Estimation of Fracture Load of the Proximal Femur using CT-based Finite Element Models

INTRODUCTION:
Osteoporosis or other conditions negatively affecting bone strength often lead to a hip fracture. Hip fracture is a major public health and healthcare problem. It is also a huge economic burden, resulting in high hospital and home care costs. Fracture predictive and fracture preventative studies are therefore vital to identify individuals at high hip fracture risk.

Finite element (FE) modeling is useful for studying mechanical characteristics of hip fracture. FE models have been recognized as a noninvasive tool to estimate fracture load. CT-based FE analysis, that includes three-dimensional geometry and bone density distribution, could estimate the strength of the proximal femur accurately.

The objective of this experimental FE study was to create a simulation model that accurately estimates the experimentally measured fracture load of the proximal femur.

METHODS:
Cadaver femurs aged 67-94 years were CT scanned and mechanically tested simulating a fall [1, 2]. Thirty-one femurs (22 females and 9 males) were randomly selected for nonlinear FE analysis to estimate the fracture loads.

CT datasets were segmented using Mimics (v12.1, Materialise, Leuven, Belgium). Trabecular bone and cortical bone were modeled using tetrahedral elements. Minimum cortical thickness of the proximal femur was adjusted to 1 mm. Average element size was approximately 3 mm.

The mechanical properties of elements were computed from the Hounsfield Unit (HU) value. Young’s modulus (E) was calculated using the equation E = 10.095ρ [3], where ρ is the density value computed from the HU equation. Density was converted to ash density using the formula proposed by Keyak [4] in order to get the yield stress that was used as fracture criterion. Poisson’s ratio of 0.33 [5] was used.

Nonlinear FE analysis was performed using the Newton-Raphson method. The mechanical properties were assumed to be bi-linear elastoplastic. Post-yield modulus was 5% of E [6]. The ultimate tensile stress was presumed to be 0.8 times the compressive yield stress [7].

Yielding of an element in compression was defined to take place when Drucker-Prager stress exceeded the element yield stress [7]. Failure of the yielded element in compression was determined to occur when the minimum principal strain was lower than -0.0073 after reducing the pre-yield Young’s modulus of the element to the post-yield Young’s modulus. Failure of element in tension was defined to occur when the maximum principal stress exceeded the element ultimate stress.

Linear regression analysis was used to evaluate the relationship between the simulated and experimentally measured failure loads.

RESULTS:
Mean (±SD) FE-based fracture load was 3104±998N, whereas mean experimentally measured load was 3260±1000N. The estimated fracture load values were significantly correlated with the experimental ones (r²=0.926, SEE = 277N, p<0.0001) (Fig. 1).

DISCUSSION:
The objective of this experimental FE study was to create a simulation model that can accurately estimate the fracture load of the proximal femur. Based on the results, experimentally measured failure loads can be estimated using CT-based nonlinear FE models.

ACKNOWLEDGMENTS:
The study was supported by the Finnish Funding Agency for Technology and Innovation (grant nr. 40463/05), the International Graduate School of Biomedical Engineering, the Academy of Finland, as well as a grant of the Deutsche Forschungsgemeinschaft (DFG LO 730/3-1), and the Finnish Cultural Foundation, North Ostrobothnia Regional fund.

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