11th. World Congress on Computational Mechanics (WCCM XI)
5th. European Conference on Computational Mechanics (ECCM V)
6th. European Conference on Computational Fluid Dynamics (ECFD VI)
July 20 - 25, 2014, Barcelona, Spain

Lack of universal bone material laws limits accuracy in subject specific FE models

Peter Augat[1,2], Michael Göttlinger[1], Julia Henschel[1] and Sebastian Eberle[1,2]

[1] Institute of Biomechanics, Trauma Centre Murnau, Prof. Kuentscher Str.8, 82418 Murnau, Germany, biomechanik@bgu-murnau.de, www.bgu-murnau.de

[2] Institute of Biomechanics, Paracelsus Medical University Salzburg, Strubergasse 21, Salzburg Austria, www.pmu.ac.at, peter.augat@pmu.ac.at

Key Words: *Finite Elemente Modeling, Inverse Dynamics, Bone Biomechanics*

INTRODUCTION

The use of computational models for patient specific predictions of mechanical stability after fracture fixation is still limited by both the limited accuracy of the models and the pre-computational effort required building the individual model. One essential factor affecting the accuracy of the computational model is appropriateness of the assumed material properties for bone tissue, which are typically obtained from bone mineral density measurements. In a previous study on subject-specific Finite Element models [1], we found that appropriate density-elasticity relationships to compute the mechanical behavior of femurs seem to be specimen-specific. The goal of this study was to test the hypothesis that the predictive error of subject-specific FE-models is lower with subject-specific density-elasticity relationships than with a cohort-specific density-elasticity relationship.

METHODS

Subject-specific FEA and inverse optimization based on response surface methodology were employed to test the stated hypothesis. FE-models of 17 human femur specimens and corresponding experimental data were taken from a previous study by Eberle et al. [1]. A typical power function for the relation between radiological bone density and elastic modulus was set up with the optimization variables $\boldsymbol{a}$ and $\boldsymbol{b}$:

(1) $E(MPa) = \mathbf{a}Á_{qCT}^{\mathbf{b}}$ (gK_2HPO_4/cm^3)

The goal of the optimization was to minimize the root-mean-square error in percent (RMSE%) between computational (FEA) and experimental results (EXP) for each measurement. FEA and optimization were performed in ANSYS Workbench® (ANSYS® Academic Research, Release 14.5, ANSYS, Inc., Canonsburg, USA).The optimization procedure was applied to each FE-model individually to determine the subject-specific density-elasticity relationships, and to all 17 FE-models at once, to determine the cohort-specific density-elasticity relationship. To show that each bone specimen has an individual density-elasticity relationship, the following null hypothesis had to be falsified:

(2) H_0: $Error_{subject\text{-}specific}$ e $Error_{cohort\text{-}specific}$

Predictive errors were defined as absolute relative errors in percent per measurement i:

(3) $Error_i := |(FEA_i - EXP_i)/EXP_i|$

A paired t-test (p=0.05) was performed on all predictive errors i between the two groups (subject-specific functions vs. cohort-specific function) (SPSS, Rel. 19.0.0, 2010, SPSS Inc., Chicago, USA). In addition, the RMSE%, the mean value (MV) and the 1.96 standard deviation (SD) of the relative prediction errors were calculated.

RESULTS

The subject-specific functions resulted in a 6% lower overall prediction error than the cohort-specific function (10% vs. 16%, $p<0.001$). Thus, the null hypothesis was falsified. Furthermore, the overall RMSE% and the 1.96 SD across all measurements were smaller with the subject-specific relations (Table 1). The determined subject-specific relations were mostly linear (Fig. 1). For the cohort-specific relation, the following power law was obtained:

(4) $E(MPa) = \mathbf{12486}\acute{A}_{qCT}^{\mathbf{1,16}}\ (gK_2HPO_4/cm^3)$

Table 1. Descriptive statistics of relative prediction errors.

Density-elasticity relation		Prediction error statistics			
		All data	Strain data	Displacement data	Stiffness data
Subject-specific functions	MV	-2%	7%	-7%	2%
	1.96 SD	27%	22%	25%	14%
	RMSE%	14%	13%	15%	7%
Cohort-specific function	MV	-4%	5%	-10%	6%
	1.96 SD	39%	32%	39%	33%
	RMSE%	20%	17%	22%	17%

CONCLUSION

Agreement between computational models and mechanical experiments is always incomplete due to inaccuracies in both the computation and the experiment. We found that individual human bone specimens require individual relations between bone density and elastic modulus. The use of a universal relationship and neglecting the individuality in the material laws adds an error anywhere between 5% and 20%. Thus we conclude, that subject specific models using universal material laws will result in inherent inaccuracies which can be reduced by individual density–elasticity relationships.

REFERENCES

[1] Eberle S, Göttlinger M, Augat P. An investigation to determine if a single validated density-elasticity relationship can be used for subject specific finite element analyses of human long bones. *Med Eng Phys*. Jul; 35(7):875-83, 2013.

ACKNOWLEDGMENT

This research has been financially supported by the German Social Accident Insurance (DGUV: FR165). The authors assume full responsibilty for the content.