DOES 3D-REGISTRATION IMPROVE REPEATABILITY OF HR-PQCT-BASED HOMOGENIZED FINITE ELEMENT ANALYSIS?

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Introduction

High-resolution peripheral quantitative computed tomography (HR-pQCT) based finite element analysis may help to better detect the progression of bone disease in longitudinal studies. Recently, a unified homogenized finite element (hFE) methodology was developed, which uses the information of bone volume fraction (BV/TV) and fabric anisotropy (**M**) of the bone. This hFE methodology can predict stiffness and strength of experimentally tested distal radii and tibiae with a high level of accuracy [1]. Though, in longitudinal studies, scan misalignments may falsify the comparison of hFE results and must be corrected. Accordingly, the goal of this study is to develop and assess the benefit of a 3D registration method in comparison to the absence of registration.

Material and Methods

HR-pQCT scan misalignments can be adjusted using a preliminary 3d-rigid-body registration (fixed image= baseline, moving images= follow up scans). Using the resulting transformation matrices of the registration, the largest common region can be evaluated which is then used to create a patient specific hFE mesh (Abaqus elem. type= C3D8). The height of the common regions differs among patients; thus, the element size is different for each patient. After mesh generation, for each element, the BV/TV and **M** were extracted in the original image (without image transformation) using the inverse of the transformation matrix and stored in the corresponding element. This approach enables to evaluate the same bone region of repeated scans without rotating and therefore interpolating the image.

The previous hFE methodology was slightly modified. The post-yield behavior (simple softening) reported in [1] is element size dependent and was replaced by perfect plasticity. Consequently, strength is redefined using the 0.2% offset yield criterion. Resulting stiffness and strength of the modified hFE pipeline were validated on the same experimental data as reported in [1] with a minor adjustment of the material constants.

The influence of 3d-registration was evaluated with a dataset of repeated distal radii and tibiae HR-pQCT examinations reported in [3]. Radii and tibiae were scanned with a double and triple stack scanning protocol, respectively. Scans were analyzed using the modified hFE methodology with and without 3d-registration. The coefficients of variation CV of the two options were calculated using the approach of [4]. Motion may occur during multiple stack scanning, resulting in a shift between the stacks. This shift limits the power of the 3d-regsitration and was detected by a dice coefficient (DC) of the mask below 99%. Complete and filtered (DC> 99%) dataset were analyzed.

Results

High correlation between modified hFE and experiments were observed in both stiffness (R^2=94,1%, p=2.7e-30) and strength (R^2= 96,2%, p=4.23e-33).

CV of repeated scans are becoming smaller by using preliminary registration (see table 1), especially for the intrinsic properties (apparent Young's modulus ($E_{app.}$) and yield strength (σ_{yield})). Furthermore, the CV is higher in the radius compared to the tibia. By filtering the dataset (DC>99%), the CV is reduced.

Radius double section; n=33, (n=26)			
Parameter	CV_{noReg} %	CV_{3d} %	p-value
BV/TV	1.1 (1.1)	0.6 (0.4)	9.1e-5 (1.4e-3)
Stiffness	2.5 (1.9)	2.4 (1.5)	ns. (4.0e-2)
F_{yield}	4.0 (3.8)	3.3 (2.3)	6.6e-3 (5.1e-3)
E_{app}.	3.7 (3.3)	2.4 (1.9)	2.2e-3 (1.3e-2)
σ_{yield}	6.4 (3.1)	3.5 (3.2)	3.7e-5 (8.3e-4)
Tibia triple section; n=39 (n=37)			
Parameter	CV_{noReg} %	CV_{3d} %	p-value
BV/TV	0.4 (0.4)	0.4 (0.3)	1.1e-3 (4.4e-5)
Stiffness	1.5 (1.7)	1.6 (1.5)	ns. (ns.)
F_{yield}	2.3 (2.5)	2.2 (2.2)	ns. (ns.)
$E_{app.}$	1.9 (1.7)	1.5 (1.4)	1.2e-3 (5.6e-3)
σ_{yield}	3.2 (2.4)	2.1 (2.1)	6.2e-4 (1.1e-3)

Table 1: Coefficients of variation with (CV_{3d}) and without (CV_{noReg}) 3d-registration and the p-values for complete and (filtered) dataset: double and triple stack protocol for radius and tibia, respectively.

Discussion

The implemented 3d-registration reduces the repeatability errors, and this reduction is statistically significant for BV/TV and the intrinsic mechanical variables. Higher CVs were observed in the radius compared to the tibia, that we attribute to the less reproducible scanning position but also to larger motion artefacts in the radius. Hence, the benefit of 3d registration is higher for the radius compared to the tibia.

References

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