CT-BASED WHOLE BONE MODELING: A COMPARISON BETWEEN NUMERICAL METHODS

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SUMMARY
In the last few years numerical models assessing the mechanical behavior of bone segments from clinical images have constituted a growing field of research. Accurate predictions are obtainable using Finite Element (FE) models based on the recovery of the bone surface; voxel-based FE models do not require the complicated and time expensive boundary recognition but until now they were applied in validation study only with coarsened CT data-set with a considerable lack of accuracy. Recently, the Meshless Cell Method (MCM), a meshless implementation of the Cell Method, obtained a good accuracy in strain predictions even using a sub-sampled CT data-set source. The present work compared MCM and voxel-based Finite Element models built at full original resolution of the CT dataset with boundary recovery Finite Elements models; the comparison were performed assessing the accuracy in predicting in-vitro experimentally measured strains. Furthermore a convergence study with respect of the spatial resolution of the data-set were performed for MCM and voxel-based FE models. The three modeling methods resulted similar in terms of strain predictive accuracy, showing a good correlation with experimental values and comparable mean and maximum errors. MCM showed a nicer degradation of strain prediction accuracy with spatial refinement of the data-set.

INTRODUCTION
The accurate prediction of mechanical behavior of bones from diagnostic data with subject specific numerical models has reached an increasing importance because of its potential clinical applications such as the assessment of the risk of fracture in osteoporotic patients, or preoperative planning in skeletal reconstruction surgery. To be considered for clinical applications numerical models must be validated comparing predictions with experimental measurements (strain and displacements) performed on in-vitro mechanical tests. The state of the art of numerical modeling is constituted by Finite Element Models which discretize the bone volume starting from an accurate recognition of the bone boundary (bFEM) obtained by a precise segmentation of the CT images. Even if highly accurate (RMSE < 10% in strain prediction), bFEM is still a semi-automated procedure which require some ours of specialized work. An alternative and less labor intensive procedure is offered by voxel-based FE models (vFEM) which directly convert each voxel of a CT data-set in an hexahedral finite element. This approach is more automated but so far few validation studies have been published, demonstrating a limited accuracy, probably because of the coarsening of the CT data-set due to the reduced computational facilities available when the studies were performed [1,2]. The Meshless Cell Method (MCM) is another alternative voxel-based method which uses a meshless implementation of the Cell Method discrete approach [3,4]. In a recent preliminary study [5] MCM demonstrated an in vitro strain prediction accuracy comparable with the bFEM on one femur at reduced resolution. The aim of the present study is twofold: (i) to compare the accuracy of voxel-based models (vFEM and MCM) at full resolution with that obtained by the state-of-the-art bFEM using the same reliable experimental benchmark on multiple bones and multiple loading conditions; (ii) to study the behavior of the MCM with respect to the resolution of the data-set, comparing it to the vFEM.

METHODS
A coupled experimental-numerical study [6] was adopted as reference. In the study 8 human proximal femurs were non destructively tested in 6 different loading conditions; principal strain at 15 different location were measured; for each specimen a CT data-set was acquired with a spatial resolution of 0.59x0.59x1.3mm in the proximal region and 0.59x0.59x5mm in the diaphysis. Each test was replicated with bFEM models following a validated procedure to obtain 10-node parabolic tetrahedral meshes where material properties were mapped from the calibrated CT data-set using the BoneMat_V3 program [7] to integrate onto each element the elastic modulus obtained from the adopted density-elastcity relationship [8]. From each CT data-set at the original resolution vFEM models were generated directly converting each voxel in a hexahedron; material properties were obtained for each element averaging nodal values obtained from the calibrated data-set using the same density-elasticity relationship used for the bFEM models; a fixed threshold based on mineral density value was adopted to exclude the stiffening effects generated from the voxels occupied by non-mineralized material. Both bFEM and vFEM were solved using the PCG implementation of the Ansys finite element solver. Adopting both the same constitutive equation and threshold filter, MCM models were generated for each femur from the corresponding data-set at their native resolution, as described in [5]. The MCM builds local meshes for each node of a cloud of points spread onto the studied domain. A local mesh of
linear tetrahedra was generated surrounding each node of the data-set; the tetrahedra were obtained connecting each node with the closest nodes along each direction of the structured grid offered by the CT data-set; material properties were applied to all the cells of the local mesh averaging nodal values of elastic modulus obtained at nodes of the data-set. For each node a tributary region was defined corresponding to a voxel centered in the node; the equilibrium equation was written referred to this region, in terms of nodal displacements of the local mesh. An assembling procedure similar to that adopted by the FEM led to a linear algebraical system solved using a home made code based on the PETSc library.

To assess the behavior of the MCM model with respect of spatial resolution of the cloud of points, a single CT data-set was interpolated to obtain a data-set with cubic isotropic voxels of edge length 1mm. Coarser data-sets were then obtained following a power-2 series for the edge length. Both MCM and vFEM models were built from each sub-sampled data-set, strain values were calculated and compared with the experimental measurements.

RESULTS AND DISCUSSION
The comparison of strain prediction accuracy and model DOF among the three modeling methods is summarized in Table 1.

Table 1: strain prediction accuracy for the compared methods

<table>
<thead>
<tr>
<th></th>
<th>bFEM</th>
<th>vFEM</th>
<th>MCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R^2 )</td>
<td>0.95</td>
<td>0.93</td>
<td>0.94</td>
</tr>
<tr>
<td>Slope</td>
<td>0.97</td>
<td>0.84</td>
<td>0.93</td>
</tr>
<tr>
<td>Intercept</td>
<td>-1.5</td>
<td>0.22</td>
<td>1.88</td>
</tr>
<tr>
<td>RMS error (με)</td>
<td>83</td>
<td>99</td>
<td>91</td>
</tr>
<tr>
<td>RMS error (%)</td>
<td>7%</td>
<td>9%</td>
<td>8%</td>
</tr>
<tr>
<td>Max error (με)</td>
<td>479</td>
<td>542</td>
<td>552</td>
</tr>
<tr>
<td>Max error (%)</td>
<td>42%</td>
<td>47%</td>
<td>48%</td>
</tr>
</tbody>
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Figure 1: RMS Error over peak measured strain for MCM and vFEM models at different spatial refinement (DOF of the models).

The three methods are almost equivalent in terms of prediction accuracy: for either correlation with experimental values, slope and intercept of linear regression of predicted versus measured strain values; the average error on the strain predictions is always lower than 10% of the peak measured strain. The convergence of the % RMS error over mesh refinement (represented by the number of degrees of freedom) for MCM and vFEM is shown in Figure 1. MCM shows a nicer degradation of strain prediction accuracy with spatial refinement of the original cloud of points.

CONCLUSIONS
The three different computer models based on CT data predicted with excellent accuracy the state of stress and strain in a bone segment subjected to known loads. Specifically, the comparison of voxel-based models (vFEM and MCM) built from the full resolution CT data-set with the state of the art Finite Element Modeling based on the boundary recovery appeared to be completely equivalent, demonstrating that many reliable modeling procedure are available to replicate experimental in-vitro measured values. So the most suitable approach should be suggested by the the purpose of the study: bFEM implicates a considerably heavy pre-processing, but leads to a truly moderate computational weight. On the other hand voxel-based methods lead to computationally expensive models but are really automated requiring a small pre-processing time; so they should be preferred as for high-throughput studies where hundreds of cases must be analyzed. If compared with vFEM, MCM models demonstrated a nicer degradation of the prediction accuracy with data-set spatial resolution. Furthermore, since MCM is based on a meshless approach and do not require a fully meshable domain, it should be preferred when is convenient to initialize the model starting from a point cloud.

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