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A comparative study on different methods of automatic mesh generation of human femurs

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Abstract

The aim of this study was to evaluate comparatively five methods for automating mesh generation (AMG) when used to mesh a human femur. The five AMG methods considered were: *mapped mesh*, which provides hexahedral elements through a direct mapping of the element onto the geometry; *tetra mesh*, which generates tetrahedral elements from a solid model of the object geometry; *voxel mesh* which builds cubic 8-node elements directly from CT images; and *hexa mesh* that automatically generated hexahedral elements from a surface definition of the femur geometry. The various methods were tested against two reference models: a simplified geometric model and a proximal femur model. The first model was useful to assess the inherent accuracy of the meshes created by the AMG methods, since an analytical solution was available for the elastic problem of the simplified geometric model. The femur model was used to test the AMG methods in a more realistic condition. The femoral geometry was derived from a reference model (the "standardized femur") and the finite element analyses predictions were compared to experimental measurements. All methods were evaluated in terms of human and computer effort needed to carry out the complete analysis, and in terms of accuracy. The comparison demonstrated that each tested method deserves attention and may be the best for specific situations. The mapped AMG method requires a significant human effort but is very accurate and it allows a tight control of the mesh structure. The tetra AMG method requires a solid model of the object to be analysed but is widely available and accurate. The hexa AMG method requires a significant computer effort but can also be used on polygonal models and is very accurate. The voxel AMG method requires a huge number of elements to reach an accuracy comparable to that of the other methods, but it does not require any pre-processing of the CT dataset to extract the geometry and in some cases may be the only viable solution.

Keywords: Biomechanics; Finite element analysis; Automatic mesh generation; Human femur; Bone and bones

1. Introduction

Since 1972 [1] the finite element (FE) method has been widely used in orthopaedic biomechanics as a powerful tool for the solution of complex problems. Review papers summarize the application of such a method to biomechanics [2,3]. However, in spite of its wide adoption, FE is frequently perceived as a"non-trustful" method. Beside the common diffidence for numerical methods, it is well known that, to be effective, FE methods require careful attention during the modelling of the physical problem and the creation of the FE mesh. Due to the intricate geometry, 3-D mesh generation of bone segments is a complex task and the resulting meshes may contain elements with severe shape distortion or large aspect ratio. Distorted elements are potential sources of ill-conditioned equations which in turn may drive to inaccurate results [4]. Vander Sloten and Van der Perre investigated the effect of element distortion with specific reference to the modelling of the proximal femur [5]. Depending on the type of distortion and on the stress pattern they found error between 7% and 100% of the nominal stress.

3-D FE models of human bones are usually derived from CT scan datasets using various approaches, most of

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which are scarcely automated and require a considerable effort. The manual generation of 3-D meshes is a complex and time-consuming task. For this reason most of the analyses reported in the literature refer to a single bone geometry, although in many cases the anthropometric variability of bone size and shape should not be neglected. Furthermore, although the complex geometry frequently demands non-optimal meshes, mesh refinements or convergence checks are rarely reported, due to the large amount of time required to produce a single complete manual mesh.

These problems have been addressed by various authors employing programs (Automeshers) able to automatically generate FE meshes of an object, starting from its geometric description. Automeshers have been used in 2-D problems frequently in conjunction with an automatic mesh refinement routine [6]. Tetrahedrons 3-D automeshers, commonly available in commercial FE pre-processors, have been used to mesh human femurs [7]. Other authors developed simpler Automatic Mesh Generation (AMG) methods relying on the slender, tubular-like structure of long bones [8–10].

A common feature of all these approaches is that the CT scan data set must be pre-processed to extract the geometry of the bone. Keyak *et al*. [11–13] proposed a new method to directly generate a mesh from a dataset of stacked images (CT scans, etc.), thus avoiding the geometry extraction step. The resulting mesh is called a “voxel mesh”. This approach, in its original form or in more sophisticated versions [14], has been widely adopted to produce FEM models of microscopic structures, like small volumes of trabecular bone [15–18]. While in these applications the voxel meshes are commonly accepted, some criticism has been drawn when it is applied to the modelling of whole bone segments [19,20].

To the authors’ knowledge, the only attempt to compare 3-D AMG methods when applied to bone mesh generation has been published by Merz *et al*. [21]. Although very interesting, this work gave only a description of main advantages and disadvantages of each AMG method when used to mesh long bones; no attempt was made to quantitatively compare one method against the other.

The aim of the present study is to evaluate comparatively a set of AMG methods when used to mesh human femurs. Automatic mesh generators tend to create meshes made of a large number of elements. In general, a good AMG method should have a good ratio between computational accuracy and computational weight. Thus, both aspects will be addressed in the present study.

2. Materials and methods

2.1. Simplified geometric model

To perform a preliminary evaluation of AMG methods a simplified geometric model was used (see Fig. 1), which allows a theoretical solution. This model approximates the shape and dimensions of a femur, and was loaded with forces comparable to those found *in vivo* in order to produce a similar stress field.

The 3-D solid model of this simplified geometry was created using EMS-PP (Intergraph Corp., USA). The solid model was passed to the AMG programs by direct database access or via Initial Graphics Exchange Specifications (IGES) neutral format. Also, a set of synthetic Computer Tomography (CT) images of the simplified geometric model were created using commercial raster images manipulation programs.

2.2. Standardized femur

To further evaluate the AMG methods on a more realistic geometry, the “Standardized Femur” model was used as reference geometry. This is a 3-D solid model, made available in public domain [22], derived from a CT-scan dataset of a commercially available human femur replica (Mod. 3103, Pacific Research Labs, USA). The mechanical behaviour of this composite model has been validated by Cristofolini *et al*. [23]. In the present study only the proximal part was considered.

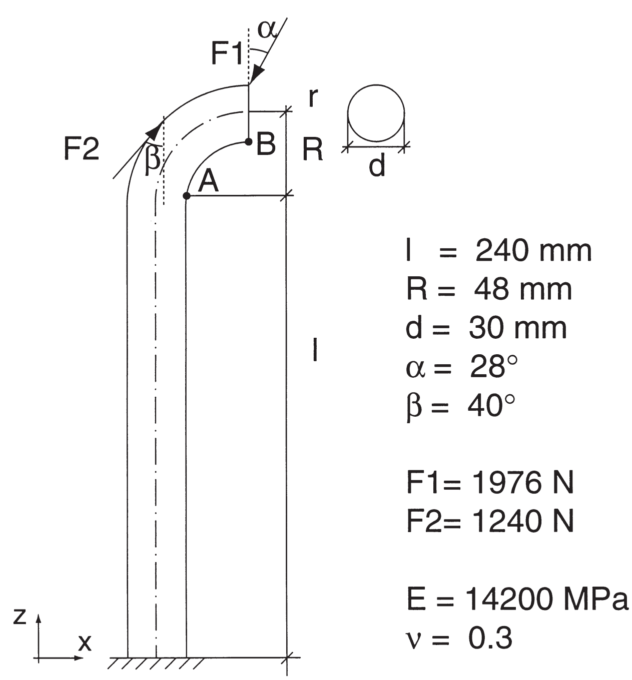

Fig. 1. The simplified geometric model used in the present study. The figure also shows the applied load case and the assigned material properties.

The solid model was passed to the AMG programs by direct database accessor via IGES neutral format. The original CT-scan data set of the femur replica was also used.

The material properties were assigned with reference to those indicated by the manufacturer and verified by McNamara *et al*. [24]. Forces, constraints and material properties are reported in Fig. 2. The boundary conditions were defined to accurately reproduce those used in the experimental set-up [25,26].

External loads were applied as nodal forces. Since the spatial position of the nodes was slightly different in each mesh the applied loads were recalculated for each model to produce the same resultants.

2.3. AMG methods

Five AMG methods were considered in the present study; all the methods allow direct control on the discretization parameters, at least defining the average element side length. The reduction of this value produces a more refined mesh and increases the number of degrees of freedom (NDOF) of the model, defined as the number of independent quantities which are needed to uniquely define the deformed configuration.

The following AMG methods were considered:

1. *Mapped mesh*: a typical procedure for manually controlled mesh generation is to decompose the object in a sequence of sub-volumes on which the program maps the mesh. The user can control the mesh refinement indicating the number of nodes the code must place on each solid edge. The PATRAN pre-processor (MacNeal–Schwendler Corp., USA) was used to mesh the solid models imported via IGES.
2. *Tetra mesh*: this AMG method automatically generates 4-node or 10-node tetrahedral elements meshes from a solid model of the body. The user can control the mesh refinement by indicating a tentative element size. After a preliminary investigation, the 10-node tetrahedral elements meshes were preferred since their convergence rate was sensibly higher than that of the 4-node elements. The I/FEM pre-processor (Intergraph Corp., USA) was used, which is able to process directly the solid models created with EMS-PP.
3. *Hexa mesh*: a new generation of AMG are able to create an 8-node hexahedral element volume mesh from a surface solid model passed via IGES. The HEXAR program (Cray Research Inc., USA) was used to produce this type of mesh. A tentative minimum and maximum element side length can be used to control the mesh refinement.
4. *Voxel mesh*: this method is substantially different from the previous ones because it can process directly a CT scan dataset, avoiding the vectorial segmentation needed by all the other methods, which can process only a vectorial geometry. In its simplest version it is based on a direct conversion of the voxel lattice in a 8-node cubic elements volume mesh with user-specified side. A code developed in-house, similar to that described by Keyak *et al*. [13], was used to produce this type of mesh. Usually the voxel mesh method is used in conjunction with empirical non-linear relationships between bone apparent density and bone Young modulus [27]. However, in the present study where homogeneous solids were analysed, a linear correlation between apparent density and elastic module was used.

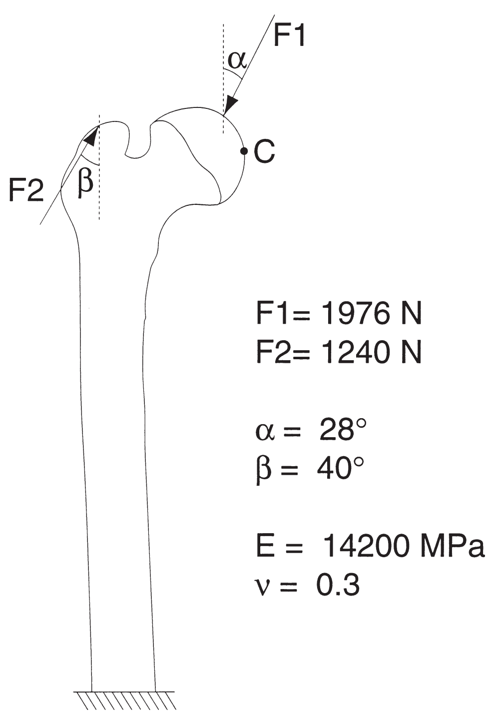

Fig. 2. The femur model used in the present study. The figure also shows the applied load case and the assigned material properties.

Example meshes created with the four methods are depicted in Fig. 3. All the FE models used in the present study were solved using the PATRAN-FEA solver (MacNeal–Schwendler Corp., USA).

2.4. AMG methods evaluation

To evaluate comparatively the AMG methods, two aspects were considered: computational weight and computational accuracy. Both aspects can be relevant, depending on the specific application.

2.4.1. Computational weight

To document the effort (in terms of computational and human resources) required by each AMG method to solve the given problem two parameters were monitored: the total operator time and the total CPU time. The first

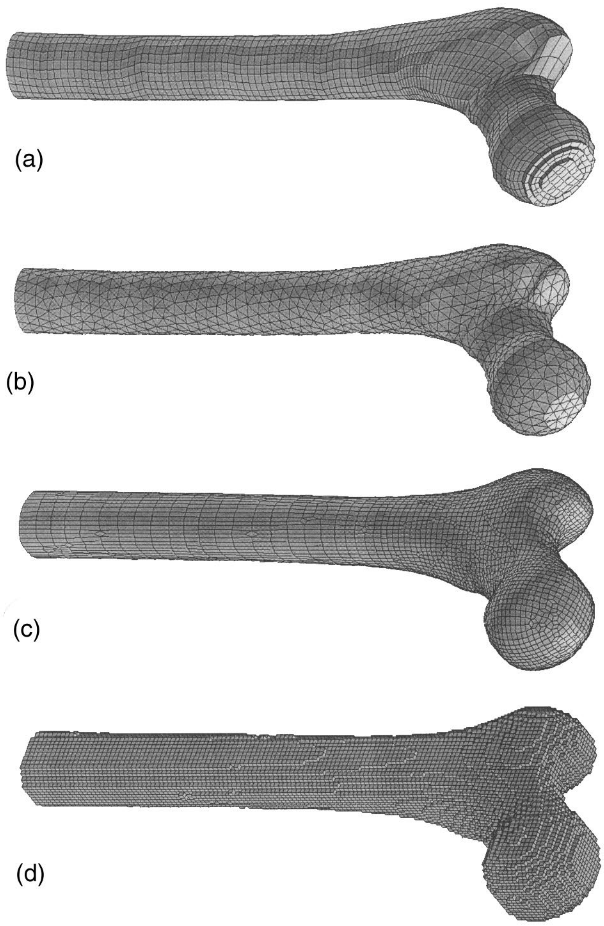

Fig. 3. Examples of meshes of a proximal femur generated with the AMG methods under investigation.

contains pre-processing and post-processing; in the case of the mapped AMG, it also contains the mesh creation time. The total CPU time accounts for the mesh generation CPU time and the solution time. All the analyses and most of the mesh generations were performed on a SGI Indy unix workstation equipped with a MIPS R4400/250 MHz. The only exception is the mesh generation using HEXAR, which runs only on Cray Supercomputers. In the present study a Cray C90 was used.

2.4.2. Computational accuracy

The computational accuracy should express the ability of a given FE model to approximate the theoretical solution of the system of differential equations. In practice, FE models tend to be more or less accurate depending on the solver used, the specific result type (i.e. displacements or stresses) and the resulting location (i.e. surface or internal stresses). Rather then trying to define a "Global Accuracy", two typical results were used to evaluate model accuracy: structural displacement and surface stresses. These two results were selected because of their significance and because of the availability of theoretical or experimental reference values. The FEM results of the simplified geometric model were validated against analytical results derived from the curved-beam theory [28]. The FEM results of the femur were compared to *in vitro* experimental measurements obtained using a well established protocol based on strain gauges [29].

The accuracy in predicting the structural displacements express the ability of the model to predict the global structural behaviour. For the simplified geometric model the displacements predicted by FEM models were verified at two control points (points A and B in Fig. 1). The two locations were chosen considering the stress gradients and the requirement of having the two control nodes always at the same co-ordinates in every mesh refinement. For the femur model the displacement of the femoral head was assumed as reference (point C in Fig. 2). Structural displacement errors were represented plotting the displacement percent error ($\%\Delta u$) versus the NDOF for each AMG method.

Surface principal strains at 10 different locations were used to investigate the ability of the FE models to accurately predict surface stresses. Reference values were calculated for the simplified geometric models and measured with strain gauges for the femur models; details on the strain gauge experimental protocol can be found elsewhere [29]. Validation of FE models with strain gauge measurements is quite common [30,13,31]. Since FE models calculate the stresses at the Gauss points of each element (which are located slightly inside the object surface) in each model, the surface stress was extrapolated at the surface element nodes. In the worst case, the distance between the centre of the element and the object surface was 1 mm. The global surface strain accuracy was expressed by the root mean square error (RMSE) defined as the square root of the average of the squared errors at the 10 control locations. Only the most refined model for each type of AMG was considered in this type of evaluation.

3. Results

3.1. Simplified geometric model

All AMG programs were able to mesh the simplified geometric model. All meshes were correct, with no disconnection or degenerated elements. The solver did not produce any warning about mesh conditioning problems. Foreach AMG at least three mesh refinements were produced. Meshes with more than 120 000 NDOF were discarded because it would be impossible to solve them with the available resources.

The manual (mapped) mesh of the simplified model was relatively simple; depending on the mesh refinement the pre-processing took from 1.5 to 5 hours of work. In comparison, the tetra mesh AMG took less than 30 min to generate the largest mesh; the voxel mesh AMG just

6 min. The hexa mesh AMG required more than 4000 CPU seconds of the Cray C90 to produce a 106 000 NDOF mesh; on a busy system this may take a few hours.

All AMG methods were able to predict the simplified model displacementswith errors lower than 4%. Only mapped meshes were able to reduce errors below 1%. Most methods monotonically improved their accuracy, increasing mesh refinement; the tetra mesh presented a very fast convergence rate but small oscillations for high NDOF meshes. Fig. 4 reports the evolution of the displacement error at the control point B for increasing NDOF.

The analytical model predicted strains at the various locations ranging between 915 and 1619 microstrains. All AMG methods but one were able to predict analytical results with an RMSE between 1 and 2% of the nominal peak strain. The exception was the voxel mesh AMG method. The best accuracy achieved with this method was only 14% of the nominal peak strain. Furthermore, while the accuracy of the voxel meshes displacement predictions monotonically improved increasing the NDOF, surface stresses were better predicted by the 4 mm mesh than from the 2 mm mesh. This was due to a strong asymmetry of the predicted strains. In the 2 mm model the RMSE of the five lateral control points was 42% of the nominal peak strain, while on the medial site it was only 1%. No other AMG method showed such significant asymmetry.

3.2. Standardized femur

All AMG programs were able to mesh the femur model. The tetra mesh AMG produced a few disconnections in the mesh with lower NDOF. The solver produced some warning messages for all AMG except the voxel mesh (which by definition produces “perfect” elements). Mesh conditioning improved with refinement. In the most refined meshes hexa mesh produced only one distorted element while the tetra mesh produced six distorted elements. Hexa meshes with less than 30 000 NDOF presented numerous disconnections and were rejected.

Meshes with more than 120 000 NDOF were discarded because it would be impossible to solve them with the available resources. The number of mapped meshes was limited to three because of the considerable human effort needed with this method.

Due to geometric complexity, the manual (mapped) mesh of the femur took almost 2 days of work for the most refined model. The other AMG methods were not significantly affected by the model complexity; the mesh generation times were similar to those recorded for the simplified model. For very large NDOF models the post-processing time significantly increased because the available computational resources were not able to sustain the interactive sessions typical of post-processing activities. Table 1 reports all timing measurements.

In all femur FE models the predicted displacement was smaller than that measured experimentally. With all AMG methods increasing the mesh refinement the model accuracy improved. The displacement was best predicted by the finest hexa mesh, which achieved an accuracy of 1.4%. Mapped and tetra reached 2.2% and 3.4% respectively. The best voxel model was the 2.4 mm model, which reported a displacement of 15% lower than the experimental measurement. Further increasing the mesh refinement did not improve the accuracy of the voxel mesh; the 2 mm model had an error of 17%. In Fig. 5 the error on displacement is plotted against the NDOF for each AMG.

The strain gauge experimental measurements are reported in Fig. 6 together with the value predicted by the most refined mesh for each AMG method. The best agreement was achieved by the finest hexa mesh with a RMSE equal to the 9.6% of the maximum measured strain. Mapped and tetra finest meshes showed an RMSE of 10% and 11.4% of peak strain respectively. The voxel meshes improved their agreement with the experimental measurements when reducing the element size. The 3 mm voxel showed an RMSE 11% of the peak strain, a result comparable to the other AMG methods. However, further increasing the voxel mesh refinement worsened the accuracy. The 2 mm voxel mesh had an RMSE equal to 23% of peak strain. Both the 3 mm and the 2 mm voxel mesh results are reported in Fig. 6.

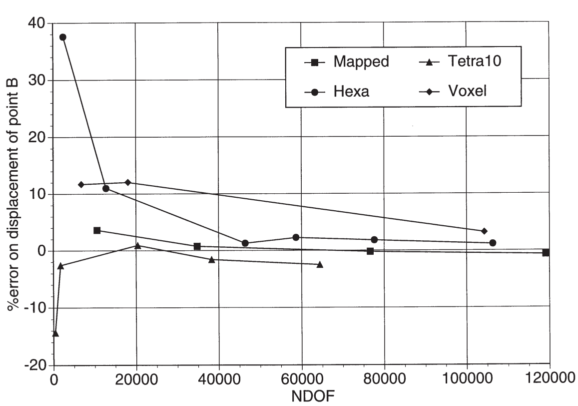

Fig. 4. Convergence curve of the various AMG methods when applied to the simplified geometric model.

4. Discussion

The two target models used in the present study were useful in investigating different aspects of AMG methods. The results obtained from the geometric model showed the basic capabilities of the different methods when applied to a relatively simple geometry. Furthermore, the comparison with analytical results gave infor-

Table 1
Femur mesh generation efforts for all AMG methods tested. The lower part of the table shows the solver warning for the different meshes

Mesh generation effort															
AMG method	Mapped			Tetra				Hexa				Voxel			
NDOF	3663	10 665	28 995	10 386	20 481	35 863	55 209	34 617	61 671	87 522	3246	13 506	30 186	53 115	99 840
Mesh generation (CPU sec)				360	600	840	1200	1520	1937	4102	100	190	240	300	800
Pre-processing (min)	260	320	510	30	40	60	80	60	60	120	120	120	180	200	240
Analysis (CPU sec)	62	124	1015	122	379	1176	2973	1260	3100	5270	41	166	818	2547	4532
Posr-processing (min)	120	120	180	60	120	120	180	120	180	240	120	120	180	180	240
Total operator time (min)	380	440	690	90	160	180	260	180	240	360	240	240	360	380	480
Total CPU time (sec)	62	124	1015	482	979	2016	4173	2780	5037	9372	141	356	1058	2847	5332
Solver Warnings															
Distorted elements	6	10	0	129	142	136	6	4	4	1	0	0	0	0	0
High aspect ratio elements	0	0	0	0	0	0	0	20	15	5	0	0	0	0	0

The hexa mesh generation CPU time is referred to a Cray C90; all other CPU times are referred to a SGI Indy R4400 Workstation.

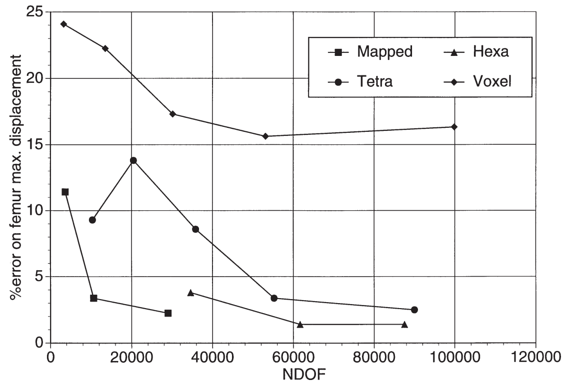

Fig. 5. Convergence curve of the various AMG methods when applied to the femur model.

mation on the intrinsic numerical accuracy of each AMG method. The femur model was useful to evaluate meshing procedures when used to solve a typical computational biomechanics problem. In this case data were obtained from experimental measurements. Thus, the reported errors are a combination of numerical errors, uncertainties about the physical problem and inaccuracies of the experimental measurements.

None of the methods here investigated was clearly better than the others. Each of them may be well suited for certain applications. Various aspects should be considered in selecting a mesh generation method.

4.1. Source of geometry data

The tetra mesher algorithm, as implemented in most commercial programs, requires a solid model of the target object. The solid model must be properly defined; tetra meshers tend to fail when used on "dirty" solid models (models affected by gaps or overlaps between surface patches, irregular parameterization, numerical oscillations of spline surfaces, etc.). In some cases the creation of such a solid model for a bone segment is not a trivial task and it may require a significant effort. In some programs it is possible to define the object through a surface mesh of triangular plane elements (tiled surface); however, since the tetrahedrons are directly generated from the triangles, ill-conditioned triangles produce ill-conditioned tetrahedrons.

The hexa mesh AMG algorithm implemented in the HEXAR program admits to geometry data formats similar to those of the tetra meshers. However, HEXAR uses

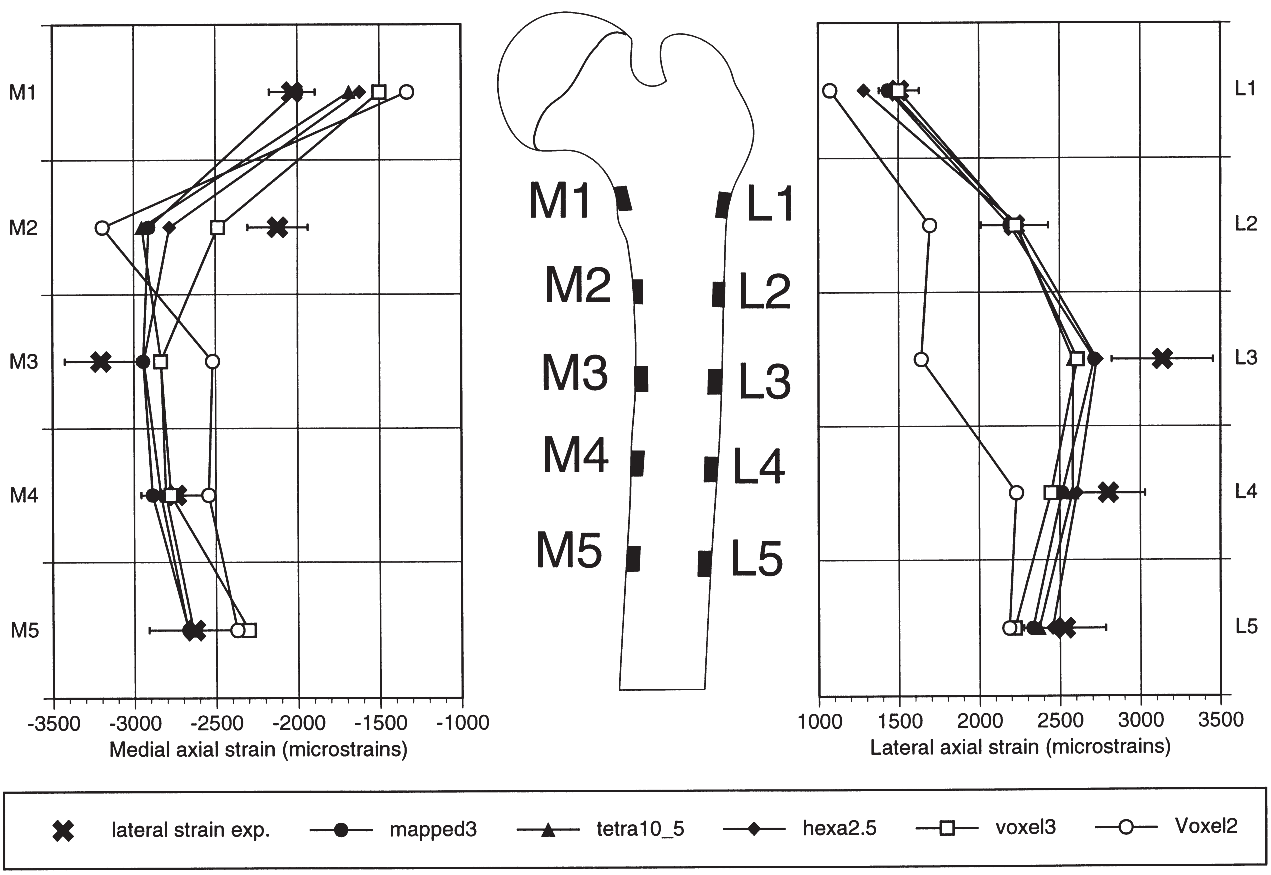

Fig. 6. Evolution of the periosteal axial strains along the femoral shaft as predicted by the most refined mesh for each AMG method tested or measured *in vitro* using strain gauges. For the voxel mesh two consecutive refinements are reported, to show the significant difference between the two sets of results. The experimental results are reported as average and standard deviation of the measurements taken from 12 femurs.

the tiled surface only to define the object boundary and the resulting mesh is not affected by the shape of the triangles. Thus, the tiled surfaces produced by automatic 3-D segmentation algorithms of CT data sets (such as the "Marching Cube" algorithm [32]) may be used as source of geometry data for the HEXAR program.

Mapped meshes are effectively generated from a solid model; however the manual mesh generation is more flexible and it can also be carried out using lower order geometry descriptors, such as wire frame models. Many authors used 2-D contours derived from CT scans to create 3-D mapped meshes.

The direct conversion of CT data sets in 3-D meshes is probably the most important advantage of voxel meshes. Every time the only available source of geometric data is a CT dataset the voxel mesh method should be considered. Voxel meshes are also used to derive local material properties from the CT density information. However, this is also possible with other AMG methods, mapping the CT densities data onto an existing mesh.

4.2. Mesh generation effort

AMG programs showed a clear advantage in terms of operator effort. In the present study, the mapped meshes were created by an expert operator, with an in-depth knowledge of the PATRAN environment. The operator had already meshed human femurs; otherwise the definition of the meshing strategy would probably take additional time.

Voxel mesh, which is based on a very simple algorithm, is the fastest mesh generation program. Conversely, the hexa mesh is the slowest and it requires a high performance computing environment.

A significant effort was required to post-process the models with more than 80 000 DOF. This is related to the available graphic subsystem, which was not able to refresh in real time the view of such models.

4.3. Computational weight vs computational accuracy

At the cost of a higher computational weight, most AMG methods demonstrated a computational accuracy comparable to that of manual meshes. On the other hand manual meshing is still the best method to be used every time a tight control of mesh topology is needed or when high accuracy must be obtained with a limited NDOF.

From the present findings the hexa mesh method appears to be the most accurate AMG method. In the femur case the hexa meshes were able to predict the displacement with an accuracy of 1.4% and the stresses with an average RMSE of less then 10%. However, the tetra mesh method was only slightly less accurate and the computer requirements to produce a tetra mesh are sensibly lower than for the hexa mesh.

The tetra mesh showed an oscillatory convergence in the simplified geometric model (see Fig. 4). This could indicate that the tetra mesh AMG would worsen the mesh conditioning increasing the refinement. However, this behaviour was not observed for the femur model and also in the geometric model the oscillations were very small.

The results obtained for the voxel mesh AMG were partially contradictory. In terms of prediction of structural displacements, the voxel mesh accuracy was comparable to that of other AMG methods. However, in the femur model the 2.4 and 2 mm meshes showed errors larger than coarser meshes. A similar behaviour was observed for the surface stresses. In the femur model the 2 mm voxel mesh had a %RMSE almost twice as large as that of the 3 mm mesh. Fig. 7 reports the evolution of surface stresses and of the structural displacement errors with the NDOF of the voxel models of the femur. These oscillations are usually found in models which are very far from convergence (i.e. with a very insufficient refinement). Other authors have already reported an oscillatory behaviour of voxel meshes near the domain boundaries [19,33,34]. From these results it seems inappropriate to use voxel meshes when very accurate surface stresses are required.

The present results are in clear disagreement with those reported by Keyak [13] and Lengsfeld [31]. However, this may be due to a different data representation. In both studies the accuracy of the voxel meshes is evaluated with a linear regression between the measured and the computed strains. The regression is described by three indicators: the regression coefficient, the regression slope and the regression intercept. If the first two are close to one and the third is close to zero, good agreement is assumed.

When the data produced in the present study are represented in the same way, the indicators are in the same range of those reported in other studies (see Table 2). More importantly these parameters do not vary significantly from one mesh refinement to another. Also, it

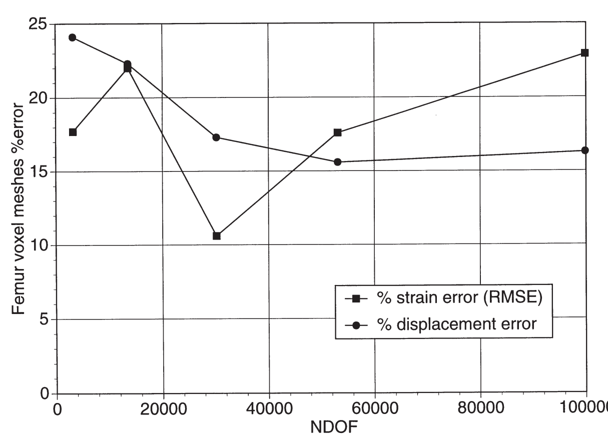

Fig. 7. Evolution of voxel mesh errors (with respect to the experimental measurements) for increasing mesh refinements.

Table 2
Correlation between voxel mesh surface stress predictions and strain gauge measurements; comparison of literature results with the present findings

Study	*R*	Slope	Intercept	%RMSE
Lengsfield *et al.* [10]	0.9–0.94	0.84–0.90	− 9 to − 53	?
Keyak *et al.* [11–13]	0.77	0.63 ± 0.13	84 ± 62	?
Present study (all refinements)	0.97–0.99	0.75–0.91	− 40 to − 270	11–23%
Present study (2 mm model)	0.97	0.82	− 270	23%
Present study (3 mm model)	0.99	0.91	− 40	11%

must be noted that in both papers only a 3 mm refinement is used, which in our study produces the best results. In a previous work Keyak and Skinner [12] investigated the effect of the element size and found a monotone improvement with the NDOF. However, they investigated only a very limited range of element size (3.1–4.8 mm) within which our results are also monothonic.

From the present findings, the voxel mesh AMG method requires a large NDOF to achieve a moderate accuracy. To reach the same global precision of the other methods the voxel mesh of the femur should probably have an element side comparable with the CT voxel size. This would produce meshes with millions of degrees of freedom. This may not be a problem; special solvers have been developed which use the voxel meshes' regularity to speed up the analysis and to reduce storage requirements [33,35].

4.4. Availability

Not all AMG methods described here are equally available. The creation of mapped mesh is possible with almost all FEM pre-processing commercial software. Also the tetrahedral automeshers are available in most commercial packages. To the authors' knowledge, there are no commercial or public domain implementations of the voxel mesh algorithm; on the other hand its implementation is relatively simple. The HEXAR program is actually available only for Cray computers; however, at least one other commercial product is able to automatically produce hexahedral meshes and more will probably appear soon.

5. Conclusion

Each of the automatic mesh generation methods described presents advantages and limits. Mapped meshing requires a significant operator effort but produces light and very accurate models. Tetra meshing is a mature method, widely available and is probably the best method when a solid model of the target object is available. Hexa meshing produces the most accurate results but it requires significant computational resources; its ability to process tiled surfaces generated from 3-D segmentation algorithms should be further investigated. Voxel meshing is the easiest and fastest way to produce a 3-D mesh starting from a CT data set. By its nature, the voxel mesh method is almost insensitive to geometric complexity and poor image contrast. Both these factors make it difficult (or sometime impossible) to use the data set segmentation needed for all other AMG methods. Although with the level of mesh refinement used in the present study the results fairly inaccurate, special solvers may allow the solution of voxel meshes of one order of magnitude larger. However, interactive post-processing of such FEM models would be extremely difficult.

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