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Journal of Biomechanics 33 (2000) 1005–1009

JOURNAL OF BIOMECHANICS

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The mesh-matching algorithm: an automatic 3D mesh generator for finite element structures

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Accepted 21 February 2000

Abstract

Several authors have employed finite element analysis for stress and strain analysis in orthopaedic biomechanics. Unfortunately, the definition of three-dimensional models is time consuming (mainly because of the manual 3D meshing process) and consequently the number of analyses to be performed is limited. The authors have investigated a new patient-specific method allowing automatically 3D mesh generation for structures as complex as bone for example. This method, called the mesh-matching (M-M) algorithm, generated automatically customized 3D meshes of anatomical structures from an already existing model. The M-M algorithm has been used to generate FE models of 10 proximal human femora from an initial one which had been experimentally validated. The automatically generated meshes seemed to demonstrate satisfying results. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Finite element modeling; Automatic meshing; Elastic registration; Inferrence; Medical images

1. Introduction

Finite element (FEA) analysis of muscular-skeletal systems has been developed in order to assess strain and stress fields within different anatomical structures. This method presents a wide range of applications in orthopaedic domains, such as bone remodeling analysis (Huiskes et al., 1993; Weinans et al., 1993), mechanical behavior of bones with or without an implant (Skinner et al., 1994; Kuiper et al., 1996; Mann et al., 1995) and fracture process understanding (Lotz et al., 1991; Janson et al., 1993). These analyses require a knowledge of the exact geometry and mechanical properties of the different structures. Unfortunately, FE analyses are usually limited to only one specimen due to the prohibitive amount of manual labor required to generate a three-dimensional mesh. According to this, many two-dimensional bone models have been developed in the orthopaedic research field, offering thus the possibility of high 2D mesh refinement, with a limited manual intervention (Carter et al., 1984; Weinans et al., 1988). In practice, when three-dimensional FE analysis for bone was carried out, some compromises were often made in terms of homogeneity (Oonishi et al., 1983), symmetry (Huiskes and Heck, 1981) or mesh refinement (Vichnin and Batterman, 1982). Moreover, 3D models, based on "average" bone geometry, have also been developed (Lotz et al., 1988; Weinstein et al., 1987), losing thus any patient-oriented specificity. However, patient-specific three-dimensional FE models are important as they would be a way of correlating mechanical predictions with clinical results. This is the reason why the automated FE modeling of bone by using CT scan voxels as developed by Keyak et al. (1990, 1993) is of great interest.

The objective of the present paper was to suggest a new method allowing automatical 3D mesh generation for structures with complex geometry as in the case of bones. The mesh-matching (M-M) algorithm has been used to generate automatically customized 3D meshes of proximal femora from an existing 3D mesh.

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PII: S0021-9290(00)00055-5

2. Materials and methods

The M-M algorithm is based on a registration method which was originally proposed for applications in computer-integrated surgery (Lavallée et al., 1995, 1996; Szeliski et al., 1996). This algorithm was applied here to transform an existing FE bone model to the same type of bone but from another patient. This paper focused more specifically on the proximal region of the femur (from the top of the head to the bottom of the lesser trochanter).

2.1. Mesh-matching (M-M) algorithm

This section presents an outline of the elastic registration method which is used to reshape an object in order to match another object using a hierarchical and adaptive 3D displacement grid called octree-spline to represent the 3D transform between object and using gradient features to match object (Szeliski and Lavallée, 1996).

The idea consists of finding the 3D transform **T** which is the combination of a rigid-body transformation RT, a global warping W and a local displacement function S built on the hierarchical and adaptive grid of displacements basis (*octree-splines*) :

$$\mathbf{T}_{\mathrm{p}} = \mathrm{RT} \circ W \circ S, \tag{1}$$

where **p** is a vector gathering the six parameters that define RT, the 12–30 parameters that define W and the thousands of local displacement vectors that define S.

Let $\mathbf{M} = \{M_i, \quad i = 1,\dots,N_1\}$ and $\mathbf{P} = \{P_i, i = 1,\dots,N_1\}$ be the sets of model and patient features, obtained by segmentation algorithms. The elastic registration algorithm minimizes a least-squares criterion $E(\mathbf{p})$, given by

$$E(p) = \sum_{i=1}^{N_1} \frac{1}{\sigma_i 2}[\mathrm{dist}(P, T_p(M_i))]^2 + R_p, \tag{2}$$

where **R** defines a regularization term which is applied to S in order to obtain a smooth displacement function,

σ_i^2 is the variance of the noise of the measurement i (Besl and McKay, 1992), and dist is the distance between the set **P** and a point M_i' (transformed by **T**). In that case, the distance dist is a 6D distance function, as proposed by Feldmar and Ayache (1996).

The optimization of $E(\mathbf{p})$ is performed by using the Levenberg–Marquardt algorithm (Press et al., 1992) and a modified conjugate gradient algorithm in the hierarchical representation of **T**, in order to smooth the solution and to speed up the minimization.

2.2. Finite element meshing using the M-M algorithm

Transverse CT images (Siemens, DRH2) were performed on 11 cadaveric femora devoid of pathological signs. One millimeter thick slices were performed at 3 mm interval for the epiphyses and at 20 mm interval for the diaphysal region. Each image was subjected to an edge detection using the threshold method in order to extract bone contour lines (SIP305, © Inserm). Each contour line was defined by a finite number of parametric cubic splines. The connection of cubic curves from two successive slices provided the 3D bone surface.

2.2.1. Reference 3D mesh

The so-called "reference 3D mesh" was constructed with the help of the mechanical software (MSC/Patran V7.5, MSC Software). The complexity of the femur geometry did not allow the mesh processing to be automatically obtained. This mesh which was based on the previously detected bone contour lines comprised hexaedric (8 nodes) and wedge (6 nodes) elements. It comprised 3572 3D elements and was widely validated by means of experimental techniques. Mechanical properties of the bone were chosen from the literature (Hobatho et al., 1991) in the case of cortical bone and from predictive relationships with the computed tomography (CT) number (Couteau et al., 1998) in the case of cancellous bone. Firstly, a vibrational technique provided a good agreement between experimental resonant frequencies and those obtained numerically. Secondly, extensometric measurements demonstrated relatively low errors between experimental strains and those calculated numerically.

The mesh generation is particularly difficult in the proximal region of the femur because element layers have to be, as far as possible, perpendicular to the curved axis of the proximal femur (Vander Sloten and Van Der Perre, 1995). This is the reason why the automatic mesh generation was evaluated on this region (proximal femoral epiphysis). Consequently, the reference 3D mesh was defined by the elements located between the top of the head and the bottom of the lesser trochanter.

2.2.2. Patient-specific data sets

The 3D surfaces of the other 10 femora which were computed from CT scans were meshed with 2D elements (quads and triangles) in order to obtain the external points of the bone structure. Then, the reference femur and each femur surface point were superimposed by using centroids of each data set as well as principal axis of inertia. The next step was the matching of the 3D reference mesh to the "target" points (Fig. 1) by means of the M-M algorithm.

2.2.3. M-M algorithm application

The M-M algorithm computed first the volumetric function **T** that transformed external nodes of the reference mesh into surface "target" points. This elastic volumetric registration took less than 30 s on a DEC Alpha 5000 workstation. Then, this transformation **T** was applied to all the nodes of the 3D reference mesh leading to

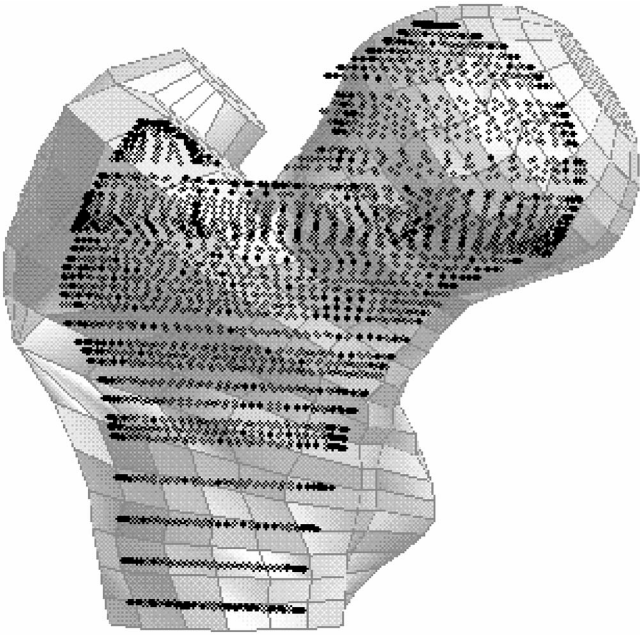

Fig. 1. Superimposition of the reference 3D mesh (grey) with the 3D surface target points (black) from one of the 10 other femora.

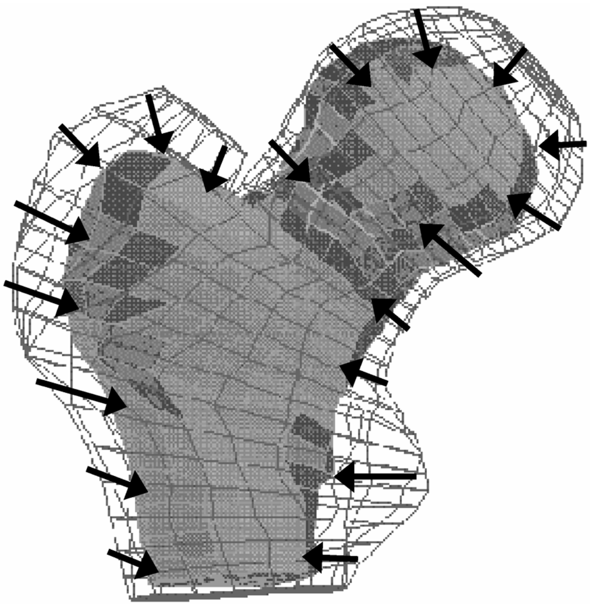

Fig. 2. 3D mesh of the donor's femur (shaded grey) generated from the "reference" 3D mesh (wireframe).

a new 3D mesh (this step required less than 10 s). Fig. 2 illustrates the mesh generation of one patient femur model based on the reference mesh transformation.

3. Results

The application of the M-M method to the 10 proximal femora demonstrated successful transformations in

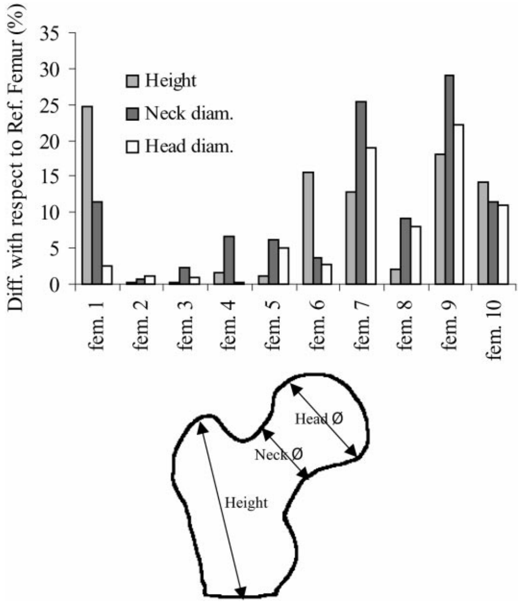

Fig. 3. Geometry differences with respect to the geometry of the reference femur. Dimensions of height, neck and head diameters were given in % of the reference femur.

spite of significant differences in bone geometry. Actually, the differences between femur geometry have been quantified by comparing geometrical parameters (height, neck Ø and head Ø) of the 10 femora with that of the reference femur. The maximum differences were around 25, 30 and 23% for ,respectively, the height, the neck and the head diameters (Fig. 3).

Moreover, the 10 generated meshes have presented element geometry as regular as that of the reference model. Generally, the mesh regularity is tested by checking element distortion with respect to an ideal shape. The mechanical software (MSC/Patran V7.5) checks the distortion of each element through the angle between isoparametric lines of the element. Classically, the criterion of this test consists in verifying whether the angle is greater than 45° or less than 135° in order to reduce the influence of the element distortion on the accuracy of the numerical integration (Dhatt and Touzot, 1984). If the angle is found outside this range of values a warning message is declared for the element. Our reference mesh had 14% of the elements with at least one angle outside the 45–135° range. Nevertheless, the mean value of the worst angles of the declared distorted elements was equal to 35°. Moreover, 75% of the distorted elements had their worst angle between 30 and 45°. This was not so far from the reasonable range and probably explained why the validation of the reference mesh was satisfactory. This mesh has been considered as a reference concerning the regularity of the elements. The 10 other generated meshes have thus been compared with this reference. For those meshes, the rate of distorted elements was around 15%

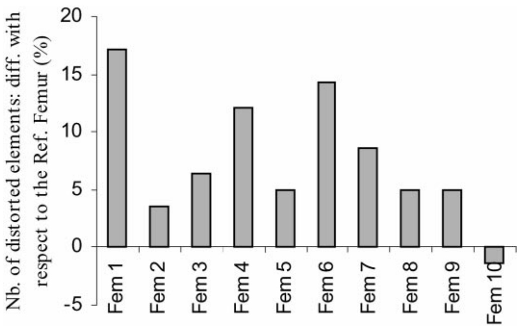

Fig. 4. Difference in the number of distorted elements with respect to the reference femur (%).

and the mean worst angle was equal to 34° (Fig. 4). Moreover, the percentage of distorted elements with the worst angle between 30 and 45° was around 72%.

4. Discussion

The M-M method allowed the automatic generation of FE meshes of patient proximal femora from an existing 3D model. For the 10 donor femora tested in this paper, the element shape checking was satisfactory in comparison with the reference model. Therefore, the potential of the M-M method to mesh complex structures becomes evident. The necessity of having an initial mesh can be seen as a disadvantage of this method. Nevertheless, this can give the opportunity to have an optimal model with desired refinement mesh regions according to the geometric irregularities. Comparing with the automatic method introduced by Keyak et al. (1990), the advantage of the M-M method consists in the smooth surface representation which allows to get strains at specific points on the surface. Moreover, this method can be extended to all sorts of elements (cubic, tetrahedral, etc.). In the light of these results, limits of the method do probably exist but they have not yet been reached. Intrinsically, the elastic registration does not accept very different shapes to match. The next step will consist in assessing the limits of the M-M method by using it with very different sizes of basic shapes. Afterwards, the M-M method will be tested with hollow shapes in order to take into account the whole bones.

To conclude, this paper has introduced a new method (mesh-matching algorithm) to automatically mesh 3D structures in the framework of mechanical analysis by the finite element method. This method seems to show a great potential for the mechanical analysis of structures and it probably represents a new approach in the meshing or re-meshing techniques. Nevertheless, evaluation of the technique has to be performed on many kinds of bone structures in order to clarify the limits of the algorithm.

Finally, the originality of this work lies in the link found between two different disciplines belonging to the orthopaedic domain, i.e. computer-integrated surgery and mechanical analysis.

Acknowledgements

Richard Szeliski and Eric Bittar are acknowledged for their contributions on the elastic registration algorithm used in this paper. Marie-Christine Hobatho is acknowledged for her initial collaboration.

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