Preoperative Insertability Analysis and Visualization of Custom Hip Implant Designs

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Abstract

This paper describes an analysis and visualization tool for assessing the insertability of cementless custom orthopaedic hip implants. The tool enables designers to determine if an implant can be inserted without interferences into a canal carved in the bone and simulate the interference-free insertion path before surgery. It allows designers to position and visualize complex, three-dimensional implant and canal shapes, compute interference-free insertion paths, and identify implant stuck configurations and interfering surfaces. The tool validates implant designs and supports shape modification and redesign.

Problem description

Hip implants are used in total hip replacement surgery to replace the damaged joint connecting the femur and the hip (Figure 1). The implant, which consists of a spherical joint and a stem, is tightly fit into a matching canal carved in the femur. The spherical joint fits into a matching cup attached to the hip and provides leg mobility. Custom implant shapes are designed for each patient from CT data [8] so that the implant remains tightly fixated in the canal without cement.

Two often conflicting requirements in designing the shape of a custom implant are tight fit and insertability. A tight fit provides mechanical stability and adequate stress distribution transfer, promotes bone ingrowth onto the implant, and preempts the use of cement, which occasionally provides poor fixation and deteriorates over time. To achieve the tight fit, the implants must also be insertable to its final working position. High accuracy in implant machining and recent robot-assisted bone canal preparation techniques with submillimetric precision allow the design of complex shapes closely matching the patient's anatomy and tight fits with clearances of less than 1/100" [6, 7, 9]. These accuracy characteristics greatly difficult insertability analysis.

In current practice, implant insertability is manually tested during surgery after the canal has been broached and reamed. This sometimes leads to loose fits, excessive bone removal, bone splitting, or suboptimal designs. Preoperative quantitative evaluation and visualization are necessary to identify possible interferences, determine shape modifications to remove the interferences, and determine the interference-free insertion path. Existing CAD systems model the implant and the canal and position them at individual configurations, but cannot show them with CT data, nor can they construct interference-free paths. Recent medical visualization systems allow for the intergation of CAD and CT data but lack interference testing capabilities [1, 2].

We have developed a tool, called EXTRACT, for computing and visualizing the interference-free insertion path of an implant into a canal from a CAD description of their shapes. The program formulates the problem as a peg-in-hole insertion problem for complex, tightly fit three-dimensional bodies requiring small, coupled six-degree of freedom motions in a preferred direction. It computes an insertion path by formulating local, linearized configuration space constraints for small motions and solving a series of linear programming problems. The program either finds a successful insertion path or reports the stuck configuration. In the stuck configuration, it identifies the surfaces causing the interference, facilitating the redesign of the implant and the canal shapes. EXTRACT allows the user to view the insertion of the implant into the canal and the stuck configurations from different perspectives. The program has been tested on real implant designs and is currently under clinical evaluation by a major medical implant manufacturing company.

This paper briefly describes the three modules of the program: modeling, path computation, and visualization. Modeling constructs an implant and canal mesh to a prespecified resolution. Path computation formulates the motion constraints and optimization problem from the mesh descriptions and finds an insertion path by solving a series of linear optimization problems. Visualization allows the user to view the insertion path and the stuck configurations. We describe variations and extensions to the basic insertion algorithm described in [3, 4] and report new experimental results on real cases.

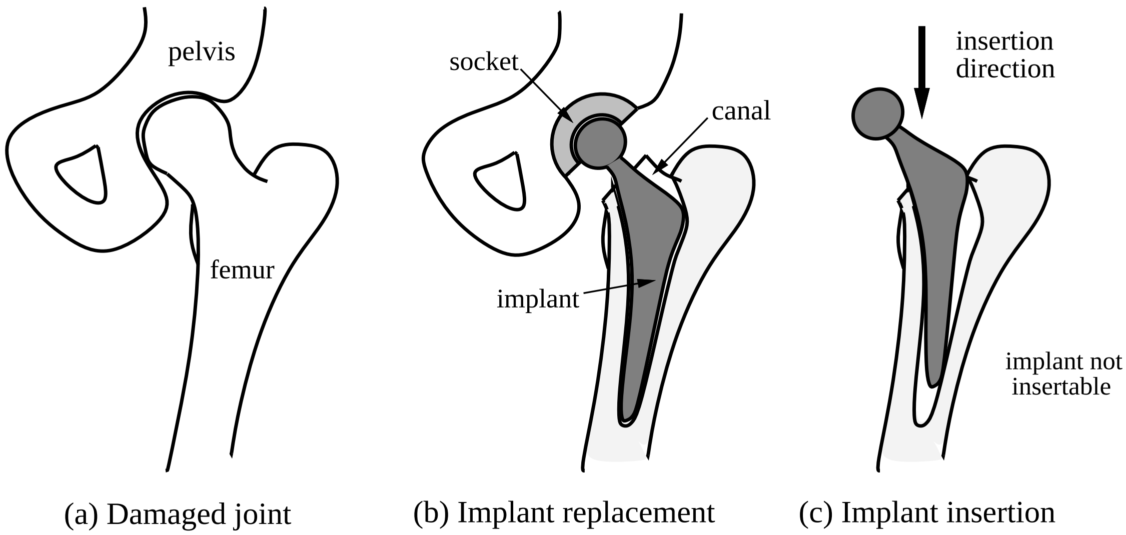


Figure 1: Illustration of a hip replacement procedure. A damaged joint connecting the hip and the femur (left) must be replaced by a metal implant inserted into a canal carved in the bone (center). Because of the desired tight fit between the implant and the canal, implant insertion into the canal fails for certain shapes (right).

Modeling

The modeling module approximates the implant and canal shapes with regular meshes constructed from their CAD representations. The shapes are specified by a stack of parallel two-dimensional slices describing the shape contour defined by cubic splines forming a closed contour. The contours are manually defined by the designer from consecutive bone cross sections obtained from CT scans. The program models the implant shape as a regular mesh of points on the implant surface, and the canal shape as a mesh of planar facets on the canal surface. The meshes are created by choosing points and planar facets within the desired shape approximation resolution. The error bound for approximation is computed directly from the analytic expression of the splines.

Path computation

The path computation module finds an *extraction* path that takes the implant from its inserted position inside the canal to a position outside the canal (the insertion path is simply the extraction path reversed). The path specifies the *configurations* (positions and orientations) of the implant during the motion. The implant configuration is uniquely defined by three rotations and three translations of the implant's coordinate frame with respect to a fixed coordinate frame. The insertion path is described by a series of small motion steps that define a sequence of interference-free implant configurations starting at the initial configuration (somewhere above the canal) and ending at the final configuration (the implant's inserted configuration).

The insertion problem is formulated as a peg-in-hole path planning problem in configuration space [5]. The formulation accounts for complex, tightly fitting three-dimensional bodies requiring small, coupled six-degree of freedom motions in a preferred direction. Deformations and dynamic effects, such as friction, are ignored. To guarantee that the insertion path is interference-free, the program formulates *configuration constraints* derived from the implant and canal shapes. The configuration constraints define the implant configurations for which the implant surface does not penetrate the canal walls. All configurations in the insertion path must satisfy the configuration constraints.

Configuration constraints are reduced to simpler local configuration constraints by observing that, because of the tight fit between the implant and the canal, the motion of any point in the implant surface is only constrained a small portion of the canal surface in its immediate neighborhood. Small motions of the implant are thus only constrained by their closest canal surface facets. Local configuration constraints, formulated for each point in the implant mesh, are linearized using a small motions approximation. The result is a set of linear inequalities defining permissible interference-free implant configurations for small motions. To account for bone compliance, approximation errors, and small design inaccuracies, we allow a small user-defined amount of overlap between the implant and the canal by adding a positive constant term to the inequalities. (For details of the mathematical formulation of the problem, see [3, 4]).

To compute an insertion step, the program formulates a linear optimization problem LP with the linear local configuration constraints and the preferred inser-

Figure 2: Example of an insertion sequence of an implant stem (dark body) tightly fit into a canal (translucid body) from the initial inserted configuration (left) to the final free (right) configuration.

tion direction as the objective function. The solution to LP yields the largest interference-free insertion step in the neighborhood of the previous implant configuration. To find the next insertion step, the program updates the pairing of implant points and their closest canal facets, updates the local configuration constraints, and solves the new LP problem. This process is repeated until no further progress in the preferred direction is possible. Each LP problem is 6-dimensional with a linear number (in the number of implant points) of inequalities. The solution to the problem LP also provides information necessary to identify interference surfaces. The active local constraints in LP (a local constraint, defined by an inequality, is said to be active when the equality condition holds) indicate contact and identify the canal surfaces that prevent the implant motion.

Local, focused search for alternative configurations is introduced to unwedge the implant and continue with the extraction. This strategy is pursued until the implant reaches a prespecified height or no progress is possible. The search strategy is determined by the form of the objective function, which is initially set to the preferred insertion direction, defined by the canal spine. It can be dynamically modified to approximate different strategies, such as wall compliance or centering, or localized search strategies, such as implant retraction or wobble. The number of implant configurations in the path, and thus the complexity of the algorithm, depends on the distance between the initial and final configuration, on the resolution of the implant and canal shape approximations, and on the amount of backtracking necessary.

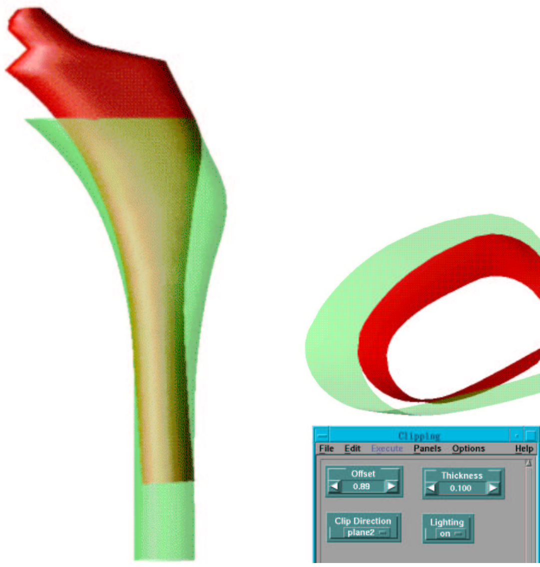
The program outputs a sequence of implant configurations that define the insertion path. The path configurations are guaranteed to be interference-free to within the resolution. The program monitors small overlaps and compiles quantitative information on the insertion path such as clearance, overlap, and angular and translational displacements. This information is useful in evaluating the quality of the path and the implant and canal design. The insertion paths produced by the program are quasi-monotone in the preferred direction (a path is monotone in a preferred direction iff it always shows progress along that direction), which avoids implant designs that require complex, time-consuming maneuvers and excessive search by the surgeon during manual insertion. Figure 2 shows an example of an insertion sequence.

Visualization

The visualization module allows the user to visually analyze the insertability problem. It realistically renders the implant and the canal and allows the user to interactively position and view the implant in various configurations (Figure 3(a)), selectively choose and view portions of the implant and canal shapes to identify interferences (Figure 3(b)), and animate the insertion path (Figure 2). The module uses the meshes created by the modeling module to render the implant and the canal. The module is implemented in using IBM's Data Explorer Visualization Package.

Implementation and experiments

EXTRACT is implemented in C and uses IBM's Optimization Subroutine Library (OSL) to solve the linear optimization problems. It has been successfully tested



(a) (b)

Figure 3: (a) 3D rendering of an implant (dark body) stuck in a canal (translucid body); (b) detail of interference surfaces and control panel.

on about 20 real examples provided by a major medical equipment manufacturer, including those shown in Figures 3 and 2.

Typical implants and canals are 4" high with cross section diameters between 0.5" and 2". The spacing between CT cross-sections from which the shapes are defined varies from 0.1" to 0.025". Shapes are described with about 80 planar slices, each described with 25 to 80 splines forming a closed contour. In most cases, the canal shape is almost the complement of the implant shapes, grown by about 1/100". Critical implant configurations are near the inserted configuration. At about 2.5" height from the bottom of the canal, the implant can be directly extracted from the canal with a straight vertical motion.

To achieve the desired resolution, the implant and canal shapes were approximated to a resolution between 0.01" and 0.025"with equal bone compliances. This approximation required between 3000 and 8000 implant points and canal neighborhoods. Between 300 and 1500 motion steps were required for a total path length of 2.5". Running times were between 10 and 45 minutes on an IBM RS/6000 Model 530 workstation with 64MB of main memory. In all but two cases, the implant insertion paths were successful. The successful and stuck cases were then validated both quantitatively (by measuring the maximum amount of overlap in the paths' configurations) and visually. For the stuck cases, we made sure was that no insertion was possible by manually exploring alternate insertion paths and measuring overlap.

Summary and future work

This paper describes an analysis and visualization tool for assessing the insertability of cementless custom orthopaedic hip implants. The tool enables designers to compute interference-free implant insertion paths to any desired resolution and identify stuck configurations and interfering surfaces. It allows designers to validate designs, identify stuck configurations and interference surfaces, modify shapes, and plan the implant insertion path preoperatively.

One area of current and future work includes semi-automatic shape modification. Shape modification seeks to minimally modify uninsertable implant and canal shapes to make them insertable. Since the program can identify the interference surfaces, the modification process can attempt to eliminate the interferences by rehaping portions of the shapes according to some optimization criterion, which can be modified manually to account for alternative choices.

Acknowledgments

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