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Preferences and Keywords
I prefer a Poster Presentation
Bone
Mechanics;Hip;Development;Orthopaedic pathology;Radiology and Imaging

ABSTRACT NO. ____________
PAPER NO. ____________
Check One: _ Clinical _ Biology _ Engineering

Disclosure
(A-INSERM) (A-CNRS)

3D FINITE ELEMENT MESHING OF ENTIRE FEMORA BY USING THE MESH-MATCHING ALGORITHM

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Relevance to Musculoskeletal Conditions:
A tool for meshing automatically bone structures, from a reference model or atlas, may be helpful for finite element analysis of muscular-skeletal system.

Introduction:
Finite element (FE) analysis of muscular-skeletal systems has been developed to predict mechanical behavior of structures as for instance the bone remodeling (1), the implant performance (2), or fracture process (3). Unfortunately, 3D FE model construction is time consuming and requires a prohibitive amount of manual tasks. These difficulties tend to limit FE studies to 2D models or to 3D "average" models. However, patient-specific models can be important, particularly for the assessment of fracture risks which requires to know the complex patient's geometry. For this reason, patient's geometry based meshing algorithms have already been proposed as for example the CT scan-based FE models using automatic voxel superimposition (4).
In the same framework, another algorithm, called the mesh-matching (M-M) algorithm, has recently been proposed (5) and is applied here to surface points of entire femora in order to generate FE meshes from an existing femur model.

Methods:
The M-M algorithm which is based on a registration method was originally proposed for computer-integrated surgery applications (6). The M-M algorithm consists of reshaping an object in order to match another object using a hierarchical and adaptive 3D displacement grid called octree-spline. In a previous work, it has been shown that this algorithm was able to generate FE meshes of patient proximal femora from an existing 3D model (5). In the present study, the M-M algorithm was applied to five entire femora.
The existing 3D mesh or reference model was based on CT scan images of a cadaver femur and it was constructed with the help of the mechanical software (MSC/Patran V7.5). This reference model was validated in terms of modal frequencies and surface strains (7). Five cadaver specimen of entire femora were scanned to obtain five sets of patients femora external surface points.
The reference femur and each femur surface points were superimposed by using centroids of each data set as well as principal axis of inertia. The next step was the matching of the surface nodes of the reference model to the patient's femur surface points using the M-M algorithm (Fig.1). At this stage, the M-M algorithm principle consists of finding the 3D optimized transform T that minimizes the distance between patient 3D points and the transformed reference model (5). Once this 3D transform T is known, it is applied to all the nodes of the reference model in order to generate a new 3D mesh adapted to the patient's geometry.

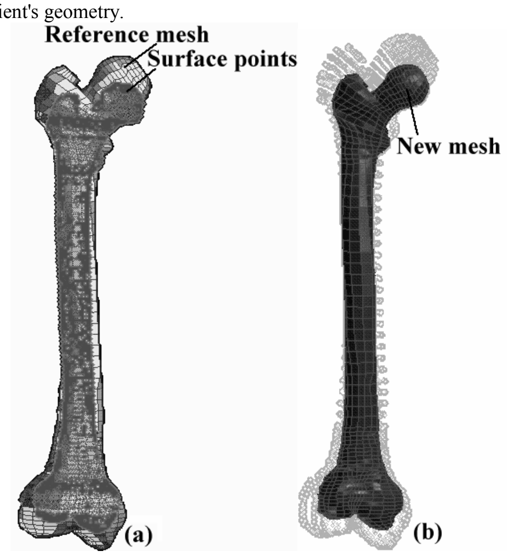

Fig.1: Reference mesh superimposed with the patient surface points (a). Patient mesh after the reference mesh matching (b).

Results:
The automatic patient mesh generation provided satisfactory results for the five femora. This means that the new meshes presented elements as regular as those of the reference model. As the reference and patient models were built with hexahedral elements, mesh regularity consisted of measuring the element distortion with respect to an ideal cubic shape. Within Patran software, the distortion is measured by the angle between isoparametric lines of the elements. According to the accuracy of the numerical integration in the element, this angle should be greater than 45° or less than 135°. The mesh regularity test of the reference model showed that 15% of the elements had at least one angle outside the 45-135° range. In the five new meshes, this rate was unchanged after transforming the reference model to the surface points using the M-M algorithm. Consequently, the M-M algorithm did not seem to alter mesh regularity even for entire femora. Nevertheless, all the femora were from adult donors and they did not present a great size difference. Actually, the reference femur length was equal to 448 mm and the length of the other five femora varied from 409 to 445 mm. So the maximal length difference represented less than 10% of the reference femur length. The greatest geometrical differences concerned the head and the neck diameters (Fig.2). The fourth femur (illustrated in Fig.1) presented the most distinct head and neck diameters that were around 20-25% lower than diameters of the reference femur.

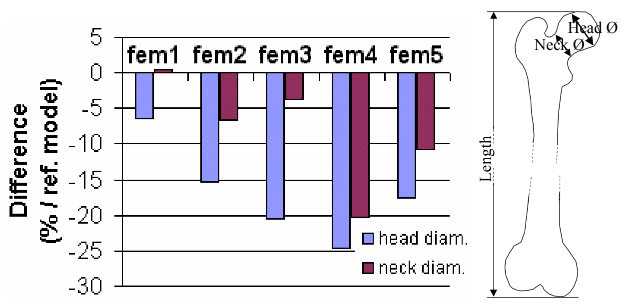

Fig.2: Difference of the head and neck diameter with respect to the reference model (%).

Discussion:
The M-M algorithm allowed the automatic generation of FE meshes of entire femora from an existing 3D model. Results showed that the new meshes did not present more distorted elements than the reference model. This is in agreement with the previous work concerning the proximal epiphysis of ten femora. Consequently, we showed that the M-M method can be applied to entire femora. This is particularly interesting for the fracture risk analysis since CT scan-based FE model is the only way to account for patient-specific geometry and variation of mechanical properties. The reference mesh requirement can be seen as a disadvantage comparing with the voxel-based fully automatic method (4). Nevertheless, the M-M method allows a smooth surface to be obtained which is interesting for the surface strain accuracy. Moreover, in a study with a large number of specimen (as for instance a crash test series), the reference mesh can be constructed with an optimal mesh refinement according to the geometric shape.
To conclude, this method seems to show a great potential for the mechanical analysis of bone structures. This is interesting because most of the commercial algorithms deal mostly with tetrahedral meshing.

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