EVALUATION OF THE ABILITY OF A PCA-BASED INDEXATION METHOD TO ACCURATELY DESCRIBE SHAPE AND BMD PROPERTIES OF HUMAN FEMURS

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INTRODUCTION

The development of statistical modeling of bone shape and mineral density (BMD), through which whatever individual bone can be reconstructed or synthesized, is a growing field of biomechanical research. Applications of statistical modeling in biomechanics range from image segmentation [1-3], to prostheses design [4, 5] and computer assisted surgery [6]. Several works are available in literature, but what currently lacks is a full validation of proposed statistical models in terms of: (i) accuracy in the representation of indexed properties and (ii) comparison to analogous state-of-the-art "standard" models. The validation of a proposed technology is mandatory for a future application of it in translational research field and, finally, in the standard clinical practice [7]. The aim of the present study is to evaluate the ability of an indexation method based on principal component analysis (PCA) to accurately describe shape and BMD properties of a population of 115 human femurs.

METHODS

DATABASE OF FEMURS. A collection of 115 femur CT datasets showing no deformities was retrieved from a database of the Rizzoli Orthopaedic Institute. CT voxel resolution ranged from 0.488×0.488×1.5mm to 0.781×0.781×3 mm. The CT images were segmented 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 geometry, using an in-house software [8], through previously proposed anatomical descriptors of the human femur: femoral shaft length [9, 10], femoral neck length [11], femoral head diameter [11], caput-collum-diaphyseal (CCD) angle [11], anteversion angle [12] and epicondyle length (linear distance between medial and lateral epicondyle). Basic descriptive statistics of the measurements conducted on the database are reported in Table 1. The large spread in most measurements suggest that the bones sample may be considered representative of Italian aging population.

Table 1

	Mean value (±SD)	Max value	Min value
Biomechanical length [mm]	406.1 (27.9)	482.5	355.8
Neck length [mm]	38.5 (4.4)	51.4	26.9
Head diameter [mm]	21.9 (1.6)	25.9	18.5
Epicondyle length [mm]	80.5 (12.8)	95.8	69.0
Anteversion angle [°]	12.8 (9.2)	45.45	0.6
CCD angle [°]	125.9 (7.5)	145.0	104.1

MESH MORPHING. Each femur of the database was morphed to obtain a collection of 115 subject-specific iso-topological finite element (FE) meshes. The morphing algorithm adopted is based on radial basis function and was previously validated (details can be found in [13]).

SHAPE INDEXATION AND PROJECTION. The shape indexation algorithm consists of two steps: (i) pre-processing of surface meshes, in which all the femurs are converted to left ones (mirroring the right femur anatomies) and normalized in terms of rigid transformations and scaling; (ii) PCA computation of eigenvalues and eigenvectors. Details on the shape indexation algorithm can be found in [14]. Since the database is made of iso-topological FE meshes, a node-to-node distance optimization criterion is adopted for the shape projection (i.e. reconstruction of the shape of a given femur through optimization of registration, scaling, and linear combination of the modes calculated during the indexation phase).

BMD INDEXATION AND PROJECTION. Material properties were mapped onto each FE model of the database using Bonemat_V3 algorithm [15]. A PCA was directly applied on the database to obtain eigenvalues and eigenvectors. The BMD projection procedure consists of two steps: (i) patient BMD distribution is described using the morphed mesh; (ii) projection into a user chosen number of modes (i.e. optimization of the coefficients of the linear combination of the selected BMD modes).

EVALUATION PROCEDURE. Shape and BMD indexation were performed on all the femurs of the database using an increasing number of modes, till the mean reconstruction error on the whole database was, respectively, comparable to the resolution of the CT data and below 10% of relative percentage error. Once the number of indexation modes to be used for projections was set, leave-one-out tests were performed on all the specimens to assess the accuracy of shape and BMD projection in reconstructing femurs not belonging to the indexation database.

RESULTS AND DISCUSSION

SHAPE INDEXATION AND PROJECTION. Node-to-node distance error for the shape indexation of the femur database at several number of modes are reported in Table 2. Using 50 modes the mean error is considerably smaller than the resolution of the CT scan images, and the maximum error among all the nodes of all the FE meshes is below 5mm.

Table 2

	Mean projection error		Max projection error	
# modes	Mean [mm]	Max [mm]	Mean [mm]	Max [mm]
5	1.42	2.63	6.9	11.72
10	1.04	1.73	5.68	11.08
15	0.88	1.34	5.02	10.17
20	0.77	1.27	4.47	8.69
25	0.68	0.99	4.03	7.27
30	0.60	0.88	3.63	6.84
35	0.53	0.75	3.18	6.31
40	0.48	0.67	2.94	6.11
45	0.43	0.63	2.70	5.52
50	0.39	0.56	2.43	4.84

As a consequence, 50 modes were used in the leave-one-out tests. Results of leave-one-out tests for all 115 femurs are resumed in Table 3.

Table 3

	Mean distance [mm]	Max distance [mm]
Mean value	1.22	5.51
Max value	2.75	16.02
St dev	0.41	2.3

BMD INDEXATION AND PROJECTION. Accuracy metrics for BMD indexation tests performed on all the femurs of the database are shown in Table 4.

Table 4

	Relative error		Mean project error		Max project error	
# modes	Mean [%]	Max [%]	Mean [g/cm^3]	Max [g/cm^3]	Mean [g/cm^3]	Max [g/cm^3]
5	17.71%	27.76%	0.068	0.086	0.688	1.217
10	15.34%	22.58%	0.060	0.075	0.636	0.915
20	12.70%	17.16%	0.050	0.061	0.548	0.866
30	11.07%	14.96%	0.044	0.052	0.477	0.799
40	9.74%	13.72%	0.039	0.044	0.414	0.758
50	8.55%	12.81%	0.034	0.040	0.354	0.730
60	7.46%	12.22%	0.030	0.036	0.303	0.687
70	6.40%	10.61%	0.026	0.034	0.257	0.550

Referring to Table 4, the relative error is defined as the ratio between the euclidean norm of the error vector and the norm of the real BMD values vector. The mean relative percentage error goes below 10% when using 40 modes. This was assumed as a sufficiently accurate estimation of BMD values (mean projection error of 0.039g/cm^3 corresponds to an Elastic Modulus estimation error of about 1GPa for 1.4g/cm^3 of BMD which is typical of very compact bone [16]), so 40 modes were used in the leave-one-out tests. Results of leave-one-out tests are reported in Table 5.

Table 5

	Relative error [%]	Mean projection error [g/cm^3]	Max projection error [g/cm^3]
Mean value	13%	0.05	0.65
Max value	21%	0.09	1.23
St dev	2%	0.01	0.14

The results of the present study evidenced the ability of the proposed shape and BMD indexation algorithms to predict shape and material properties of a population of 115 femurs with a satisfactory accuracy. To authors' knowledge this is the first work reporting an extensive validation of PCA-based indexation algorithm in terms of accuracy in describing shape and BMD properties for a population of human femurs. The leave-one-out tests showed that there is a mild worsening of all the accuracy indicators when predicting shape and BMD of an out-of-database specimen. This may indicate that the actual collection of 115 femur anatomies, though one of the largest reported for statistical modeling studies, is still not sufficient to fully reproduce anatomical variability. As a consequence future works will look at increasing the number of specimens in the database. As to the shape projection metric, Hausdorff distance [17] computation will be implemented to improve the reliability of shape-matching results.

Other future work will regard joining shape and BMD projection in order to obtain a full mechanistic (shape and material properties) statistical projection of a femur specimen. The so obtained projected femurs could then be validated in terms of strain and fracture risk prediction accuracy using a previously proposed experiment [18, 19] as a benchmark.

CONCLUSIONS

A recently proposed method for shape and BMD indexation and projection has been tested in terms of prediction accuracy on a collection of 115 femur anatomies. Through the proposed instrument, a set of parameters from 3D data can accurately represent the variation of bone morphology and material properties, with several possible developments that range from the synthesis of realistic femoral anatomies, to the definition of parameterised response surfaces of FE simulation results.

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