. The planning proceeds in four steps: 1) automatic generation of the 3D geometric models of the relevant bone fragments selected on the CT scan slices, 2) fracture visualization and exploration, 3) fracture reduction planning, and 4) fracture fixation planning. The outputs are the bone fracture models, the standard and custom fracture fixation hardware models, and their locations.

The first step is performed by segmenting the bone fragments using the graph-cut method whose inputs are several user-defined scribbles on the fragments of interest on several CT slices followed by standard iso-surface mesh generation [22]. The resulting models are then imported for fracture visualization and evaluation -- type and severity of the fracture based on established classification schemes. The surgeon then manipulates the bone fragments to align them to their estimated original locations to restore their function. The fracture reduction can be manual, semi-automatic, or automatic (see below). Having obtained a virtual reduction of the fracture, the surgeon proceeds to plan its fixation with screws, nails, and/or reduction of the plates. The plan includes the screws -- their lengths, diameters, locations, and number --

Fig. 2: Block diagram of the planning system (reproduced with permission).

and the custom plates. The surgeon can produce more than one fixation plan, and perform further analysis and comparison with finite-element methods [23]. The preoperative plan is then exported for use during the surgery.

3.4 Planning system

Fig. 2 shows the system architecture. It consists of six user interaction devices -- a computer screen, a pair of glasses for stereoscopic viewing, a keyboard, a computer mouse, and two PHANTOM Omni haptic devices (Sensable Technologies Inc., USA), each with a hand-held 5 degree of freedom stylus that allow the user to touch and manipulate virtual objects. The haptic device has translational force feedback of 0.8–3.3 Newtons and a spatial resolution of 0.05mm. These values are the translational forces that can be generated by the PHANTOM Omni device according to the manufacturer's specifications. We use the entire range to stiffen the resistance as the interpenetration between surfaces increases.

The software modules of the system are as follows.

1. *Objects Manager*: manages five types of objects from the database: 1) bone/bone fragments -- surface meshes, centers of mass, locations, CT voxels; 2) screws -- cylinders defined by their radius, length, axis origin, and axis orientation; 3) fixation plates -- surface meshes; 4) ligaments -- 1D springs defined by their start/end points; and 5) virtual pivot points -- spheres defined by their origin and radius. The module manages individual objects and groups of objects.

2. *Physics Engine*: performs real-time dynamic rigid and flexible body simulation. It simulates physical behavior and interaction between objects, prevents objects interpenetration, and provides the data for a realistic tactile experience of object grasping and objects contacts. The module uses the Bullet Physics Library physics engine [24].

3. *Haptic Rendering*: controls the manipulation of grasped objects and produces the forces that are acted upon by the haptic device for tactile perception. It ensures real-time and stable user interaction with the virtual environment and generates the coupling forces and torques for the Physics Engine and for the haptic devices. The interaction between the haptic device and an object is modeled with a proxy [25], which is a point that follows the position of the stylus. In free space, the locations of the proxy and of the stylus pointer are identical. When a contact with an object occurs, the proxy remains outside the object, but the stylus pointer penetrates slightly the object, exerting a reaction force akin to a virtual spring damper coupling. To facilitate grasping, a gravity well attracts the stylus pointer to the object surface with force whose strength is proportional to the stylus point distance to the object surface. The module is implemented with The Haptic Library and Haptic Device Application Program Interfaces [26].

4. *Graphics Rendering*: generates the views of the virtual environment. The camera viewpoint is interactively changed by the user with a virtual trackball that is also used for the interactive spatial rotation of the models. Four viewing modes -- monoscopic solid, monoscopic translucent, stereoscopic, and X-ray view -- are available. The monoscopic solid mode is used for general scene viewing and for fracture exploration. The monoscopic translucent mode is a see through of the bones used for screws insertion and positioning inside the bone. The stereoscopic mode provides depth perception for accurate positioning during fracture reduction. The X-ray mode shows simulated X-ray images of the bone fragments and their contours as they may appear in the X-ray fluoroscope. The module is implemented with the GLUT and OpenGL libraries [27].

5. *Object Creation*: supports the grouping/ungrouping of bone fragments and the creation of fixation hardware, ligaments, and virtual pivot points. Ligaments are modeled as 1D springs with a start and end point whose number and locations are determined from anatomical atlases. They facilitate the interactive virtual fracture reduction by providing realistic anatomic motion constraints that restrict the bone fragments motions during reduction and hold them together. Custom fixation plates, whose purpose is hold the bone fragments together and whose shape conforms to the bone surface morphology (Fig. 1c), are created by touching the bone fracture surface with the virtual stylus pointer and sliding it along the bone fragment surface. A surface mesh in contact with the bone fragment surface is automatically generated following the pointer trajectory. The plate can span one or more bone fragment surfaces. Its width and thickness can be adjusted as desired. Screws are created by indicating their start and end points with the virtual tip of the manipulator and then interactively positioning it in their desired location. During the insertion, the outside bone fragment surfaces resistance is turned off. To ensure that the screws remain inside the bone, the translucent view mode and/or turns on/off the internal resistance of the bone fragment surfaces to prevent the screws from protruding outside the bone.

6. *Fracture Reduction*: computes the transformation between two bone fragments to reduce the fracture. It also supports the interactive annotation of fracture surface points for semi-automatic reduction. There are three fracture reduction modes.

a) Manual fracture reduction. In this mode, the surgeon grasps a bone fragment or a bone fragments group with one of the haptic devices and moves it until the fracture is reduced. The main difficulty is to simultaneously align several contact surfaces. To allow the sequential alignment of the matching surfaces, the system provides allows the temporary reduction of the bone fragments freedom with virtual pivot points. A virtual pivot point constraints the translation of the bone fragment (or group) to the center of the pivot. By placing a virtual pivot point at the intersection of two bone fragment surfaces, a connection that allows one object/group with respect to the other is enabled. The virtual pivot point constraints the manipulation of the object/group and facilitates the alignment of the bone fragment surfaces in another location. The virtual pivot points can be added and removed at any time as necessary.

b) Semi-automatic fracture reduction. When the bone fracture surface interface area is large, the precise alignment of the bone fracture surfaces requires many small and delicate manipulations. We automate this fine-tuning alignment by providing the surgeon with the ability to interactively mark the two bone fragments surfaces that are to be matched. The surgeon starts by interactively selecting the points on the surface of each bone fragment with the virtual tip of the haptic manipulator. The surgeon then brings two bone fragments into coarse alignment and instructs the computer to perform the fine alignment by Iterative Closest Point (ICP) rigid registration method with outliers' points' pairs removal.

c) Automatic pairwise fracture reduction. Automatic fracture reduction between two bone fragments is performed by computing the rigid motion transformation that best aligns one bone fragment with the other. This is a rigid registration problem that is solved by identifying the fracture surfaces to be matched in each bone fragment and then performing ICP registration between. The fracture surfaces are identified by finding the points on the surface model for which a neighborhood relation, defined on the intensity profile of the CT scan and on the curvature of the fragments surface, holds. The bone cortex voxels are identified by intensity thresholding since the density of the bone cortex is much higher than the densities of the interior spongy bone and the medullary cavity. Points on the outer bone surface whose corresponding voxel intensities are low are classified as fracture contact surface points. We also add points whose maximum principal curvature is high, as these correspond to sharp fracture edges.

7. *Control*: handles the user commands and determines the actions of the system based on a state machine automation. The mouse controls the camera viewpoint and allows the selection of menu options. The keyboard provides access to the modules' options, e.g., object type selection, viewing mode, motion scaling, and enabling/disabling the haptic rendering. The haptic device enables the user to manipulate virtual objects and to select fracture surface points for semi automatic reduction.

3.5 Evaluation and validation

We evaluated our fracture planning system with two studies. In the first study, we evaluated the use of the system for manual fracture reduction and quantified the accuracy of the manual bone fracture reduction. First, we generated the ground-truth reference of the bone fracture reduction by simulating fractures on healthy bone models on four CT scans of patients whose pelvic bone was intact. We then virtually created on the 3D model of the pelvis six realistic perfect-fit two-fragment fractures with no comminution. The position of the resulting bone fragments is the ground-truth final position of the fracture reduction. For each model, we displaced one of the bone fragments, created six scenarios, and asked five surgeons from the Dept. of Orthopaedic Surgery, Hadassah Medical Center, to manually reduce the fracture with our system. We then compared the bone fragment positions to the ground truth. The anatomical alignment error is the Hausdorff distance between each of the bone fragments with respect to their ground-truth configuration. The user interaction times were 10–30 mins depending on the surgeon's familiarity with the system. The surgeons expressed satisfaction with the system in an informal qualitative usability study. They achieved a mean and RMS surface match error of 1mm or less. For some cases and for some surgeons, the maximum surface error in specific areas of the fracture surface was $> 2\text{mm}$. These errors were considered by all surgeons to be very accurate and clinically adequate in all cases.

The second study quantifies the accuracy of the virtual bone fracture reduction algorithm. We created virtual fractures on four healthy femoral bone models as in the first study. We developed a new method for realistic fracture simulation which consists of computing a realistic fracture surface by segmenting a bone fracture surface in a CT scan of a fractured bone and then using it as a cutting surface template on a healthy bone model. For each model, we simulated three types of bone fractures: femoral neck fracture, proximal femoral shaft fracture, and distal femoral shaft fracture. We then applied our method and compared the configuration of the resulting reduced fracture to the original healthy bone. The mean final Target Registration Error is 1.79mm (std=1.09mm). The algorithm running time was 3mins (std=0.2mins). The surgeons examined each one of the cases and determined that the reduction was clinically acceptable in all cases.

3.6 Perspectives

Treatment planning for orthopaedic trauma surgery has the potential to improve patient outcomes, improve functionality, and reduce revision surgery rates. An effective user interface, coupled with automatic features and advanced analysis will go a long way towards providing an effective computer-based tools for treatment planning.

4. Treatment planning for keyhole neurosurgery and percutaneous ablation

Image-based surgical planning is also commonly used to help find an appropriate access to a pathology in minimally invasive interventions. In this type of interventions, the surgeon does not have a direct visualization of the surgical site. Therefore, image-based planning approaches are essential to select the most appropriate placement for the surgical tool before the start of the surgery. This is a very important aspect, as sometimes candidates to surgery cannot be treated because no feasible access can be found before surgery. Image-based preoperative planning consists in helping the surgeon in this decision-making process by solving automatically tool placement rules to propose feasible -- or better, optimal -- solutions. These are often called *trajectories* or *tool placements*.

Access planning has two different and complementary objectives: computing the entire set of feasible access sites, and computing the optimal one. In this Section, we will discuss both problems, and illustrate them with two different types of interventions: keyhole neurosurgery and percutaneous thermal ablations in the abdomen.

4.1 Background

For both surgical applications, the general clinical objective is similar: insert one or several straight surgical tools in a specific part of the body, through the skin or the skull, towards a chosen target, and while maximizing the positive effects of the treatment and minimizing its risks or side-effects.

Deep Brain Stimulation (DBS) for the treatment of Parkinson's disease, and Stereoelectroencephalography (SEEG) recording to detect the origin of seizures in epilepsy, are two representative examples of keyhole neurosurgery. DBS consists in implanting a permanent electrode in a deep and small nucleus of the brain, and stimulate it with a current sent by a pacemaker to reduce the tremors. It was first proposed in 1987 by Benabid et al. [28], and was successfully applied in 1994 to treat Parkinson's disease [29]. The treatment of choice consists of implanting one electrode per hemisphere to achieve a good laterality in the treatment. Because of the very small size of the targeted structures, i.e., the subthalamic nucleus (STN) and the globus pallidus interna (GPI), the insertion of the electrode must be performed with a millimetric accuracy. The choice of an optimal electrode placement is mostly a geometry problem, based on the anatomy of the patient's brain. In SEEG interventions [30], a higher number of electrodes has to be implanted -- around 15 on one side of the skull. The electrodes are placed in such a way that all anatomical structures to be monitored are covered by the region that the contacts along the electrodes can record [31]. An optimal placement combines safety and good coverage and ensures that the electrodes do not interfere with each other, which adds a new complexity. Commercial solutions exist, such as BrainLab Element [32] or Medtronic StealthStation [33]. They are often used in clinical routine, and mostly provide assistance to interactive planning, thanks to image processing and fusion functionalities, and an interactive choice of the target and entry points.

Percutaneous thermal ablations [34] consist in the localized destruction of malignant cells by hyperthermia using either extreme cold or extreme heat delivered at the tip of custom-designed needles inserted through the skin inside the tumor. While treating pathologies with heat or cold has been studied from centuries, modern percutaneous techniques have made them very popular in the 90's due to their minimal invasiveness and good efficacy. Examples of

percutaneous thermal ablations include radiofrequency ablation, often used for liver tumors, or cryoablation, often used for renal tumors. Radiofrequency [35] consists in heating the tumor above 60°C for about 10-15 mins. to allow for the complete destruction of the malignant cells. A variety of devices and needle models are commercially available, including straight rigid needles, umbrella-shaped needles, and multi-array needles. Advanced needle designs allow the treatment of large volumes. Their advantage they require a single application in most cases to treat the entire tumor. However, in other situations, i.e., cryoablation [36], several needles are usually required to form an iceball large enough to cover the tumor. The tumor ablation process is also longer, as it requires two freezing cycles of 10 minutes, with a thawing cycle of 5 mins. in-between to achieve the complete tumor obliteration. For this type of abdominal percutaneous thermal ablation, no planning tool is currently commercially available. The surgeons usually plans the entry and target points based on preoperative images in their minds. This is a difficult task, especially for cryoablation, where several needles and a complex resulting iceball shape are involved.

In all these procedures, the placement of the surgical tool needs to be very accurate to guarantee full coverage of the tumor and include a safety margin, while avoiding damages to surrounding healthy structures and other side effects. To define accurately the insertion plan, the surgeons usually rely on preoperative images and on a set of placement rules gathered from the professional literature and learned from their mentors and from their own experience.

4.2 Placement constraints

One of the challenges of preoperative image-based surgery planning is to realistically model the placement rules before they are used to solve the placement problem. In fact, most of the placement rules can be expressed as geometric constraints between the anatomy of the patient and the tools to be inserted (electrodes or needles), or the shape of their resulting effect. To simplify, the tools can be at first modeled as straight line segments whose endpoints are their tip and the entry point. The effect shapes can also be approximated by simplified shapes, as described in earlier papers [37,38] to reduce computation times, or be simulated with realistic mathematical formulas for a better accuracy of the prediction [39,40].

Surgical rules are most often expressed by the surgeon in natural language, so it is necessary to convert them to a formal, computer-enabled representation so they can be processed by a solver. The formal representation of these rules, called *surgical constraints*, can be expressions in a formal language [41], trees, or mathematical cost functions. While all these representations are conceptually equivalent, we found that the cost functions representation is the most convenient to implement.

The compilation and formalization of the surgical rules is a time-consuming and convoluted task, as some of these rules are implicit, may differ from one surgeon to another, and may change over time. To accommodate this, we chose to develop a generic and adaptable surgical constraint solver [42].

Fig. 3: Volume of necrosis of an RFA intervention represented by a simplified deformed ellipsoid (left), and ice balls of a cryoablation with two interacting cryoprobes simulated using a mathematical modelling (right).

We distinguish between two types of surgical constraints: hard and soft surgical constraints. *Hard constraints*, also called *strict* are mandatory, i.e., “*do not cross any vessel with the needle*”. Their evaluation is a Boolean value, indicating if they are satisfied or are not satisfied. All candidate trajectories that do not satisfy any of the hard constraints must be discarded. *Soft constraints* express preferences, i.e., “*keep the needle as far as possible from the vessels*”. Their evaluation is a numerical value, indicating their degree of compliance. Note that this preference can be expressed as a rule describing the distance between the needle line and the vessels shape. When solving such constraints, the objective is to minimize or maximize their value.

4.3 Constraint solving

Once the surgical rules have been established and the patient-specific 3D model has been created from the preoperative images, the next step is constraint solving.

The hard and soft constraints can be solved separately or together. When solving them separately, a good approach is to first solve the hard constraints so as to restrict the solution space to the set of feasible solutions. This can be achieved by examining all possible solutions and eliminating the ones that do not satisfy all the strict constraints. Since the initial solution space is infinite, it is necessary to discretize it beforehand. One common way to do this is to set the target point (for instance to the centroid of the targeted structure), and then examine the resulting entry points either by browsing the vertices of the skin’s surface mesh, or the centers of its triangular cells, or to use an angular discretization of the space around the target point. The second step is to further explore the set of feasible solutions to find the solutions that best satisfy the soft constraints. This actually consists in the resolution of a multi-criteria optimization problem. Depending on the clinical application, the target point can still be set in advance (either by using its centroid, or by asking the surgeon to select it) to examine only possible entry points, or it can be included in the search for an optimal solution, which is

an optimal pair entry/target points. The latter approach increases the number of degrees of freedom and the search space but might be useful in some applications, in particular when multiple surgical tools -- electrodes, needles -- are involved.

The first and most commonly used technique to solve the soft constraints is the weighted sum method. It consists of representing the soft constraints as cost functions f_i to minimize, and then combine them using individual weighting factors w_i that can be predefined or adjusted by the surgeon. In this way, a unique global cost function f is defined as described in converting the multi-criteria problem in a single-criterion problem that can be solved using a minimization algorithm. Formally, the function is:

$$f = \frac{w_1 \cdot f_1 + w_2 \cdot f_2 + \dots + w_n \cdot f_n}{w_1 + w_2 + \dots + w_n}$$

In this approach, the choice of the minimization function is key, as the results and the computation times will depend on it. When using a local minimization function, e.g., the Nelder-Mead downhill simplex method [43,44], an initialization is required to ensure convergence. Global approaches can also be considered, provided that adequate parameter values can be found that do not require re-adjusting for each patient [45].

Another very interesting approach is to find the best compromise between soft constraints based on a real multi-criteria optimization method, such as Pareto front computation. The general idea is that since it is in general impossible to find a solution that simultaneously optimizes all of the soft constraints $f_1 \dots f_n$, the best is to find compromises between them. Each solution with a specific evaluation of functions $f_1 \dots f_n$ constitutes compromise. The compromises will always satisfy some of the constraints better than the others. The best among the compromises are called the Pareto-optimal solutions. The set of all Pareto-optimal solutions constitutes the Pareto front. Note that choosing a Pareto-optimal solution requires ranking the soft constraints by their importance, as all such solutions optimize equally the soft constraints, each one in its own way. In the end, the choice of which of the Pareto-optimal solutions are the most suitable for a specific case depends on which constraint(s) we want to satisfy most. This requires the quantification of optimality.

In [46], we defined an optimality quantification based on dominance and described how to compute the corresponding Pareto front for the specific case of trajectory planning for surgery. In this work, the weighted sum and the Pareto front approaches were compared. We showed that the weighted front approach, although more intuitive for the user in terms of presentation and visualization of the solutions, was missing many possible solutions. We also showed that the missed solutions found by the Pareto front method were the ones most often chosen by surgeons, suggesting the superiority of this approach.

Finally, note that it is also possible to simultaneously solve hard and soft constraints by representing hard constraints as cost functions with a maximum penalty outside the feasible area. This approach has the drawback of being computationally more expensive when parameters, such as weighting factors, are changed.

Fig. 4: Color map representing the quality of each feasible insertion point on the skull (red - poor quality, green - high quality) for a Deep Brain Stimulation intervention, with the three most optimal electrodes positions located in three separate valleys (purple).

4.4 Evaluation and validation

The evaluation and validation of the planning solutions is performed in two ways. The first is to display the results for visual assessment and to provide the surgeon with the necessary information to decide which solution to adopt. The visualization consists of displaying color maps over the skin mesh as illustrated in Fig. 4. This is particularly useful for visualizing the results of the weighted sum approach. Usually, the least appropriate zones are displayed in red, while the most appropriate ones in green or blue. The color map shows results from the two phases. Its border shows the limit of the feasible entry points, computed by solving the hard constraints, and the colors represent the quality of each feasible entry point, computed by solving the soft constraints. When hard and soft constraints are solved together, the zone outside the border is displayed in red.

It is important to note that this kind of display is partial and has bias. Indeed, color-coding an entry point to represent the quality of its associated trajectory presupposes that this trajectory is unique. However, an entry point may represent an entire family of trajectories, aiming at various target points when the target point was not set in advance. In this case, the color of the entry point should be determined by the value of the most optimal trajectory using this entry point. Note that although color-coding is a good way to get a rough idea of the possible good locations for insertion points, this kind of visualization is not very accurate.

The second approach is to show the first few first few most optimal solutions. Indeed, when visualizing the color maps, it is very common to see that there is usually not a unique good location. Most often, there are a few good candidate areas, also called “valleys” that represent connected zones with the lowest values of f . A good way to indicate the most suitable entry points to the surgeon is therefore not to display the trajectories with the global lowest evaluation of f , that could be located within the same valley and very close to each other, but rather to display the most optimal trajectory within each valley, as shown on Fig. 4.

Fig. 5: Pareto-optimal solutions (red spheres) displayed over a weighted-sum color map for a Deep Brain Stimulation intervention.

When using the Pareto front method, the display can be somewhat different. All the entry points retained as equally optimal can be displayed with an equal visualization. However, this might be confusing when trying to select one of them, especially when the front is large and the solutions numerous. Some help to shrink the selection of the points can prove very useful, for instance by setting minimal evaluations for all cost functions $f_1 \dots f_n$. It is also possible to ask the surgeon to rank the importance of soft constraints, which will allow a coloring to be done, or to display the Pareto-optimal solutions over a weighted-sum dynamic colormap with adjustable weights as a hint, as illustrated in Fig. 5.

With both approaches, we see that ranking the importance given to each soft constraint helps in the resolution of the problem. An interaction from the user allows to set respective weights and update the visualization in real time. Interactive repositioning of the surgical tool, real-time 2D/3D and tool-axis (“probe-eye”) visualization, and numerical information displayed dynamically, such as the distance to major organs to avoid, are among the useful features that trajectory planning software should provide.

The evaluation of the result can also be seen in terms of clinical validation. Either to assess the robustness and accuracy of a method in general, or to evaluate the clinical relevance of a patient-specific solution, numerical validation is useful. In many other fields, this is usually done by comparing the results with some ground truth. However, in our case, defining ground truth is a delicate issue.

An option can be to study retrospective cases, in which the position of the tool chosen by the surgeon is retrieved from either automatic or interactive segmentation based on postoperative images. However, without assessing the quality of the surgeon planning in those cases, it is not possible to consider that the very best location was always selected. In many cases, the surgeon might have chosen purposely a suboptimal position for a variety of reasons, or might have lacked some information to find the most optimal one, or even the tool simply deviated from the planned trajectory when inserting it. Therefore, retrospective cases cannot be considered directly as ground truth. The best way to proceed is to gather candidate positions from different sources, manually planned from retrospective cases and automatically planned with the proposed methods, and have them blindly ranked by experts.

4.5 Perspectives

Image-based preoperative planning can also benefit from other features to improve their accuracy, especially when mechanical or physiological phenomena can influence the procedure. Simulating those phenomena help to anticipate them and provide a more optimal planning.

Deformations in general are the first cause of inaccuracies. Image-based planning means using still preoperative images to choose a strategy. However, even if the patient is in the exact same position during the intervention, many phenomena can cause motions of the anatomical structures surrounding the target. For abdominal interventions, breathing is of course the first cause of deformations. Movements due to friction and pressure forces also occur during insertion of needles into the soft tissues of the abdomen. In neurosurgery, the well-known phenomenon of brain shift is due to leaks of cerebrospinal fluid, gravity, and various other factors. Attempts have been made to take those phenomena into account to improve the predictability and the accuracy of the planning.

Another kind of phenomenon interesting to model is the effect that will be produced by the treatment. In the case of thermal ablations, such as radiofrequency or cryoablation, simulating the propagation of heat around the tip of the probe allows to anticipate the coverage of the tumor by isotherm surfaces representing the zone of full necrosis, confirm that the treatment will be a success, or identify potential surrounding structures that could be affected. In the case of DBS, simulating the electrical field around the tip of the electrode allows to visualize what structures will be included inside the stimulated volume.

5. Future challenges

Image-based preoperative planning is a key component of the trend towards precision and personalized medicine. Its role in an ever-growing number of procedures is increasing and is an enabler for new surgical systems and procedures for more structures and pathologies. This creates technical demands that need to be addressed with existing and new technologies.

We foresee several technical trends that will play an important role in the near future. For segmentation and model construction, we foresee an increase in the use of atlas-based segmentation and deep learning segmentation. A main challenge for these methods is the acquisition and/or generation of ground-truth organ and structures segmentation for atlas construction and for network training. For simulation, we foresee challenges in the development of multi-physics models and their simulation with high computational demands.

Another topic of interest is the integration of preoperative planning and intraoperative execution, hereby allowing plan modification and adaptation in the operating room. For some procedures, the progress of a surgical step, e.g., the insertion of a needle, is monitored with intraoperative images. For example, during cryoablation surgery of liver tumors, surgeons usually monitor the insertion of the needle to see if it matches the planned trajectory, and then follow the growth of the ice ball with 2D ultrasound or fluoroscopy X-ray images. Based on these intraoperative images, they may adjust the plan to correct possible inaccuracies of the needles placements or complement the ice ball formation. The original plan can then be

automatically adjusted to adapt and preserve the optimality, safety and accuracy of the needles placements according to the observed structures deformations.

A third topic to explore is to link post-treatment imaging and evaluation to the preoperative plan. The goal is to establish a correlation between the preoperative plan and the post-operative outcome and to determine if the treatment was effective and if an alternative plan could have yielded better results. For example, for orthopaedic bone fracture surgery, a postoperative CT scan can help to determine if bone union was completed successfully and if the fixation plate and screws did not undergo displacement. Based on this assessment, it could be determined that thicker and/or longer screws should have been used. This conclusion can then be taken into account when planning the next surgery.

Finally, we note that image-based preoperative planning also have an important role in clinician training, education, and evaluation. Indeed, image-based surgical planning systems such as the bone fracture surgery system in orthopaedics described in this chapter can serve as a component in simulation systems to provide a hands-on, realistic virtual environment in which the users can perform a variety of procedures, such as suturing and knot tying, with simulated instruments on virtual models of tissues and organs. Indeed, surgical simulators are gaining acceptance as a training tool for residents and as a rehearsal and preoperative planning tool for experts. A variety of commercial simulators are nowadays available for laparoscopic, endoscopic, and endovascular procedures.

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