Personalized finite element mesh of human body structure using 3D reconstruction and kriging technique

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Introduction
Finite Element (FE) Method is useful to analyze mechanical behavior of human body structures. It requires meshing process which may be complex when dealing with a personalized model. Automatic mesh generators from CT-scan are available but for living structures, which are highly irregular, they often yield excessively refined meshes and high numerical costs.
In this paper, a new method based on the kriging technique is proposed to automatically generate a personalized FE mesh of any patient structure from its 3D reconstruction and from a generic mesh.

Methods
This method of mesh generation was based first on an existing generic FE model of this structure and secondly on a 3D reconstruction of specific points pertaining to the structure (obtained using stereoradiography, CT-scan…) called reference points. These specific points were localized on functional areas (articular surfaces, ligaments insertions …) and embrace the volume of the structure. A set of equivalent points, called control points, were considered on the generic FE model. Finally, using a kriging technique [1], geometric transformations were applied on the generic mesh to fit control points with equivalent reference points.
The mesh quality was estimated by examination of elements distortion and by quantification of the “points to surface” distance between the surface of the FE model and that of the 3D reconstruction.
The feasibility of this technique was assessed on 3 kind of human structures for which generic FE models were available:
- thoraco-lumbar spine: for each vertebra, 877 nodes per vertebra were generated from 25 control points issued from a 3D reconstruction obtained by stereoradiography
- pelvis: 1906 nodes from 58 control points issued from a 3D stereoradiography
- femur: 587 nodes from 11 control points issued from a CT-scan reconstruction.

Results
The rate of distorted elements created with this process was very low: less than 5% of elements were distorted with the mesh of pelvis and scoliotic spine and no distortions were found with the mesh of femur.

Vertebra mesh:
Table below and figure 1 summarize the “points to surface” error:

<table>
<thead>
<tr>
<th></th>
<th>Mean Error</th>
<th>RMS</th>
<th>Max error</th>
<th>Number of points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole vertebra</td>
<td>1.08 mm</td>
<td>1.35 mm</td>
<td>5.40 mm</td>
<td>455</td>
</tr>
<tr>
<td>Vertebral body</td>
<td>1.04 mm</td>
<td>1.26 mm</td>
<td>2.99 mm</td>
<td>188</td>
</tr>
<tr>
<td>Posterior arch</td>
<td>1.08 mm</td>
<td>1.34 mm</td>
<td>5.40 mm</td>
<td>257</td>
</tr>
</tbody>
</table>

Femur mesh:
We focused on the functional area. Means errors of 1.4 mm and 2 RMS of 3.6 mm were found (figure 2).
Pelvis mesh:
Means errors of 3.8 mm and 2RMS of 9.3 mm were found (figure 3)

Furthermore, this method enabled to build a FE mesh very quickly: 30 seconds for the femur (600 points) and 6 minutes for the whole spine (17000 points) on a Pentium II PC.

Discussion
In the case of pelvis, the mesh of 1900 nodes is obtained with only 60 control points, yielding a error of 9.3 mm. The precision of mesh generation may be improved by increasing the number of control points issued either from CT scan or from improved pelvis X Ray reconstruction.

This process allowed to generate automatically meshes for FE analysis of spine, pelvis and femur.

In order to avoid manual corrections, algorithm development are in progress for automatic correction of distorted elements (aspect ratio, warp angle …). By opposition with the mesh issue from a CT-scan, this technique yield a personalized meshing of the human structures with a chosen refinement adapted to the numerical requirements.

Conclusion
This process has already be used to generate a personalized FE model of scoliotic spine in order to evaluate if deformed geometry has a share in specific behavior of scoliotic spine [2]

References

Figure 1: Vertebra mesh, point to surface errors
Figure 2: Femur mesh, point to surface errors

Figure 3: Femur mesh, point to surface errors

Figure 4: Detailed FE model of a whole scoliotic spine