BONE MECHANICAL PROPERTIES ARE BEST EXPLAINED BY INDIVIDUAL DENSITY-ELASTICITY LAWS

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Introduction

Previously [Eberle 2012], we found that density-elasticity relationships for 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 Finite Element (FE) models is lower with subject-specific density-elasticity relationships than with a cohort-specific relationship.

Methods

FE-models of 17 human femur specimens and corresponding experimental data [1] were used to determine subject-specific and cohort-specific density-elasticity relationships by optimization. The experimental data included normal strain measurements from 103 strain gauges, local displacement measurements from 171 optical markers, and axial stiffness measurements of all 17 specimens. An inverse optimization procedure was applied to determine density-elasticity relationships based on experimental data [Bosisio 2007]. The goal of optimization was to minimize the percent root-mean-square error (RMSE%) between computation and experiment. 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 cohort-specific density-elasticity relationship. For statistical analysis the RMSE%, the mean value and confidence interval of the relative errors were calculated across all measurements and for each category of measurement.

Results

The subject-specific functions resulted in a 6% lower overall prediction error than the cohort-specific function (10% vs. 16%, $p<0.001$). The overall RMSE% and the 1.96 SD were significantly ($p<0.05$) smaller for all measurements with the subject-specific relations. The determined subject-specific relations were mostly linear (Fig. 1), with variable exponent from 0.68 to 1.40 (1.05 ± 0.20). For the cohort-specific relation, the following power law was obtained:

$$E = 12{,}426\,\rho^{1.16} \qquad (1)$$

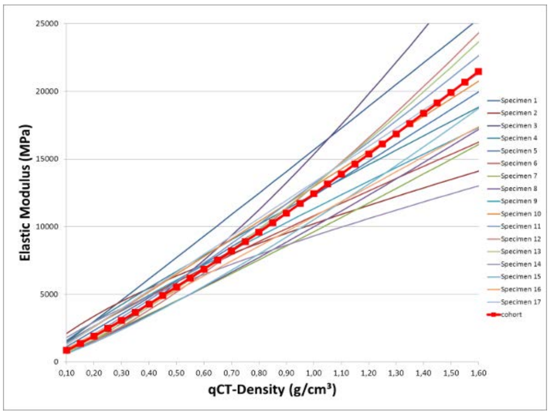

Figure 1. Cohort-specific and subject-specific density-elasticity relationships for all 17 specimens.

Discussion

We demonstrated that every human femur bone specimen has its individual density-elasticity relationship. Our findings might explain the spread in experimentally determined data regarding density-elasticity relationships. A potential explanation for the variability might be the contribution of the collagen phase to the mechanical properties of bone [Chen 2011]. Also the overall mechanical properties of bone were dictated by cortical bone, which has linear relation between density and elasticity. Thus, linear relations might be considered appropriate for subject-specific FE-models. Another approach could be the inclusion of variability into probabilistic density-elasticity relations [Wille 2012]. Our findings are limited by the applied material behavior, which was isotropic, and not site specific or tissue specific. In conclusion our findings indicate that every human bone specimen has its individual relation between bone mineral density and modulus of elasticity.

References

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