Three-dimensional Geometric Constraint Evaluation and Analysis for Determining Commercial Knee Prosthesis

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Abstract

This paper describes a method of automatically determining a knee prosthesis by evaluating geometric constraints that include avoiding abnormal bone tissue in sections and interfaces between prostheses and bones, and achieving maximum contact but avoiding incomplete contact. Our algorithms manipulate volume data of patient's knee to complete the above evaluations. These include using interfaces of prosthetic femur and tibia to intersect with the volume-representation femur and tibia and then detect abnormal bone tissue inside the interface, defects and incomplete contacts on interface boundary, and using tangent plane on curve-shaped prosthetic femur to obtain the patella platform for inserting the prosthetic patella and thus compute the size of the prosthetic patella.

Keywords: Prosthetic determination algorithm, Knee arthroplasty, 3D reconstruction, Volume visualization

Introduction

Current modalities for knee arthroplasty include preoperative evaluation using x-rays and intra-operative procedure determination using guiding tools and template prostheses [1-7]. The x-ray evaluation can determine whether there exist abnormal structures inside bones and suggest acceptable prosthetic parts. The guiding tools can help determine precise anatomical axes, saw bones to generate interfaces between bones and prosthetic components (femur, tibia and patella) [8-15]. By the guiding tools and template prosthetic parts, surgeons can try a suitable prosthesis that is considered relatively acceptable to achieve the knee function [16-21].

However, these modalities may achieve acceptable arthroplasty but are not optimal results [22-29]. Besides the above-described functions achieved in current modalities of knee arthroplasty, surgeons should use as better as larger prosthesis to reduce the average loading on the new joint, let all interfaces between bones and the prosthetic parts contact closely. In addition, operation time in selecting sections of distal femur and proximal tibia interfaces, tries in template prosthesis should be reduced, and procedures should be easier as better. However, because of no enough preoperative evaluations, uncertainties and compensation impossible cases can be only deleted by trial and error.

In this study, we propose an automatic method that preoperatively evaluates selections of sections of distal femur and proximal tibia interfaces, contact conditions of other interfaces between bones and prostheses, and contact conditions between prosthetic parts. Based on these evaluations, an optimal prosthesis can be determined. Uncertainties of incomplete contact by defects and determination of anatomic axes, compensation impossible overesection can be avoided.

This method uses volume data consisted by CT slices not x-rays because there exist perspective errors in determining 3D data of anatomic structures [30-32]. High-quality 3D images about chosen prostheses and surgical procedures (by our previous reported surgical simulator [33-35]) are also provided to impress the outcomes that will occur during operations. Then, an optimal prosthesis and successful arthroplasty can be expected by our method.

Materials and Methods

Prosthesis preparation

We have prepared all sizes of template prostheses of several manufacturers before applying our method to real arthroplasty. Prosthetic data can be obtained by transferring manufacturer-providing data with standard representation into a 3DS MAX or by interactively input into the 3DS MAX by the manufacturer-providing cross-sections (dimensions and shapes) for each prosthesis. Then, the prostheses are converted into volume representation. Fig. 2 and Fig. 1 illustrate prosthesis with four components and its prosthetic femur only. In each figure, real template, 3D image rendered in 3DS MAX and 3D image rendered in the volume after the isosurface reconstruction [36] are shown sequentially for comparison. In

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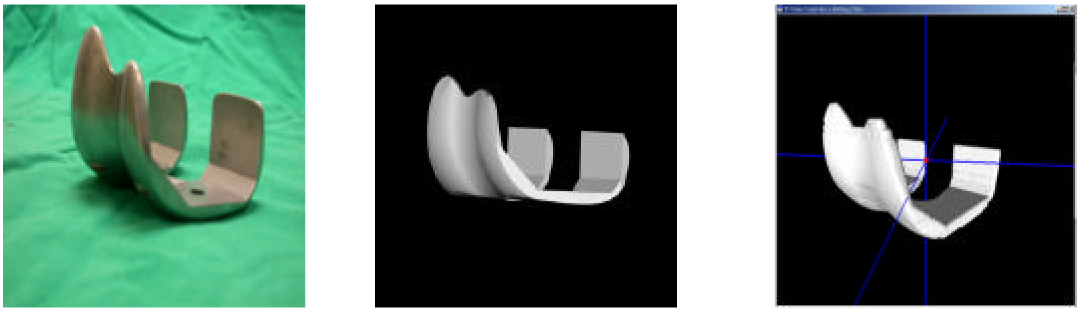


(a) real template (b) 3D image rendered in 3DS MAX (c) 3D image rendered in volume

Figure 1. prosthetic femur

(a) real template (b) 3D image rendered in 3DS MAX (c) 3D image rendered in volume

Figure 2. prosthesis with four components (femur, meniscus, tibia and patella)

Fig.1, the U-shape curved surface can be clearly illustrated. The sizes of the prostheses are the same in Fig 1(b)(c) and 2(b)(c). While, the images with the volume representation show some alias because volume approximation instead of exact mathematic representation in 3D MAX. However, the prostheses must be converted into volumes for implementing geometric and topologic operations with the patient's volume data.

CT slices (in the DICOM protocol [37]) resolving the knee for arthroplasty are then transferred into our system to obtain the patient's volume data. During the CT imaging, the angles between anatomic axes of tibia and femur and the volume axis are also investigated to determine the prosthetic axis. In the following, we use the volume coordinate system, meaning that the three coordinate components of each voxel center are all integers.

Prosthesis determination

Fig. 3 shows the flow chart of determining an optimal prosthesis for each available manufacturer. First, optimal sections for distal femur and proximal tibia interfaces are chosen according to the following requirements: (1) abnormal bone tissue (bone defects or severe osteoporosis) must be removed; (2) the better the smaller removed bone; (3) the better the larger contact interfaces between the prosthesis and bones. Therefore, if no abnormal bone tissue, the sections on the distal femur and proximal tibia should just cut out cortical bones to satisfy the second requirement. To satisfy the third requirement, as larger as better prosthesis should be used. However, too large prosthetic size may bring incomplete contacts on some interfaces of prosthetic femur or tibia (Fig. 4(b)).

Therefore, we check whether there exists abnormal bone tissue on the sections for generating distal femur and proximal tibia interfaces, and incomplete contacts or defects on the interfaces. We achieve these purposes by intersection computation between every pair of edge sample points. Fig. 5 shows the computation for the distal femur. Sample points on edges of the distal femur are chosen to generate a set of parallel lines for implementing the intersection computation. Two smaller (e.g. x, y) components of the surface normal of the interface are chosen to determine the parallel lines (Fig 5(a)). For example, the parallel lines has a constant integer y coordinate, in which each line space has one x coordinate unit.

Every line traverses the patient's knee volume by a 3D DDA algorithm [38-39] that can obtain all voxels traversed by the line. A boundary voxel of bone is defined as either of its six neighboring voxels does not belong to bone. Then, from the intersections of the line with bone boundary (I_1, I_2, B_1, B_2, B_3, B_4) and boundary (P_1, P_2, P_3 and P_4) of the interface, we can obtain the following information. If there exists interior boundary (I_1 and I_2) meaning that interior abnormal bones exists. This section is not a good choice and should be set upper to avoid the tumor. If the range of interface intersections (P_1 and P_2) is inside the range of bone boundary (B_1 and B_2) meaning that the bone and the prosthetic femur here contact well (closely). However, if the range of interface intersections (P_3 and P_4) is not inside the range of bone boundary (B_3 and B_4) this interface is too large to form incomplete contact or there exists defects on the contact section. If only few neighboring lines belong to such case (Fig. 5(b)), we consider it is a small

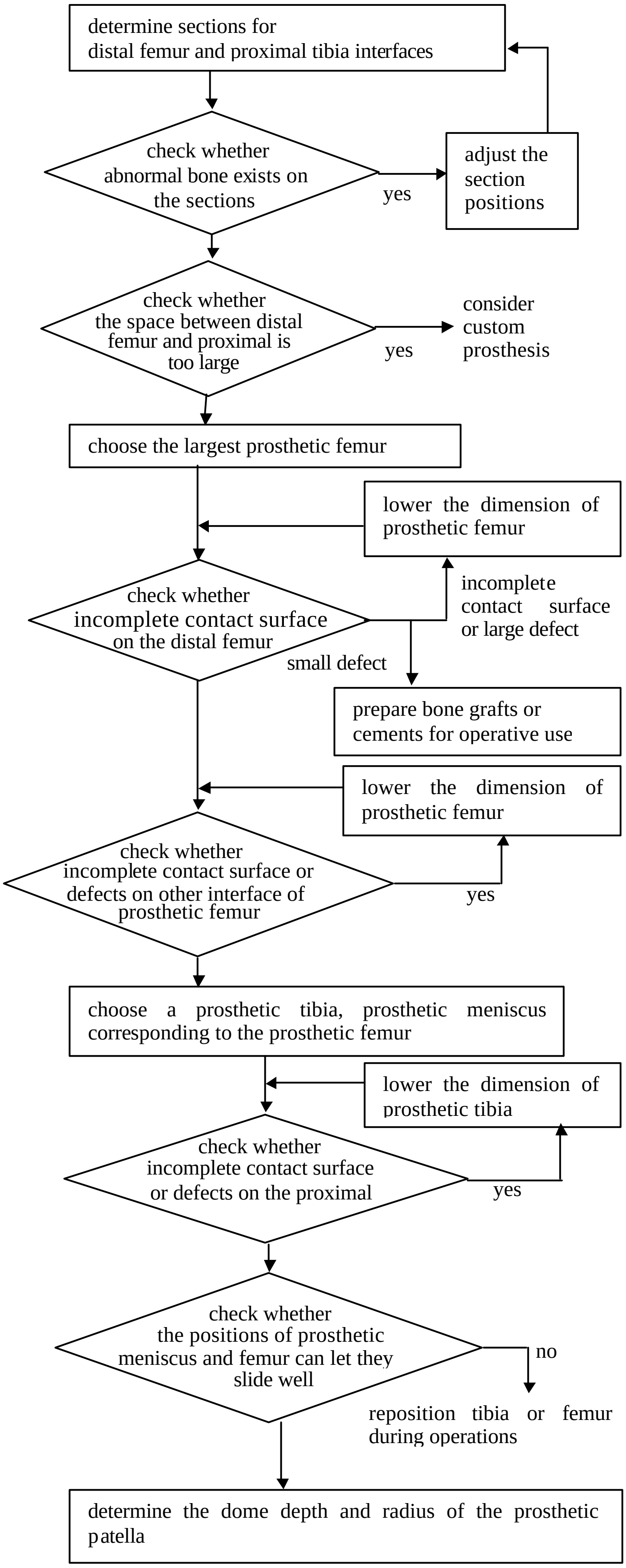


Figure 3. Flow chart of prosthetic determination algorithm

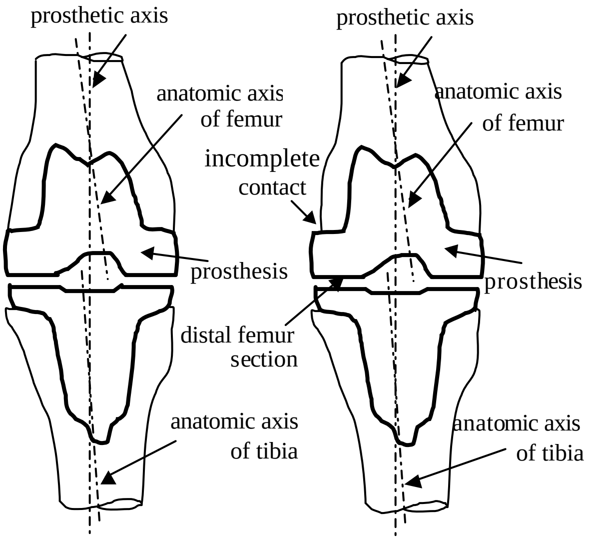
defect that can be compensated by bone graft or cements. Otherwise, it is an incomplete contact or large defect meaning that a smaller size of prosthetic femur should be used. Similar computations are implemented for the proximal tibia. A prosthetic meniscus is determined after the sections for the distal femur and proximal tibia were determined. If the space for inserting prosthetic meniscus is too large meaning that the function of the knee cannot work well and custom prostheses are suitable for the knee arthroplasty.

Second, we check whether other (anterior and posterior) interfaces of the prosthetic femur exists incomplete contact or defects. If there exit incomplete contacts meaning other (smaller) size of prosthetic femur should be used, and all interfaces after changing the size should be computed again. After the choice of the prosthesis, the positions of the prosthetic femur and meniscus are check to confirm whether the U-shape curve surface of the prosthetic femur and dome-shape surface of the prosthetic meniscus can slide well. If their positions are not optimal, a reposition on the tibia or femur should be implemented during operation to adjust their position.

Last, the dome-shape prosthetic patella is determined by evaluating the patella geometry with the following constraints: (1) the center axis of the dome-like prosthetic patella should be inserted passing the center of the patella; (2) high-dome patella (with 9-12mm thickness of prosthetic dome and peg) are preferred than low-dome patella (with 7-9mm thickness of dome and peg) but at least a certain amount (5mm) of bones should remain after the insertion; (3) domes with suitable diameters (corresponding to the size of prosthetic femur) are preferred but at least a certain distance (3-5mm) from the rim of the patella to the dome should remain. A plane that is parallel to the prosthetic axis, tangent to the U-shape curved surface of the prosthetic femur and spaces in high dome-thickness (9-12mm) to the first voxel of the patella is used to intersect the patella. The intersection calculation is the same to the one described in the previous subsection. The intersections on the plane form the boundary of the platform and determine its center about the boundary. The center of the prosthetic platform is chosen as the center axis for inserting the dome and determined as the center of the platform (from where the prosthetic is inserted into perpendicularly). To satisfy the second requirement, a line beginning from the center of the platform is used to traverse in the patella until reaching the opposite boundary by the 3D DDA algorithm and calculate the remaining distance to the boundary. If this distance is smaller than 5mm, a low-dome instead of the high-dome should be used. Then, a plane spaces in low dome-thickness (7-9mm) is used to repeatedly implement the above process. To satisfy the third requirement, the distances from the center to the intersections of the boundary are calculated to determine the diameter of the dome. The smallest distance from the patella rim to the center of the platform should be 3.5mm larger than the radius of the dome. If it is not satisfied, the dome with smaller radius should be used.

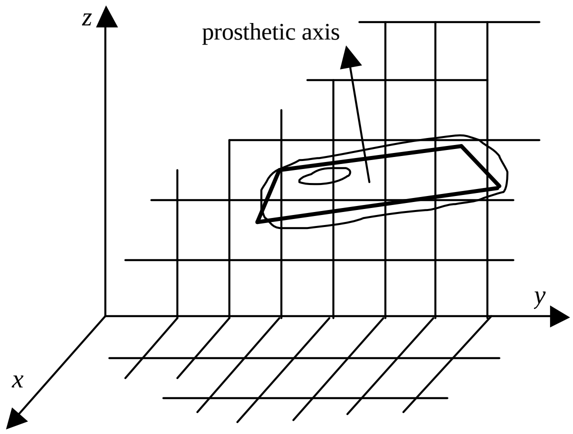
Confirm of sizes and positions of prosthetic components by surgical simulation

Surgical simulation of arthroplasty can be implemented by

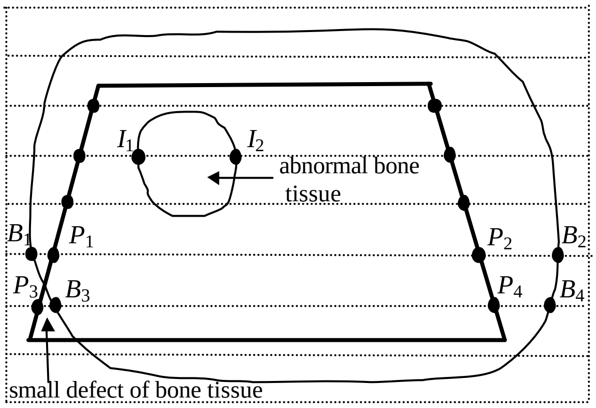


(a) Well fit prosthesis (b) Prosthesis with incomplete contact

Figure 4. Relation between a knee and prosthesis



(a) Distal femur and its section in a volume



(b) Defect and abnormal bone determination

Figure 5. Section computation on interface of prosthetic femur

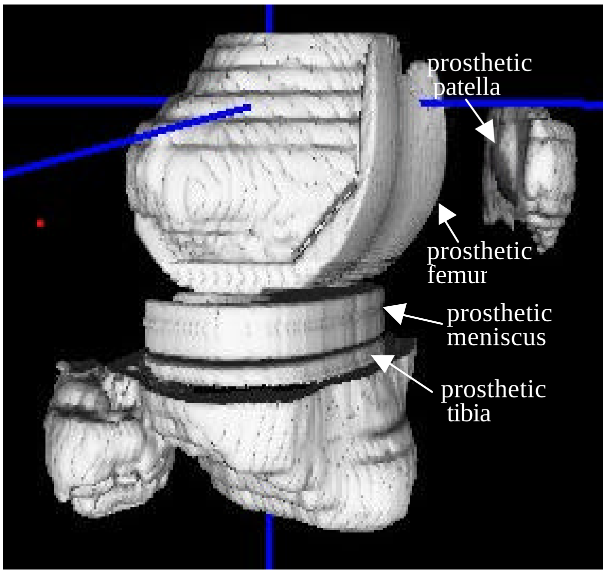


Figure 6. knee joint inserted with a computed optimal prosthesis

our reported simulator with the determined prosthesis and the patient's volume data. The simulation results of every procedure can be used to impress surgeons the geometric relations between the knee joint and the prosthesis.

Results

We have already determined knee prostheses preoperatively, and find the determined prosthetic components almost all agree the sizes that tried by template prostheses during operations. However, the number of tries may reach 3 for a template component in real operations. (Total sizes are usually 5). In addition, the prosthetic determination provide more important data include the geometry of sectioned knee for accommodating prosthesis, the positions to insert prosthetic components and the geometric relation between the knee and prosthesis.

Fig. 2(c) shows automated determined knee prosthesis for a patient of a 70 years-old woman with osteoarthritis. Fig. 6 shows the image after all prosthetic components were decided and inserted into the knee in which a large size of prosthetic femur and one size smaller prosthetic tibia was used. The thickness of the prosthetic meniscus is 15mm and the diameter of the prosthetic dome is 20mm and it is a high dome. We can observe that the dimensions and positions of the prosthetic patella and tibia are good choices in which the areas of the interfaces of the prosthetic femur and tibia are near to the ones on the sections and no defects can be observed. That means the largest contact area between the prosthesis and the bone can be achieved by an optimal sizes and positions of prosthetic femur and tibia. The radius of the prosthetic dome also near 4mm smaller than the shortest one on the patella platform and the center of the dome was near the center of the patella meaning as large possible prosthetic components can be chosen by our method. Fig. 2(c) shows automated determined knee prosthesis for a patient of a 70 years-old woman with osteoarthritis.

Discussion

In this study, we developed an automatic prosthesis determination method that computes geometric data during knee arthroplasty including anatomic axes of the femur and tibia, intersections of a surface with bones using volume data. The computing results provide optimal choices of transverse sections of the distal femur and the proximal tibia, and a prosthesis that is the comparatively largest one and can ensure all interfaces of the prosthesis can contact completely with bone tissues and the prosthetic parts well fit to each other. The intraoperative uncertainties of incomplete contact on the interfaces with bone defects, bad choices of prostheses and sections for the distal femur and the proximal tibia, and compensation impossible overcuts can be avoided by the preoperative evaluation modality.

Optimal parameters of surgical procedures such as sectioning positions, angles, width and depths can be also determined by our method. Thus, intraoperative trial and error can be avoided to reduce operation time, ease operations and promote success rate of operations. However, this modality may bring some pitfalls including adding imaging fee because CT (or MRI) slices must be used instead of a pair of plane X-rays using in current arthroplasty modalities. Surgeons have to read the information revealed by the prototype system pre-operations to replace the trial and error during operations of current modalities.

This study suggests that similar methods may be applied with few modifications to other arthroplasty such as hip or shoulder joints. In addition, the successful virtual reality simulation of the surgical procedures of the knee arthroplasty indicates that this prosthesis determination tool can be combined with our surgical simulation tool for use in automated surgical planning and verification, prognosis assessment and management; thus, promote effective management and a high treatment success rate. However, training surgeons to use the simulator is needed.

Conclusion

It was revealed, in this study, current modalities for knee arthroplasty have to choose suitable positions dimensions of prosthetic components by trial and error during operations. Our preoperative evaluation method provides an automated way of determining an optimal prosthesis and the useful information for operations includes positions of prosthetic components and defects for compensation. Our future work should prove the feasibilities of the method by applying to more clinical cases, and thus to develop a new modality.

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