Collision Detection and Free-Form Deformation for a Total Hip Replacement Planning System

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Abstract

We present an application using Continuous Collision Detection and Free-Form Deformation to assist with defining the surgical access required for Total Hip Replacement in a multisensorial virtual surgery-planning system. Defining the access route is critical for the success of the clinical intervention, so the system must allow the surgeon to plan the procedure effectively and accurately.

Keywords: Modelling, collision detection, free-form deformation.

1. Introduction

Improvements in computation and reductions in its cost have led to the adoption of advanced computational approaches to many medical applications. In particular, the use of multimedia environments has become interesting for clinical personnel training [1] and VR techniques have been used in neurological [2], craniofacial [3] and orthopaedic surgery [4].

Pre-operative planning is a fundamental phase in total hip replacement (THR) surgery [5] that has been supported by a number of systems in recent years [4,6,7]. However, these approaches have generally made limited use of advanced technologies such as immersive environments, 3D interaction, soft tissue modeling or synchronised visualisation of different medical modalities.

In this context, the MULTISENSE project [8] aims at combining different sensorial devices (haptics, speech, stereoscopic visualization and tracking) in a VR environment for pre-operative planning of THR surgery. Although the focus of the project is initially on a specific application, the effectiveness of this approach, after validation, will also be of great relevance to many other orthopaedic and medical applications. The pre-operative planning application involves the following steps:

- creation of a subject-specific model
- planning of the surgical access
- positioning of components
- testing of the planned procedure
- preparation of the surgical session.

The planning of the surgical access is critical for the success of the procedure. The surgeon must ensure that he has good visibility of the structures affected and that he causes minimum damage to them. Usually the aperture is made as small as possible, compatible with being able to perform the operation, which requires clear access to the femur and the acetabular cavity in order to section and extract the head of the femur and sufficient room to be able to introduce the various prosthetic components and tools.

2. Planning of the surgical access

The planning of the surgical access consists of two distinct tasks: skin incision and muscle retraction.

Skin incision is fairly straightforward: the surgeon performs an initial straight cut and then retracts the skin revealing the muscles. There is generally little probability of doing damage and hence we have implemented this as a semi-automatic procedure.

Muscle retraction is a more complex task, in which the probability of causing damage to muscles and other tissues is greater, so a more realistic simulation, with more advanced algorithms is needed.

A simplified description of the retraction process is as follows: the surgeon introduces the retractor between two muscles and retracts one of them towards the edge of the skin incision. The retractor is held in position (holding the muscle), while the surgeon proceeds to the next muscle. Retraction and holding are performed successively on the different muscles until the head of the femur and acetabulum are visible.

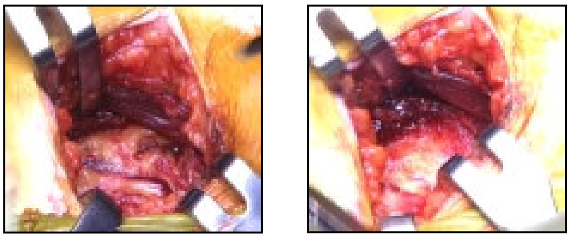

Fig. 1: Examples of surgical access with retracted muscles

Figure 1 shows two examples of muscle retraction. The retractors are in their final position and the surface of the bone is visible.

Taking this procedure into account, the following design decisions were considered appropriate:

- deformation is limited by the skin incision
- retraction is performed one muscle at a time
- only the active retractor is visible at all times
- after a muscle is retracted, the deformation remains fixed until the operation is completed
- the retractor pulls the muscle
- the muscle deforms under the action of the retractor.

The first four items define the context of the muscle retraction operation, whereas the last two determine the most important technical requirements:

- detection of contact between the retractor and the current muscle
- deformation of the surface model representing the muscle, subject to constraints.

The visual modules must also interact with the haptic force feedback component of the application. The detection of contact and subsequent deformation generate forces that are passed on to the surgeon as additional information. Both components remain synchronised by passing information about the start and end of the contact and about the extent of the displacement allowed by the underlying physical muscle model.

Figure 2 shows the appearance of the simulated surgical access in our application. The tool is shown retracting one of the muscles involved. The head of the femur is already visible through the access created.

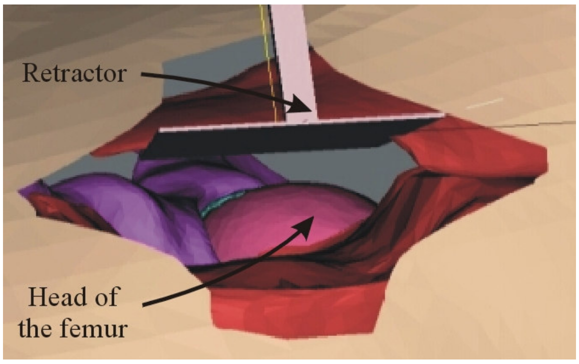

Fig. 2: The resulting surgical access in our application

Visualisation plays a critical role in the effectiveness of this virtual procedure. The focus of this paper is on the necessary visualisation algorithms to accomplish the tasks introduced above. The following sections give details about the solutions adopted and their implementation.

3. Continuous Collision Detection

Collision detection is used to determine when contact occurs between the surgical tool and the muscles, and as input for the deformation algorithm. Continuous Collision Detection (CCD) is employed in our application as opposed to Discrete Collision Detection. This ensures that no collisions are lost (even when the system is very busy). It also allows for effective computation of the time of first contact and the contact state of all colliding objects [9].

The surgeon moves the tool and, typically, when collision occurs, the tool attempts to penetrate the muscle. A set of displacement vectors can be computed to deform the affected region of the muscle so that it remains in contact with the tool, thus avoiding penetration. This simulates the effect of using the tool to pull aside a certain region of the muscle.

In our particular implementation, the retractor defines an active volume as it moves. The face of the retractor used for deformation is tracked, and two consecutive positions of this face define the caps of an *active* volume. Four more surfaces, based on the displacement of the retractor, are used to close the volume. If, at any time, this volume encloses part of the current muscle, then collision and penetration have occurred. From the position of the retractor within the muscle, the penetration depth can be computed. Figure 3 illustrates the creation of the active volume as the tool moves. The tool has encountered an object on its path and a corresponding penetration depth results.

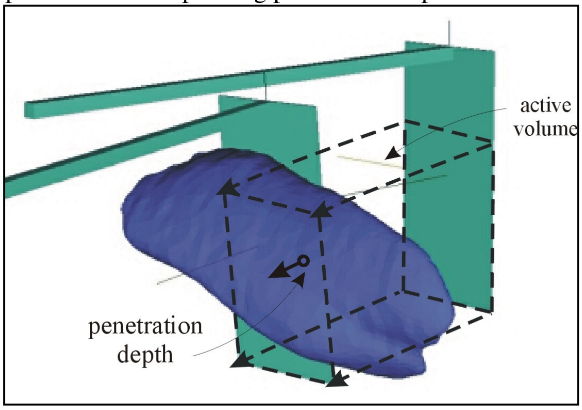

Fig. 3: The active volume defined by the tool

To compute the depth of penetration, the time of first contact needs to be determined. Although the real position of the retractor is known only for specific time instants, CCD assumes that those known positions are sampled values of an underlying continuous motion. Therefore, a certain type of motion for the retractor has to be assumed. In our case, it was assumed that between two known positions the retractor moves with constant translational and rotational velocities.

A fast first step based on the *separating axis* is used to eliminate the need to create the active volume. The separating axis theorem states that two convex polyhedra do not intersect if there exists a line for which the projections of the objects onto that line do not intersect. This can be applied to moving polyhedra with constant velocity by considering the intervals defined by their starting and ending positions [10].

The penetration depth indicates by how much the muscle should be deformed to keep muscle and tool in contact, while avoiding penetration. The result of the collision detection is a list of surface mesh vertices together with their corresponding displacement vectors. This is passed on to the deformation as input.

Alternatively, should the retractor collide with a structure flagged as non-deformable, it is also possible, from the computed depth of penetration, to determine how much the tool is allowed to move (if at all) to produce contact without penetration.

4. Direct Manipulation of a Free-Form Deformation

Direct manipulation of a free-form deformation (DMFFD) is used to perform the deformation of the muscle under retraction. DMFFD [11] is an extension of the free-form deformation (FFD) modelling technique in which a set of points of the surface model are constrained to move to specific positions.

In the original FFD an object is deformed indirectly by warping its surrounding space. The object is set inside a grid of control points which are manipulated and their displacements transmitted to the embedded object which is thus deformed. Many different variations of the basic scheme have been proposed. See for example Bechmann [12] for a survey and mathematical formalisms.

However, in our application, the deformation of the muscles is not determined by moving some control points in a grid, but is guided by the motion of the surgical tool. As it was mentioned in section 3, the collision detection module returns a list of surface vertices together with constraints indicating how these points should be displaced.

DMFFD is an inverse problem solved in two steps: (1) starting from the set of constrained points and their required displacements, the necessary modifications of the lattice control points are computed; (2) the complete embedded object then undergoes FFD. As a result, the constrained points will move to the specified positions and their neighbouring regions will show displacements that taper off to create a smooth deformation. The smoothness and extent of the deformation around the tool are controlled by the characteristics of the grid and of the volume within it.

The most important step of DMFFD is the determination of the lattice alterations. Typically, several object points are displaced simultaneously and the necessary modifications of the lattice control points must be obtained. This usually involves solving an underdetermined least squares problem and needs the computation of the pseudoinverse of a large but sparse coefficient matrix which expresses the relationship between the constrained surface points and the lattice control points.

Several techniques to obtain this pseudoinverse have been proposed, including the naïve brute-force method used by Hsu [11] and several alternatives explored by Gain [13] such as Greville's method, Householder QR factorisation and the method of normal equations, which he preferred.

Unlike in most of the previous DMFFD applications, where the number of constrained points n is small, in our case the retractor typically displaces a large number of surface points. Computing the pseudoinverse by any of the techniques mentioned before is costly and likely to be inaccurate.

To solve the inverse problem of DMFFD we have used the method proposed by Hu et al. [14]. They demonstrate that the deformation induced by simultaneously displacing several surface points can be obtained by consecutively displacing each of the individual points. The problem of computing the pseudoinverse is replaced by the problem of computing these modified displacements. This involves solving the linear system of equations

$$\Delta Q = K \cdot \Delta Q',$$

where ΔQ is the original point constraints, $\Delta Q'$ the modified displacements and K the $n \times n$ matrix that expresses the mutual influence among the constrained points. Once $\Delta Q'$ has been obtained, n individual FFD steps can be performed.

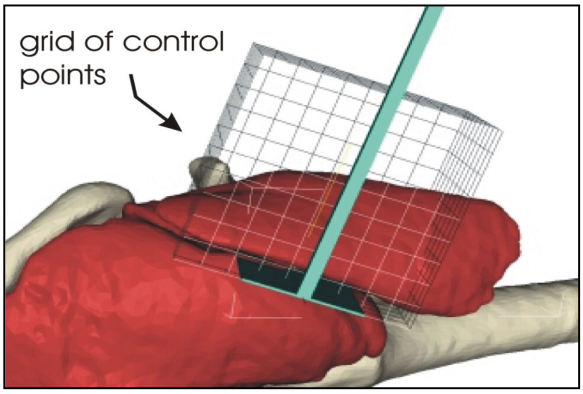

Fig. 4: Tool and FFD grid in relation to deformable surface

Two other important aspects must be handled: local control and avoidance of foldover.

In our implementation, the grid of points which controls the deformation is attached to the tool (and moves with it) and not to the muscle. This provides improved local control and allows the lattice to have an arbitrary orientation with respect to the muscle. Figure 4 shows the tool and the attached lattice oriented with respect to the currently selected muscle. This is necessary for a suitable definition of the surgical access, since the working space available to the surgeon is limited. It also means that every time a deformation process is started at a different muscle location, the polynomial coefficients relating surface and control points must be recomputed. However, this is only done for the region of the muscle within the grid, and calculating the coefficients intelligently – only as they are actually required – it has no adverse impact on the performance.

Self-interpenetration and foldover are avoided by resetting the control grid after every DMFFD step. This way the tool cannot be moved beyond the extent of the grid. This is similar to subdividing large tool transformations into small intermediate ones as proposed by Gain and Dodgson in [15].

5. Conclusions

This paper presents the solutions developed for the visual definition of the surgical access in an operation planner for Total Hip Replacement. Visualisation plays a critical role in the effectiveness of this virtual procedure since it is the main source of information for the surgeon. However, the graphical modules created are used in the context of a complex multisensorial application where they must co-operate and be synchronised with other technologies like haptic force feedback and speech recognition. Refer to [16] for a discussion of the system's integration within the MULTISENSE project. Currently the application is undergoing validation with the aim of establishing the effectiveness of the techniques employed including visualisation. The main aspects considered are:

- capabilities not provided by existing systems
- inherent accuracy
- time required to perform the task
- global accuracy in performing the given task
- repeatability and learning curve.

It is believed that true benefits can be gained with the use of this multimodal interface in all aspects of medical planning and training.

Regarding visualisation specifics, the case when muscles must be sectioned is being considered. Also, in line with current trends, we are investigating the possibilities of implementing the FFD in hardware taking advantage of the capabilities of modern GPUs is being investigated.

6. Acknowledgments

This work was supported by the MULTISENSE (IST-2001-34121) project, funded by the European Commission.

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