Graphic and geometric tools
for analyzing morphology of the human knee

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Abstract

Medical images (X-ray, CT, MR or PET) of human organs are widely used in the every day clinical praxis. A deeper insight of the anatomical properties can be obtained by building a three dimensional computer model from the images. In order to properly evaluate the 2D images and also the 3D objects physicians need efficient and robust graphical and geometrical tools. The paper presents methods that were specifically developed to investigate the morphology and functionality of the human knee joint. These are mainly contour detection in images, reconstruction of tessellated and continuous surface models, geometrical calculations in images and in space.

Keywords: *Biological models, image analysis, reconstruction*

1. INTRODUCTION

The knee joint is a very important component of the human motion system; it is delicate yet frequently damaged. A wide range of medical imaging techniques (MR, CT) is available to the clinicals to investigate the different parts of the knee joint. By making visible the shape and morphology of some of the joint diseases these methods offer invaluable support to the practicing physician and also to the orthopedic surgeon. The same tools can be applied to the analysis of the kinematic behavior as well as the morphology of the articular cartilage.

CT and MR images are usually evaluated by a human evaluator in the medical praxis. In case of the human knee, however, this can be extremely difficult due to the similar gray-scale representation of the synovial fluid between the opposite cartilage surfaces of femur and tibia, and the partly covering surfaces. Efficient and sensitive computer methods for contour detection and segmentation can improve the quality of evaluation. Accurate computation of distances, directions, angles within the joint provide solid basis for orthopedic handling and surgery.

Many important properties of the knee joint can only be evaluated in three dimensions. The bone and cartilage surfaces have complicated shapes in 3D, and also the motion takes place in 3D. Consequently, a 3D computer model must be built, using information extracted from the 2D images. Beyond the usual 3D manipulations (3D transformations), specific geometric tools are needed such as 3D computations and interrogations, corresponding to the structure of the knee and the relevant questions to be answered.

Currently available software tools (as part of CT/MR imaging devices or general purpose systems e.g. 3D SLICER [9]) satisfy needs of the everyday clinical praxis; however, they are not appropriate for detailed scientific investigation of the knee joint and for creating a computer navigation system for knee surgery We developed a complete system to investigate the human knee joint by computer tools. It consists of input, storing and handling of CT/MR images of the knee, methods and programs for image analysis, 3D surface reconstruction, and graphical and geometrical tools for the detailed analysis of the shape and motion of the knee. Most important elements of the system are reported in the paper.

Methods of image processing, geometrical modeling and surface reconstruction implemented in our system are based on fundamental techniques of the related fields. Even so, they have to be adjusted and modified according to the specific features of knee images and geometry. Also new tools for the precise evaluation of the geometry have to be added. Integrating of these methods and techniques into one system is also an important achievement.

2. ANALYSIS OF 2D IMAGES

CT and/or MR image sequences of the knee are read in DICOM format A computer program was built for visualizing the acquired data of the scans, using commercial programs (IDE, Integrated Developing Environment by MetroWerks Inc, Houston, USA, Volume Graphics, GmBH [1]), assembled and modified according to the requirements of the knee investigations. The image sequences are stored on a 3D grid as a volumetric model, allowing creating pictures in the main anatomical directions (sagital, coronal, horizontal). Different image analysis and graphical tools have been developed to analyze the morphology of the knee.

2.1 Graphical tools

Study of the anatomical structure of the knee requires specific tools beyond the usual graphical techniques (rendering, shift, rotation, scaling, zoom, etc.) provided by commercial graphical systems. For the clinicals it is important to be able to localize points exactly in the space and to take measurements in 3D.

We added the following graphical tool to the basic services of the above system.

- Fast localization of anatomical points in three dimensions, independently of which slice is selected currently. The cursor is located and displayed at the intercept point in the anatomical planes, which correspond to the three coordinate planes.
- Distance measurement in 3D. The distance between a fixed and a movable point is displayed and calculated in 3D. To perform distance calculations precisely a resampling of the

input data is needed, which is synchronized to the location of the end points

- Angle measurement. Angle between two intersecting straight lines defined by three points arbitrarily selected in the space is calculated.

In Figure 1. the orientation and the angle between moving knee parts (tibia and femur) are shown in two projections. The end points of the straight lines (measuring triangle) can be localized in any selected slice by moving the projection plane to the desired slice. The figure shows the knee in two orthogonal planes, the sagital and coronal plane, frequently used in orthopedic investigations. The actual cursor position is listed on the upper left corner (in mm) and the actual spatial angle (in degrees) on the upper right corner. One side of the measuring triangle crosses the contact point between the tibia and femur.

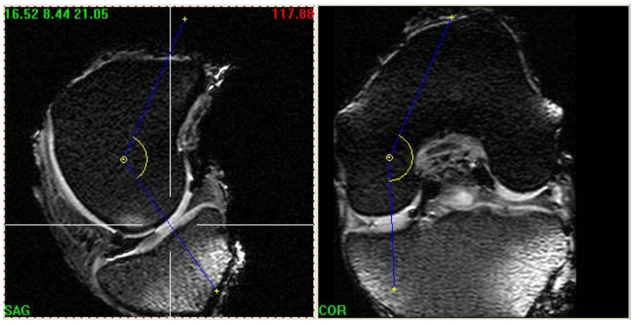

Figure 1. Measuring angle on the MR image.

2.2 Contour detection

Segmentation of contours in images is based on the fact that regions corresponding to different anatomical structures are represented with different intensity values. Contour detection algorithms detect the boundaries of that regions i.e. lines, where the intensity gradient has a great value.

Active contour detection is basically a marching process, which proceeds along points with high intensity gradients in the image. To improve the quality of the contour shape information of the anatomical structures must be taken into consideration. In addition to the gradients, we included geometrical properties (continuity, smoothness) into the quantity to be optimized along the contour. The optimization is an iterative process.

The segmentation process works in a slice-by-slice manner. In each slice it always starts with an existing contour, which is extracted from the previous slice. The deviation is measured and minimized, in order to maintain smooth transition between consecutive contours.

Contour detection is basically an automatic process. It starts with interactive definition of a rough contour in the first slice, than automatically generates contours in the next slices. All contours appear in their correct spatial position, providing a tool for the medical inspection of the contours, and also for the creation of a complete surface (bone or cartilage) in 3D, described by the contours. Details of the active contour method are discussed in [2], an example of the detected bone contours are given in Fig. 1.

Automatic contour detection woks reliably and efficiently in many cases, however in certain cases manual delineation of the cartilage seemed to be superior to fully automated segmentation. Medical images regularly contain artifacts, sometime in quite considerable amount, which produce blurred pictures in consequence of the technical imperfection of the equipments, or of the spontaneous motion of the persons; etc. Eventually, when the noise in the MR images makes a blurred picture or the synovial fluid limits correct evaluation of the joint space, visual control is needed by an experienced physician. The efficiency of his/her work can be greatly increased by suitable computer tools.

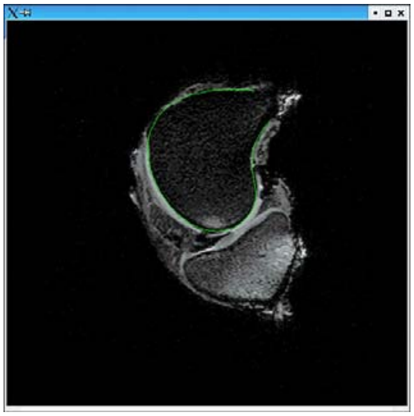

Figure 2. Automatic detection of bone contours

A fast and flexible way of extracting contours manually from images and to define them in an interactive way has been developed. The physician has to pick a few characteristic points on the images to establish the shape of the contours. The points are immediately stored in three coordinates. For displaying contours with good quality, and also for further computer processing continuous contour curves are needed. It is expected, that the shape of the contour curve corresponds exactly to the expectations of the physician, which is reflected in the sequence of the specified contour points.

In computer graphics and geometry several methods are known for generating continuous curves from discrete data points [3], [4]. One of the most popular, efficient and robust methods are spline curves. A parametric spline curve is defined by the expression

$$\mathbf{c}(t) = \sum_{i=0}^{n} \mathbf{C}_i N_i^k(t)$$

where the curve shape is defined by the $\boldsymbol{C}_i$ ($i=0.....n$) 3D vectors, (so called control points), and the $N_i^k(t)$ are polynomial basis functions, t is the curve parameter. There is a built in continuity (smoothness) in the curve, which depends on the degree of the curve k. The vector coefficients $\boldsymbol{C}_i$, can be computed with the condition that the curve passes through, i.e. interpolates the data points, specified by the observer [4].

The above type of interpolating spline curve performs well in many graphical problems; however, it may produce unexpected shapes with undulations and waves in medical applications. The reason is that medical images always contain noise, and the observer introduces subjective errors. The continuous curve will reflect (interpolate) all noise and error, moreover continuity condition may even amplify them along the curve. The difficulty can be eliminated by applying another condition for defining the shape parameters $\boldsymbol{C}_i$ of the curve. If we do not require that the curve passes exactly through the prescribed points (approximating spline), we can gain extra freedom to eliminate the effect of random errors on the curve shape. Of course, deviations between the curve and the data points must be carefully controlled. The mechanism of curve construction is as follows.

Let define the shape parameters $\boldsymbol{C_i}$ of the curve by minimizing the quantity of

$$F(\mathbf{c}) = \sum_{i=1}^{n} \left(\mathbf{c}(t) - \mathbf{P}_i\right)^2$$

which measures the (squared) distance of the data points $\boldsymbol{P}_{\mathrm{i}}$ from the curve ***c(t)***. Mathematical analysis of the problem shows that minimization of the above expression leads to a system of linear equations for the unknown curve parameters $\boldsymbol{C_i}$, which can be solved by stable and efficient algorithms [5].

If we assume that there is an error with normal (Gaussian) distribution in the data (which is a fairly good assumption for random errors), then the continuous curve will reproduce the shape without errors. Our experiment shows, that this result can usually be achieved by an average deviation less than 0.09 mm, and a maximum deviation less then 0.2 mm when reconstructing contours in MR images of the knee.

The above method provides continuous and smooth curve in good quality for noisy data points. Even more important that using approximating spline geometric quantities relevant for knee analysis can be computed in a more stable and robust way compared to the interpolating spline. Table 1. gives radii of condyles (left and right in mm) in sagital directions, computed from approximating and interpolating splines in different flexion angles (degree) of the femur. It is clear, that real values are obtained by the approximating spline.

Degree	**Left**		**Right**	
	Approx.	**Interp.**	**Approx.**	**Interp.**
0°	50,98	45,03	44,26	33,30
15°	26,74	17,15	38,02	25,30
30°	24,64	7,40	36,47	11,31
45°	23,94	23,55	27,78	7,98
60°	22,85	12,62	24,71	20,07
75°	26,04	8,25	25,49	19,20
90°	31,61	46,72	27,44	40,18

Table 1. Radii of condyles

The same method was used whenever continuous curves have to be generated for a sequence of discrete data points (e.g. contact curves in the knee).

3. RECONSTRUCTION OF KNEE SURFACES

Many anatomical properties of the knee can be evaluated in MR images that are plane intersections of the spatial structure. For detailed investigations, however 3D modeling and visualization of bone and cartilage surfaces are needed. We have developed three types of surface reconstructions; isosurface, triangulated surfaces and continuous surfaces.

Isosurface reconstruction is based on voxel intensity data segmented by an adjustable gray-scale threshold [6]. The isosurface model represents the identical gray level points. Before visualization, the program automatically completes the segmentation based on intensity threshold. Standard methods for modeling surface material, lighting, illumination and transparency are used. The basic purpose is to visualize surfaces, but graphical objects like points, markers, paths and polygon meshes can be added to a 3D scene.

Surface points extracted from the isosurface model represent only rough information on the shape. The advantage of the isosurface representation is that the physician gets an idea of 3D morphology developed from planar images. For exact demonstration and numerical representation of 3D parameters, however, isosurfaces are not sufficient..

Continuous representation of anatomical surfaces is often needed for detailed investigation of their shape and geometry. Triangulated representation of the knee in the medical practice is generally sufficient but to delineate fine details and for motion analysis high degree, smooth surfaces are needed. Relevant geometrical properties (normal vectors, tangent planes, curvatures, plane intersections, etc.) can be computed for both surface representations, but the accuracy is considerably different.

A triangulated surface consists of very small triangles between data points, which are consecutively connected to each other. The data points come from MRI scans, as the points of the corresponding contours. The sequence of contour points is positioned in 3D according to the spatial position of a slice containing the contour. In case of cadaver studies, data points can be collected by a (laser) scanning process. A good triangulation must meet several requirements: it must be topologically correct (no holes and flying triangles appear in the triangulation), must eliminate outlier points, triangles must have comparable side lengths and angles, their size must reflect the curvatures of the surface, etc. We have developed algorithms and computer programs to triangulate and decimate point sets of anatomical structures, which are able to handle imperfections coming from contour detection and measurements [7]. If necessary, topological corrections are performed, or the triangulation is decimated to reduce the size of the data set. Figure 3. shows the surface of the tibia and femur as triangulated surfaces. Although it looks quite smooth, it is not tangential continuous because of triangulation.

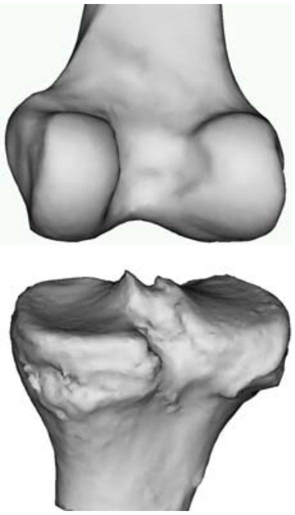

Figure 3. Triangulated surfaces of tibia and femur

Our experiments show that accurate and smooth representations of the functional surfaces of the knee are needed for detailed biological or medical investigations (especially for studying the size and shape of the contacting regions of cartilages and motion of the knee).

Input data for creating smooth surfaces is a point set, coming from contours of MR images, or from scanning. The point set must be filtered against noise and decimated.

Continuous surface fit starts with topological ordering of points, which is usually done by creating a triangulation over the surface points. Triangulation provides neighborhood relations, which is important for fitting surfaces and for geometric calculations. Because we fit parametric surfaces commonly used in computer graphics and CAD (e.g. Bézier, B-spline, NURBS) over the point set, parameter values must be attached to the data points. This is performed by projecting the data points to a simple and rough approximating surface, which is usually the bicubic Coons surface defined by the boundary points of the point set [4].

The shape defining data of the surface are computed by minimizing a functional:

$$F(\mathbf{C}_{ij}) = \sum_{k=1}^{N} \left(\mathbf{S}(u_k, v_k) - \mathbf{P}_k\right)^2 + \lambda \iint_{\mathbf{S}} \left(\mathbf{S}_{uu}^2 + 2\mathbf{S}_{uv}^2 + \mathbf{S}_{vv}^2\right) \mathrm{d}u\,\mathrm{d}v$$

$$\mathbf{S}(u,v) = \sum_{i,j} B_{ij}(u,v)\mathbf{C}_{ij}$$

where the continuous surface **S***(u,v)* is fitted to the N number of data points $\boldsymbol{P}_{k}$. The surface is defined by the basis functions $B_{ij}(u.v)$ and control points as shape parameters $\boldsymbol{C}_{ij}$. The functional contains two terms; one is the squared distances of data points to the surface points with the same parameter value, and reflects accuracy of the surface. The other describes some geometrical quantity responsible for smoothness, here the approximation of the surface curvatures (lower indices denote derivatives). Parameter λ (set by the user) defines the ratio between accuracy and smoothness. Minimization of the functional defines control points of the surface and thus its unique mathematical representation.

We have developed methods for parametrizing point sets, solving the functional minimization problem, and improving parameterization during the fitting process; the details can be found in [7]. In Figure 4. active surfaces of femur and tibia (where motion takes place) are shown, together with the underlying point sets.

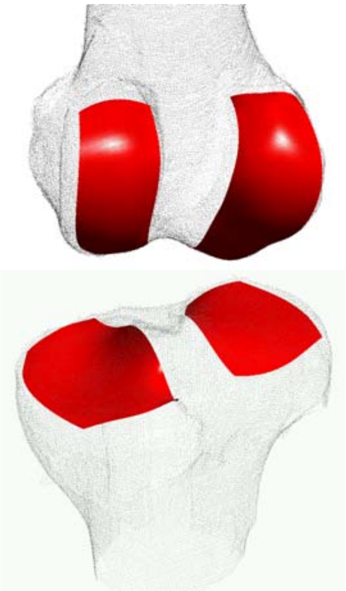

Figure 4. Active surfaces of femur and tibia

4. SHAPE ANALYSIS

We have developed several methods and programs, to evaluate the shape and morphology of knee surfaces. Various geometrical properties such as tangent planes, normal vectors, extreme points, lines of intersections, distribution of mean and Gaussian curvatures, feature points, characteristic lines, etc. can be calculated, visualized and evaluated. As an example plane intersections of the tibia plateau perpendicular to its axis is shown in Figure. 5.

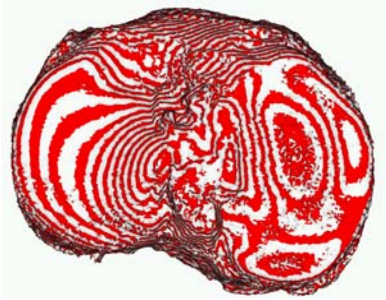

Figure 5. Plane intersections of the tibia plateau

From pathological and clinical point of view it is of basic importance to have precise measures of the thickness of the cartilage layer, covering the bone surfaces and characterize its spatial distribution. When bone and cartilage surfaces are precisely reconstructed, theoretically it would be possible to calculate the cartilage layer between them. The problem is that this layer is very thin, (1-2 mm, light layers around bones in Figure 1.), and inaccuracy in surface reconstruction may destroy the geometry of the cartilage layer.

In case of cadaver studies correct positioning in space of the surfaces (registration) is also a crucial point. After bones with and without cartilage are scanned independently, the point clouds must be merged. To perform this, surface part not covered by cartilage can be used, because they have an identical shape. For registration we applied a modified version of the ICP (iterative closest point) algorithm [8]. Using the above surface reconstruction, the ICP registration, with a careful adjustment of their parameters a precise reconstruction of the cartilage layer can be achieved. In Figure 6. plane intersections of the cartilage layer are shown. It faithfully reflects fine variations of the thickness expected from the anatomy of the knee.

Figure. 6. Cartilage layer on the tibia plateau

Contact properties of cartilage surfaces (their shape and extension) can be best evaluated by a distance function defined between the two surfaces. This is the length of the shortest path from a surface point to the other surface. We have developed a procedure to evaluate the distance function for the continuous surface models of the cartilages. Surfaces can be color coded according to the distance function, which provides an extremely efficient tool for evaluating the shape and size of the contact regions. Figure 7. shows the color coded distances between for the contacting cartilage surfaces of femur and tibia.

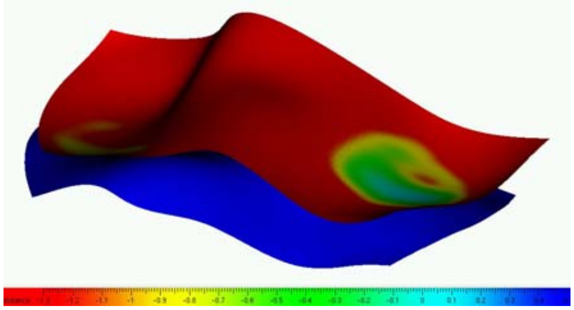

Figure 7. Color coded distance function of cartilage surfaces

5. CONCLUSION

Analysis of the geometrical properties of the knee is important from many points of view. Based on shape information clinicals can draw conclusions on the healthy and pathological state of the knee. Surgeons can design surgical intervention using geometrical data of the knee. Better understanding of the morphology and functionality of the knee may lead to better than existing prostheses. Accurate geometrical information facilitates preoperative design of knee surgery and computer control during surgery.

In Computer and Automation Research Institute, Budapest, Hungary efficient and robust graphical and geometrical tools were developed to analyze MR and CT images, to perform geometrical calculations in 2D, to reconstruct medical/biological surfaces from images and scans, to registrate and merge them and to evaluate them in 3D. Although the methods and programs were developed to satisfy specific aims and requirements of knee studies, many elements can be efficiently used to investigate similar biological structures.

Our aim in the future is to develop a complete computer aided knee surgery and navigational system based on the graphic and geometric components discussed above.

6. ACKNOWLEDGEMENT

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