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Image-based vs. mesh-based statistical appearance models of the human femur: Implications for finite element simulations

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ABSTRACT

Statistical appearance models have recently been introduced in bone mechanics to investigate bone geometry and mechanical properties in population studies. The establishment of accurate anatomical correspondences is a critical aspect for the construction of reliable models. Depending on the representation of a bone as an image or a mesh, correspondences are detected using image registration or mesh morphing. The objective of this study was to compare image-based and mesh-based statistical appearance models of the femur for finite element (FE) simulations. To this aim, (i) we compared correspondence detection methods on bone surface and in bone volume; (ii) we created an image-based and a mesh-based statistical appearance models from 130 images, which we validated using compactness, representation and generalization, and we analyzed the FE results on 50 recreated bones vs. original bones; (iii) we created 1000 new instances, and we compared the quality of the FE meshes. Results showed that the image-based approach was more accurate in volume correspondence detection and quality of FE meshes, whereas the mesh-based approach was more accurate for surface correspondence detection and model compactness. Based on our results, we recommend the use of image-based statistical appearance models for FE simulations of the femur.

1. Introduction

Statistical shape models provide a compact and efficient description of shape variability within a dataset. They were introduced by Cootes and Taylor in 1995 [1], and since then, they have gained remarkable popularity. In the medical image analysis field, statistical shape models have been used to study shapes of human anatomy [2–6] and morphological changes due to various pathologies and trauma [7–9]. Moreover, these models have been applied to image segmentation [1,10,11], 2D/3D reconstruction [12–15] and prediction of anatomical shapes from sparse data [16–20]. The statistical core of shape models is principal component analysis (PCA) [21], which is calculated on corresponding landmarks derived from the dataset objects. The outputs of the model are parameters and modes of variation, which can be used to investigate the variability around the mean within a dataset and to create new plausible instances [1].

Statistical appearance models represent a natural extension of statistical shape models, as they describe the variability of shapes combined with image intensities [22]. This combination is particularly relevant in bone mechanics, where computed tomography (CT) intensities are related to bone mechanical properties [23–25]. In calibrated CT images, intensities correspond to bone mineral density [26], which in turn relates to the Young's modulus through empirical relationships [25]. Bone geometry and material properties can be extracted from CT images and used for finite element (FE) simulations to assess bone quality and strength [23,27]. Commonly, FE simulations are performed on a small amount of samples due to the difficulty in retrieving data and in creating FE models, thereby limiting the generalization of findings to larger populations. Whereas a fast creation of FE models could be achieved with technical development, the collection of large homogeneous datasets is still challenging. Statistical appearance models represent a possible solution as they allow the creation of

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realistic instances, suitable for population-based studies. Moreover, the parametric description of the instances allows statistical control on shape and material property variations. For these reasons, statistical appearance models have recently been combined with FE simulations to predict bone strength [28,29] and fracture risk [9,30].

The most challenging requirement for the creation of statistical models is to establish accurate correspondences among similar features of dataset objects. For statistical appearance models, correspondences have to be accurate, not only on the surface but also in the volume. Two different approaches have been proposed for the creation of bone models, based on different representations of bone: image-based and mesh-based. In image-based approaches, bones are represented as volumetric images [9,28,31], thus voxels contain information of both shape and intensity. Correspondences among images are detected using image registration algorithms, like free-form deformation [32] and demons [33]. In the mesh-based approach, bones are represented as volumetric meshes [7,29], therefore mesh nodes contain information of shape and the intensities are associated with each node. Correspondences among meshes are established using mesh morphing techniques [30,34,35]. Both approaches have advantages and drawbacks. In the image-based approach, registration allows dense anatomical correspondence among the dataset objects. However, new instances can be generated only with invertible deformation vector fields, and they have to be meshed individually, creating difficulties when comparing mechanical results. In the mesh-based approach, morphing provides FE meshes that are directly suitable for FE calculations and that have corresponding elements. However, the variation of node positions to guarantee valid mesh elements could limit the accuracy of correspondences.

In this study, we aim to compare statistical appearance models created with one image-based and one mesh-based approach and to evaluate their implications for finite element simulations. We compare (i) the performances of two approaches for correspondence detection algorithms, image registration and mesh morphing; (ii) the quality of statistical appearance models created with the two approaches and their implications for FE results obtained from reconstructed bones vs. original bones; (iii) the quality of the FE meshes created for new instances.

2. Materials and methods

2.1. Subject data

A total of 155 left femur CT images were used in this study. Among the subjects, 70 were male and 85 female (age = 62 ± 16 years, height = 166 ± 7 cm, weight = 71 ± 16 kg), 124 were Caucasian, 28 were Asian and 3 were African. The resolution of the CT images was between 0.61 × 0.61 mm and 1.17 × 1.17 mm, with a slice thickness of 1 mm. Data acquisition was fully anonymized and controlled by a governmental data protection agency (Datenschutzbeauftragter Stadt Bremen, Bremen, Germany).

From the 155 images, we randomly selected 130 images to calculate the statistical appearance models, and we used the remaining 25 images to validate the model.

2.2. Creation of statistical appearance models

We computed two statistical appearance models: one image-based and one mesh-based. For the image-based case, we considered bones as volumetric images, and we constructed the model using image voxels. For the mesh-based case, we considered bones as volumetric meshes, and we computed the model using mesh node positions and corresponding intensities at the nodes. We implemented the two approaches following the scheme depicted in Fig. 1. For both the image-based and the mesh-based approaches, we established bone anatomical correspondences (Step 1), built a statistical appearance model (Step 2) and created new instances (Step 3). For each step, we validated and compared the performances of the two approaches. We performed all computation using VTK 5.6.1 (Visualization Toolkit, Kitware), ITK 3.20.0

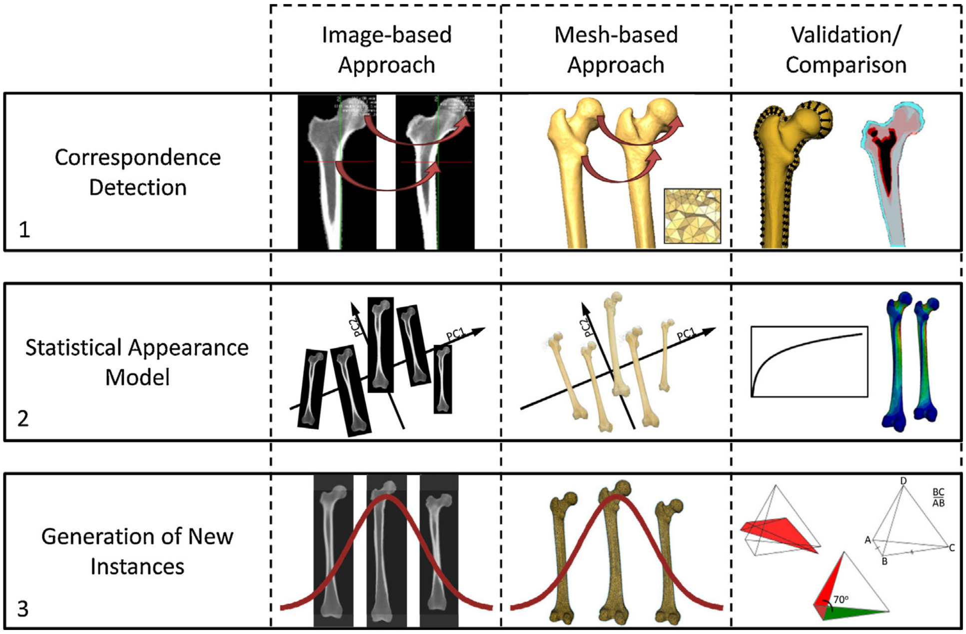

Fig. 1. Creation and evaluation of statistical appearance models using an image-based and a mesh-based approach. The models were created in three steps. Step 1 is the detection of corresponding anatomical landmarks, Step 2 is the creation of the statistical appearance models, and Step 3 is the generation of new instances. For each step, we validated the model, and for the last two steps, we compared the FE performances. For Step 1, we evaluated the accuracy of the correspondences on the bone surface using the Hausdorff distance and in the bone volume using overlapping metrics. For Step 2, we validated the models using compactness, representation and generalization, and we evaluated the FE results on the original bone vs. reconstructed bones. For Step 3, we evaluated the quality of the created meshes using Jacobian, edge ratio and minimum angle.