Robust and Intuitive Meshing of Bone-Implant Compounds

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Abstract:

To preoperatively assess the functional outcome of a total joint replacement, finite element analysis can be used for an objective evaluation of individual implant configurations. For large scale studies, where the implant configuration is varied in size, position or design, numerous finite element meshes have to be generated. To improve the planning process we propose a method that outputs a merged tetrahedral mesh of the patient's joint anatomy and an arbitrarily positioned implant geometry suitable for finite element analysis. Our approach has several advantages: (1) it avoids error-prone intermediate stages, e.g. data type conversion, (2) it is able to preserve constraints such as sharp edges and (3) it can be fully automated by initially defining a few parameters that describe the desired geometric accuracy and element quality. Based on the meshing of 100 different patient-specific bone-implant setups at the tibia (shinbone), we show that our approach produces high-quality meshes in all cases automatically.

Keywords: orthopedics, finite element analysis, 3d mesh generation, multi-material

1 Motivation

Finite element analysis (FEA) has become an approved instrument in orthopedic surgery to preoperatively assess the functional outcome of joint replacement procedures as it allows for an objective evaluation of bone-implant compounds. When optimizing implant size and position for a single subject or when investigating new implant designs for a large population [1], numerous different implantation setups have to be analyzed to determine and compare characteristics like the expected strains and stresses during everyday activities. To perform such analyses, FE-meshes (typically tetrahedral grids) have to be automatically generated that minimize computation time while maintaining reasonable accuracy of the FEA outcome. In other words, the resulting meshes have to be accurate w.r.t. the patient's anatomy and the implant shape, must be of FE-suitable quality, and consist of as few as possible number of elements [2].

To generate finite element meshes in a joint replacement scenario the input is typically given as a combined description of the subject-specific bone, provided as a geometry or a voxel representation, and the positioned implant that is usually given as a geometry. From those overlapping bone and implant structures, the output is aimed to be a conformal multi-material mesh, i.e. a set of tetrahedra, each of which is assigned to one material and two neighbouring tetrahedra share exactly one of their respective faces (Fig. 1).

Current approaches to generate such tetrahedral meshes typically require an explicit fusion of the objects to be discretized before meshing, for instance using a single voxel- or surface-representation. While inconsistencies resulting from object overlaps are resolved easily within a voxel grid, the resulting mesh typically suffers from artificially introduced inaccuracies, for example lost information about sharp edges [3]. Alternatively, a consistent description as a surface triangulation that separates the different objects (or domains) can be computed. This is likely to cause problems where boundary intersections introduce small angles or narrow inter-boundary regions occur. A triangulation of those regions leads to very small or badly shaped triangles (Fig. 2a). If a meshing approach is used that depends on this boundary representation, like the advancing front method, unnecessarily small or badly shaped finite elements will be introduced.

Recently, Pons et al. [4] introduced a meshing approach, where a so called *oracle* is employed during the mesh generation procedure. At each phase of the meshing process the *oracle* can perform a query to retrieve the current object (or material) at an arbitrary point in 3D space, thus providing an implicit representation of each possible input type, like voxel representations, implicit surfaces or triangular surfaces. This approach allows for a direct meshing without an intermediate generation of a single (explicit) domain description, i.e. no Boolean operations are necessary before the actual volume meshing. The parameters that are set for the volume mesher are the only constraints that guide and restrict the meshing process. However, the *oracle* does not allow for an explicit definition of features to be preserved, like sharp edges (Fig. 2b). In scenarios where the geometry of an object has to be preserved as accurately as possible without introducing too many finite elements, as for mechanical parts like a prosthesis, this might turn out as a significant drawback.

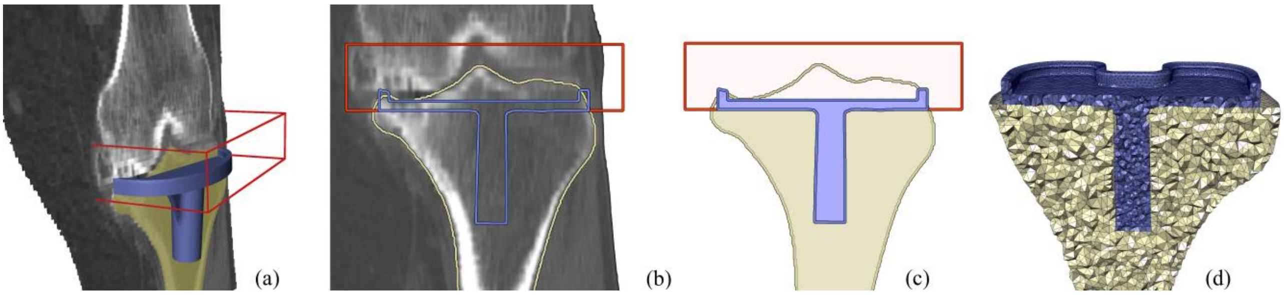

Fig. 1: Meshing setup. (a) Segmented tibial bone (yellow) with aligned implant (blue) and the region where bone will be cut off (red box), (b) 2D view of the setup, (c) overlaps are resolved: the implant covers all other objects, bone within the red box is removed (d) conformal tetrahedral grid.

Contribution We extended the approach of Pons et al. [4] by a method that is specifically designed to handle the above mentioned problem, but still preserves the general concept of the *oracle* approach. Additional geometric constraints can be defined to preserve relevant features at specific locations in the mesh. Furthermore, we provide a hierarchical management of the input objects to intuitively handle their overlaps, e.g. between implant and bone (Fig. 1c). By comparing the results of our new meshing approach to 100 meshed tibiae from a large scale study on biomechanical behaviour [1] we can show that our feature preserving method is able to automatically generate good finite element meshes in terms of element quality.

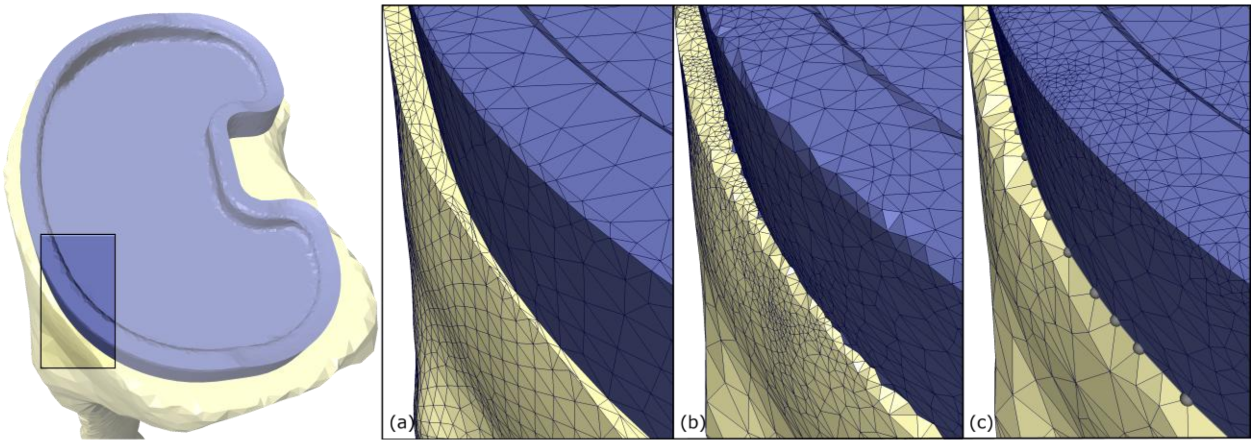

Fig. 2: Meshed bone/implant compound with a narrow region between bone and implant surface. (a) Close-up view of surface-based method; badly shaped or very small triangles are created. (b) Result of the *oracle*-based method without prescribed features, elements have good shape but sharp features are poorly resolved. (c) Close-up view of *oracle*-based method with our feature preserving extension applied to the implant. While sharp edges of the implant have been maintained, the shape of the bone is approximated by the mesher according to desired element size and shape.

2 Methods

The method introduced by Pons et al. [4] is based on refining an initial Delaunay triangulation of randomly selected boundary points, i.e. points that lie on material interfaces. Successive insertions of points locally refine the mesh and are used to adjust the tetrahedralization to the prescribed quality criteria. During the refinement, lists are maintained that contain all *bad* surface triangles (called facets) and all *bad* tetrahedra, i.e. elements that do not fulfill the desired quality criteria. First the algorithm aims at clearing the list of bad facets by adding more interface points in their proximity. As a second step the bad tetrahedra are refined by adding their circumcenter to the point set. This can introduce new bad facets that have to be removed from the facet list before continuing the refinement of the tetrahedra. The algorithm terminates when the mesh contains no more bad facets and tetrahedra, i.e. all quality criteria are fulfilled. The method lacks a criteria for one-dimensional characteristics such as edges and ridges as they appear on mechanical objects like implants. Such features are only represented implicitly by the *oracle* and are being recovered by refinement of the facets according to their quality criteria only. The actual edge is unlikely to be discovered exactly and sharp edges are smoothed out in the final mesh (Fig. 2b).

To explicitly maintain such features, we extended the existing method by another list containing all segments that are prescribed by the user but do not appear in the current meshing stage. The first priority is to maintain those segments before refining any facets and tetrahedra. Analogously to the original method, point insertions for facets and tetrahedra can cause further refinements of the prescribed segments. Boltcheva et al. [5] proposed a similar extension to preserve one-dimensional features for medical image data. Their approach includes an extraction of such features from a single voxel image but does not allow for an adaptive refinement of these edges to assure that the desired quality criteria are met.

To handle overlaps of bone and implant, we implemented a hierarchical model that assigns a priority to each object according to its position in the input list. During the meshing process each point query to the *oracle* automatically returns the material with the highest priority. This allows for an intuitive combination of multiple overlapping objects into a single compound representation. The implant, which should be completely preserved, receives the highest priority. Its vicinity, where bone will be removed, has mid-level priority. Overlaps of this region and lower priority objects will be treated as empty (Fig. 1b). Note that this is different from meshing it beforehand and removing the corresponding material afterwards as this would affect the mesh generation process. In our implant case, bone material with lowest priority will only be meshed in areas where no object with higher priority is located.

The actual meshing method is driven by Delaunay refinement minimizing the overall radius-edge ratio (quotient of radius of the circumsphere and minimal edge length). This ideally leads to meshes that do not contain tetrahedra with very small dihedral angles, because these are mostly induced by elements with at least one short edge but a large circumsphere radius. Small dihedral angles cause an increase of the FE's stiffness matrix' condition and therefore slow down the FE computation or even significantly distort the computational outcome [6]. Delaunay refinement tends to generate so-called slivers that consist of four equally spaced vertices roughly around a circle, exhibiting a small *radius-edge ratio* but also small dihedral angles. To remove slivers, we employ post-processing steps proposed by Cheng et al. [7] and Tournois et al. [8] that locally change the mesh in order to increase the minimal dihedral angle (MDA). We implemented our approach as an extension to the existing 3D Mesh Generation package available in CGAL (version 3.7) [9].

3 Results

From a previous study, FE meshes of implanted tibiae were available that were meshed by an advancing-front approach to compute strains at the bone-implant interface [1]. We randomly selected one hundred virtual total knee replacement settings from that study, including geometric representations of the tibia and the tibial component. For each implant the region where protruding bone is removed was given and its sharp edges were marked as line segments to be preserved. Note that edge features had to be defined only once and could also be computed automatically by a feature extraction algorithm [10]. The one hundred datasets were then meshed with and without our feature-preserving extension, where the latter essentially equals the original method by Pons et al. [4]. In both setups the desired quality criteria were chosen as follows: (1) a maximal *radius-edge ratio* of 1.1 for all materials, (2) a maximal *cell size* (circumsphere radius) of 1mm for the implant and 3 mm for the bone and (3) a maximal *facet distance* of 0.1 mm to approximate the surfaces for the implant and 2 mm for the bone material. While meshing failed in 7 cases with the previous method due to distorted elements, all meshes were generated successfully with our new approach.

The FE-meshes generated with our feature preservation enabled met the quality criteria with 437,000 tetrahedra on average (range 295,000 to 707,992). The number of tetrahedra generated without feature preservation was significantly larger with an average number of 900,898 tetrahedra per mesh (range 614,234 to 1,533,011).

During FEA the condition of the stiffness matrix plays a crucial role for the efficiency of finite element analysis. This property is closely related to the worst tetrahedral element of the grid in terms of the minimal dihedral angle [6]. For the new meshes, generated including feature preservation, the average MDA was 8.72° (±1.31°). The models that where generated using an advancing front approach and used for FEA [1] obtained an average MDA of 4.09° (±3.18°) (Fig. 3).

4 Discussion

We introduced a new method to automatically generate tetrahedral meshes of bone-implant compounds from any configuration of implant and bone suitable for FEA (Fig. 2 and 4). In contrast to state-of-the-art methods, our approach does not require the error-prone generation of intermediate representations to resolve overlaps of the objects to be meshed. Instead a hierarchy on these objects implicitly represents the compound. Features like sharp edges can be predefined to explicitly maintain such geometric properties if necessary. The desired mesh quality is guided by only a few parameters. The quality of the generated meshes and the possibility to fully automate the meshing process make our new method an ideal tool for FEA on a large amount of meshing configurations or clinical implementations of FEA-based decision support systems in orthopedic surgery and beyond.

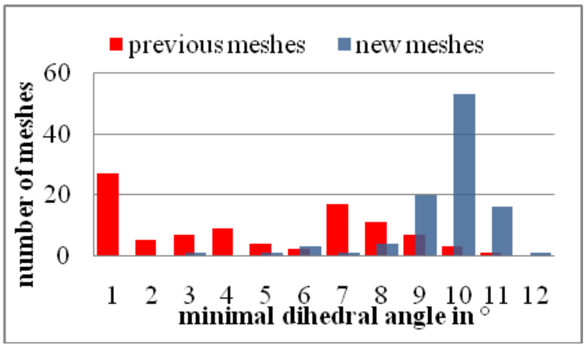

Fig. 3: Minimal dihedral angles (MDA) of all 100 meshed bone-implant compounds. A large number of models meshed with the previous method has very small MDAs. With our new approach only a few models exhibit MDAs below 5 degrees.

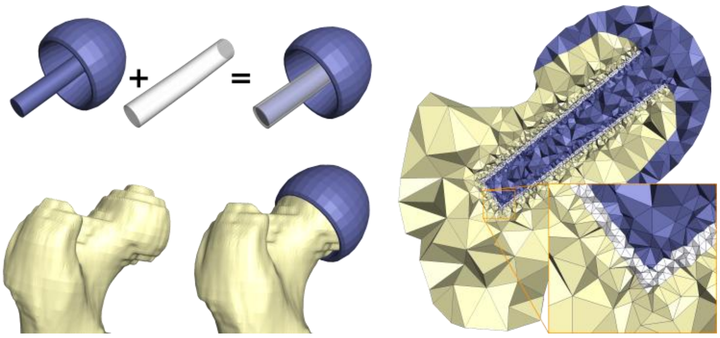

Fig. 4: Example implantation setup for a hip resurfacing (proximal femur). A cement layer surrounds the implant's stem. Bone will be removed were it interferes with the implant.

With our feature preserving extension we obtain significantly fewer tetrahedral elements compared to the original method using identical quality criteria. We attribute this to the fact that for the original method geometric accuracy (mainly guided by the facet distance) is achieved by further *unguided* refinement of the mesh in areas where the quality criteria are not met. Our method specifically aims at reconstructing the requested features first due to a more targeted point insertion during the refinement process in those areas. The minimal dihedral angle (MDA) of the new meshes (with feature preservation) is significantly larger than the MDA obtained with an advancing front approach we used to generate FE-meshes for a large scale study. This is an important indicator that the models generated with our method are suitable for FEA. Proving termination of our extended Delaunay refinement method is subject to future work as well as investigating the influence of our new approach on the FEA in terms of convergence time and simulation outcome.

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5 References

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