Does cortical bone mapping improve FE strain prediction accuracy at the proximal femur?

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***Abstract*— Our research hypothesis is that the explicit modelling of cortical bone layer through cortical bone mapping (validated for cortical thickness and density estimates) can improve the accuracy of CT-based FE models of the proximal femur, locally limited by CT partial volume artefacts. This hypothesis was tested in terms of elastic strain prediction on a published cohort of 10 femurs, against strain measurements in stance and fall loading configuration. Preliminary results in two specimens modelled with constant cortical density confirmed that in focal areas where reference models showed peak errors, strain accuracy can be greatly improved, at the cost of a global over-stiffening of the structure, which may be resolved by modelling variable cortical density in the study follow-up.**

***Keywords*— proximal femur, cortical bone, finite element, CT deconvolution algorithms.**

I. Introduction

AFTER more than 20 years of technical development, femoral strength estimates from CT-based FE models (*FE-strength* for short) have reached clinical trials. Notably, three *FE-strength* studies demonstrated a superior fracture classification ability than the current standard of care (*aBMD*) [1-3], but the cost-effectiveness ratio of *FE-strength* is not yet appealing for routine clinical application. The *FE-strength* methodologies of [1-3] diverge significantly as to model creation, material modelling, and failure criterion. We observed a similar concordance of results and difference in methods in *FE-strength* validation studies [4]. Also in these, results are overall good, yet sub-optimal.

What are current models lacking to improve their performance? One morphological feature usually not modeled in current *FE-strength* approaches is the cortical/trabecular distinction. This omission is mainly due to the blurred appearance of the thin cortical bone layer, caused by the partial volume effect (*PVE*) inherent in CT images. There is evidence that *PVE* in CT images influences FE results [5], and impairs FE strain prediction accuracy: in a past study we found that peak errors in FE predictions against experimental strain gauge measurements happened at sites of thin cortical bone shell (i.e. all around the femoral neck) [6]. These sites correspond to areas of actual fracture development [4].

Recently, Treece et al. developed and validated cortical bone mapping (*CBM*), which estimates cortical bone thickness from CT images by way of a deconvolution algorithm, [7]. A newer version of *CBM* accurately estimates not only cortical thickness but also cortical density [8].

Our research hypothesis is that the explicit modelling of cortical bone layer through *CBM* can improve the accuracy of CT-based FE models of the proximal femur. In the present study we focused on testing this hypothesis in terms of strain prediction accuracy in the elastic field, on a published cohort of 10 femurs where strain gauge measurements were available for stance and side-fall loading configuration [9].

II. Materials and Methods

A. Specimens

This study used specimens, images, and reference models from a previous experimental campaign. Specimen and imaging details of the ten fresh-frozen cadaveric femurs were presented in [9]. It is worth recalling that no donors suffered from musculo-skeletal diseases, and that CT scans were taken over the whole femur with a clinical protocol.

B. Experimental tests

Details of the experimental protocol for mechanical testing of the femurs were presented in [10] for stance (all specimens) and in [11] for fall (specimens #4-10) loading configurations. It is worth recalling that:

(i) a uniaxial testing machine (Mod. 8502, Instron, US) with low-friction bearings was used;

(ii) 12 triaxal strain gauges (KFG - 3-120-D1711L3M2S, Kyowa, Japan) were glued on the four anatomical aspects at three distal levels (head, neck and metaphysis) to measure the magnitude and direction of principal strains.

(iii) six different loading directions were applied directly to the femoral head to mimic stance configuration (0°, 3°, 8° and 24° in the frontal plane, –3° and 18° in the sagittal plane;

(iv) twelve different directions combining three internal rotation (0°, 15° and 30°) and four adductions angles (0°, 10°, 20° and 30°) were applied to mimic fall configuration, delivering the load through aluminium spherical caps cemented to the femoral head and greater trochanter.

C. Cortical bone mapping

We performed the *CBM* using the freeware Stradwin 5.2 (http://mi.eng.cam.ac.uk/~rwp/stradwin/). We segmented the proximal femur to have an initial estimate of the surface, through which profiles of HU values are sampled, and used to obtain deconvolved cortical thickness and density. We then:

(ii) ran the deconvolution algorithm keeping cortical density constant so to estimate the cortical layer (i.e. periosteal and endosteal cortical surfaces), called Cortical model I (*CmI*)

(iii) ran the deconvolution algorithm with variable cortical density so to estimate both the cortical layer, and cortical density at profiles normal to the surface (*CmII*).

D. FE models

To generate the FE models using *CBM* we first obtained B-spline representations of the surfaces (Geomagic Studio, v. 7, Raindrop Geomagic, Inc., USA), then meshed with 10-node tetrahedra the cortical layer (mesh size ≤1 mm) and the trabecular compartment (Hypermesh 13.0, Altair Engineering Inc., USA). In the trabecular compartment, we mapped bone properties with Bonemat (freeware at www.bonemat.org). For the cortical layer, we developed a specialised Bonemat (still unpublished) that takes as input cortical density values sampled at outer surface locations. Two models were thus generated, from *CmI* and *CmII* (variable cortical density).

To define inhomogeneous isotropic material properties, radiological density from the densitometric CT calibration was converted first to ash then to wet density according to [12]. The density-elasticity relationship of [13] was used.

Boundary conditions mimicked those of the experimental tests, following a spatial registration procedure. As only the proximal femur cortical model was available, we adopted a cut-boundary displacement method to replicate the experimental distal constraint, as in [10].

Linear FE analyses were performed (Ansys Inc., v. 15, USA). At the surface, we assumed a plane-stress state. Principal strains were calculated by averaging for each surface node (corresponding to the closest point where each strain gauge was located on the femur) the strains values in a circle of 3 mm to guarantee the continuum hypothesis.

III. Results

We here present preliminary results on two specimens, for the FE model featuring constant cortical bone density (*CmI*), compared to results of reference FE models [9]. Two different result trends clearly emerge from the data.

Locally, at sites of cortical thinning where reference model was inaccurate, all accuracy metrics improved (Table 1).

TABLE I

Local FE Strain Accuracy (Anterior Neck Strain Gauge)

Title	Reference Model	Cortical model I
R^2	0.97	0.99
Slope	2.70	1.01
Intercept (με)	6	-5
RMSE%	90.0%	3.8%
Max err%	193.2%	7.1%

FE strain accuracy at a neck site where reference model errors were high

TABLE II

Global FE Strain Accuracy (All data pooled)

Title	Reference Model	Cortical model I
R^2	0.90	0.89
Slope	1.24	0.69
Intercept (με)	-10	-7
RMSE%	14.0%	11.5%
Max err%	74.4%	45.1%

FE strain accuracy pooling all 816 strain data

Conversely, global accuracy metrics remained almost unaffected (Table 2), although peak error was significantly reduced. Reduction in peak errors but concomitant global over-stiffening (as witnessed by regression slope well below unity) explain these global figures. Separating data per specimen or loading configuration had almost no effect on accuracy metrics.

IV. Conclusion

We incorporated for the first time (to our knowledge) accurate local cortical thickness estimates from a CT image deconvolution algorithm into CT-based FE models of the proximal femur. Preliminary results confirmed our hypothesis that explicit modelling of the cortical layer can improve FE strain accuracy where reference models are usually show the highest errors. However, these improvements were counterbalanced by a general over-stiffening of the model response, possibly due to the assignment of constant density to the cortical layer, resulting in an homogeneous, high elastic modulus (around 18-20 GPa). We expect that modelling local variation of cortical density can help resolve this problem.

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