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Comprehensive evaluation of PCA-based finite element modelling of the human femur

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ABSTRACT

Computed tomography (CT)-based finite element (FE) reconstructions describe shape and density distribution of bones. Both shape and density distribution, however, can vary a lot between individuals. Shape/density indexation (usually achieved by principal component analysis—PCA) can be used to synthesize realistic models, thus overcoming the shortage of CT-based models, and helping e.g. to study fracture determinants, or steer prostheses design. The aim of this study was to describe a PCA-based statistical modelling algorithm, and test it on a large CT-based population of femora, to see if it can accurately describe and reproduce bone shape, density distribution, and biomechanics.

To this aim, 115 CT-datasets showing normal femoral anatomy were collected and characterized. Isotopological FE meshes were built. Shape and density indexation procedures were performed on the mesh database. The completeness of the database was evaluated through a convergence study. The accuracy in reconstructing bones not belonging to the indexation database was evaluated through (i) leave-one-out tests (ii) comparison of calculated vs. in-vitro measured strains.

Fifty indexation modes for shape and 40 for density were necessary to achieve reconstruction errors below pixel size for shape, and below 10% for density. Similar errors for density, and slightly higher errors for shape were obtained when reconstructing bones not belonging to the database. The in-vitro strain prediction accuracy of the reconstructed FE models was comparable to state-of-the-art studies.

In summary, the results indicate that the proposed statistical modelling tools are able to accurately describe a population of femora through finite element models.

1. Introduction

Biomechanical properties of bones are often investigated by means of three-dimensional (3D) reconstruction and finite element (FE) model generation, usually from computed tomography (CT) data. This is because 3D FE models of bones can reproduce both shape and material properties, which are acknowledged to be key factors in determining their biomechanical behaviour.

The variability of shape and densitometry among individuals is high, and the possible changes induced by pathologies may even enhance it. In order to properly and generally answer many research questions it would be helpful to have available large collections of models that can completely describe a whole population (i.e. a group that can be categorized by a unique general determinant, be it ethnicity, pathological status, etc.). Conversely, one of the most common limitations of FE bone modelling studies [1–4] is the limited size of the bone database investigated, which usually cannot be stated to be representative of a population, and may fail to achieve a good statistical power if used to discriminate between different conditions [5].

Unfortunately, the availability of large bone databases is often scarce, due to different reasons (CT scans cannot be executed on volunteer subjects, having access to clinical archives is difficult for privacy reasons, in-vitro cadaver specimens are scarcely available). One alternative is to generate large datasets of bones using statistical models. Limiting the view to the femoral bone, the availability of a database of realistic femora generated from statistical models allowed researchers to overcome limitations due to the small sample size when investigating bone fracture risk [6], analyzing the influence of anatomy on biomechanics

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[7], or exploring possible correlations between biomechanics and pathology [8]. These datasets are generated starting from reduced-parameter representations of the variability of shape and density distribution [9–12], obtained from different sources (2D or 3D images, 3D models) often using methods based on principal component analysis (PCA) [13–15], on which this study will focus.

The reliability of FE models generated from statistical models may be affected, depending on the generation technique, by several factors: (i) the representativeness of the starting database, from which the statistical model is inferred, with respect to the population to be studied; (ii) the adequateness of the number of statistical modes chosen to represent the population model; (iii) the ability of the synthesizing algorithm to replicate the characteristics of a specimen not belonging to the starting database. Moreover, these statistically-generated FE models should be comparable to the state-of-the-art models in terms of accuracy of the results [3,16,17]. A systematic approach towards the evaluation of statistical bone modelling has been recently proposed [18]. However, to the authors' best knowledge a comprehensive validation in terms of: (i) representativeness of the database, (ii) accuracy in reproducing shape and material properties of specimens not belonging to the starting database, and (iii) accuracy of the produced finite element models, is lacking.

The aim of the present work was to evaluate, on a large database of human femoral anatomies derived from CT scans, the ability of a PCA-based statistical modelling algorithm to accurately represent shape, bone mineral density (BMD) distribution, and strain distribution.

2. Material and methods

A database (DB) of femoral CT datasets was collected and morphologically characterized. Isotopological meshes with material properties mapped from CT were built for each femur. Shape and BMD indexation procedures (developed by ANSYS) were performed on the mesh database. The completeness of the database was evaluated through a convergence study on the number of indexation modes to be used. The statistical representation of shape and BMD was evaluated (i) through leave-one-out tests to assess the accuracy in reconstructing femora not belonging to the indexation database; (ii) through comparison of simulated vs. in-vitro experimentally measured strains to assess the mechanical reliability of the reconstructed femora.

2.1. Femora DB

A large database of bi-lateral whole femur CT datasets, collected for pre-surgical planning of total hip replacement on osteoarthritic patients was available at Rizzoli Orthopaedic Institute, Bologna, Italy. From that database, we identified a collection of 115 femora (44 males, 71 females) that according to an experienced surgeon had no pathological deformities. All CT datasets were obtained with a standardized protocol [19] and densitometrically calibrated [20]. CT voxel resolution ranged from $0.488 \times 0.488 \times 1.5$ mm to $0.781 \times 0.781 \times 3$ mm. Femoral bones were segmented from the CT images using Amira (v4.0, Visage Imaging Inc., USA), and a polygonal geometry in stereolithography file format was obtained for the external contour of each bone. The anatomical variability was characterized on the 3D reconstructed geometries, using an in-house developed software [21], through the following anatomical descriptors: femoral neck length, femoral head diameter, caput-collum-diaphyseal (CCD) angle (all detailed in [22]), anteversion angle [23], and epicondyle length (defined as the linear distance between medial and lateral epicondyle). Basic descriptive statistics of the measurements conducted on the database are reported in Table 1. Bone mineral density was evaluated in the femoral neck of all femora from calibrated CT images, yielding a mean volumetric BMD of 0.308 g/cm^3, with maximum and minimum values of 0.542 g/cm^3 and 0.151 g/cm^3, respectively.

Table 1
Descriptive anatomical and anthropometrical parameters of the collection of 115 femora used to perform the indexation.

	Mean (SD)	Minimum	Maximum
Anatomical parameters			
Biomechanical length [mm]	406 (28)	356	483
Neck length [mm]	39 (4)	27	51
Head diameter [mm]	44 (4)	36	52
Epicondyle length [mm]	81 (13)	69	96
Anteversion angle [°]	13 (9)	0	46
CCD angle [°]	126 (8)	104	145
Anthropometrical data			
Age [years]	58 (15)	26	84
Height [cm]	166 (9)	192	147
Weight [Kg]	73 (14)	50	118

The large range spanned by most measurements shows that our database largely encompasses the anatomical variability reported in [22,24].

2.2. FE model generation

Each femur of the database was meshed, morphing the mesh template presented in [25] (56809 nodes and 298866 10-noded tetrahedral elements, average element edge size 2 mm) to obtain a collection of 115 subject-specific isotopological finite element meshes. The morphing algorithm adopted (developed by ANSYS) is based on radial basis functions and has been recently reported and validated [25].

Material properties were mapped onto each FE model of the database using Bonemat_V3 algorithm [26] with the configuration parameters identified in previous validation studies [27].

2.3. PCA-based modelling of shape

A pre-processing and an indexation step were necessary to set both the shape and the BMD models, as explained in details in Section 2.3.1.

2.3.1. Shape pre-processing step

A pre-processing step [28] was applied, in which all the femora were converted to left ones (mirroring the right femur anatomies) and normalized in terms of rigid transformations (3 translations and 3 rotations) and scaling. The following operations were iterated:

- Calculate a mean bone shape, averaging nodal coordinates for each node in the 115 isotopological meshes.
- Adjust the mean shape to a default scaling, orientation and origin. To define the default scaling, the mean bone was scaled so that the distance between two anatomical landmarks used in the mesh morphing process (fovea of the femoral head and most superior point of the greater trochanter) was constant and equal to the mean value of the database of bones. To define the default origin and orientation, the mean shape was translated so that the centroid has (0,0,0) coordinates, and the rotations were adjusted so that the two above cited landmarks lay on the *Z* axis (fovea) and on the XZ plane (most superior point of the greater trochanter).
- Once a mean shape was determined and its position adjusted to the default position, the scaling, origin, and orientation of each bone were optimized to minimize the distance with that mean shape, and at the end of this process a new "mean shape" was calculated.