

Implementation of Asymmetric Yielding in Case Specific Finite Element Models improves the Prediction of Femoral Fracture Risk

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Introduction

Case specific non-linear finite element (FE) models have shown to be promising in the prediction of individual femoral fracture risk.^{1,2} Previous studies mainly adopted non-linear behaviour using the Von Mises (VM) yield criterion, assuming equal bone strength in tension and compression. However, it is commonly known that compressive yield strength ($\sigma_{y,c}$) is higher than tensile yield strength ($\sigma_{y,t}$) in bone.^{3,4} This asymmetric yielding is better described by the Drucker-Prager (DP) yield criterion, as already shown in micro scale bone models⁵. To our knowledge, the DP criterion was applied in one macro scale femur FE study before.² Failure criteria in that study were based on bone material properties, but parameters defining the yield behaviour were not. Using bone properties in DP is further hampered by the fact that reported yield strength asymmetries are highly variable.

In this study it was verified that asymmetric yielding in bone is better captured by the DP yield criterion than by the VM yield criterion. Subsequently a sensitivity analysis was performed, focusing on the effect of variable asymmetric yielding on bone failure in terms of failure force and failure location.

Materials and methods

Two paired cadaver human femora were CT-scanned with a calibration phantom, and mechanically loaded under compression until failure. In one femur of each pair one or two holes were drilled (representing bone metastases), whereas the other femur was kept intact. During the experiments failure forces and displacements were registered.

Case specific FE models comprising tetrahedral elements were generated. Based on ash densities determined from the calibrated CT-data, non-linear isotropic material behaviour was first implemented with the VM yield criterion, according to Keyak et al.¹ (Figure 1, 'VM'). Second, material behaviour was implemented with the DP yield criterion, defined by the initial yield stress (σ_y) calculated from ash densities, and α , which relates to yield asymmetry as follows:

$$\alpha = (\sigma_{y,c} - \sigma_{y,t}) / [(\sigma_{y,c} + \sigma_{y,t}) * \sqrt{3}].$$

The variation in α was calculated based on the range of yield asymmetries reported in literature^{3,4}, using the formula stated above, setting α to 0.027, 0.082 and 0.135. Implementing material behaviour with the DP criterion enlarged $|\sigma_{y,c}|$ and decreased $|\sigma_{y,t}|$ compared to the VM simulation, such that $|\sigma_{y,c}| > |\sigma_{y,t}|$ (Fig.1, 'DEFAULT').

Next, $DP\sigma_{y,c}$ was equated to $VM\sigma_{y,c}$ ('COMP'), resulting in a decrease in $|\sigma_{y,t}|$ compared to the DEFAULT case. Finally, $DP\sigma_{y,t}$ was equated to $VM\sigma_{y,t}$ ('TENS'), which

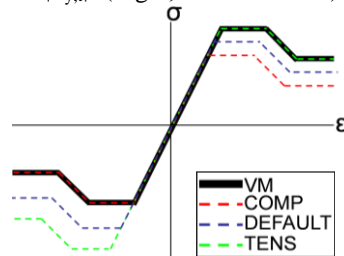


Fig 1. Varying yield stress

enlarged $|\sigma_{y,c}|$ compared to DEFAULT and COMP cases.

Results of the VM and DP FE simulations were compared to the experiments in terms of fracture location and failure force.

Results and discussion

The fracture location was best predicted in the simulations using the DP yield criterion (Fig. 2). The larger the yield asymmetry (i.e. the higher the values of α), the more the fracture location was in line with the experimental results. Varying the initial yield stresses had no effect on the fracture location.

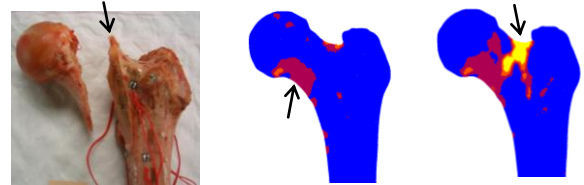


Fig 2. Fracture location in experiment, VM FEM and DP FEM. Arrows indicate the start of the fracture course.

In the DP TENS and DEFAULT cases, the failure force was higher than in the VM-simulation, and more in line with experimental results. An additional increase in yield asymmetry caused a synergetic effect on the failure force (Fig. 3). The DEFAULT case with $\alpha=0.135$ resulted in failure forces and fracture locations corresponding best to the four experimental results.

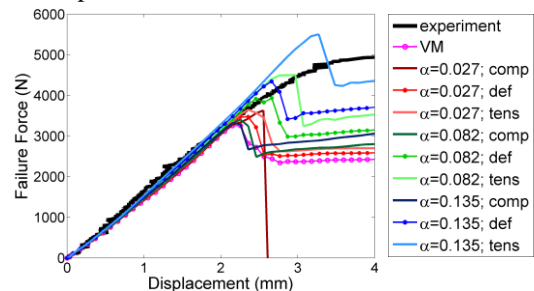


Fig 3. Synergetic effect of varying asymmetry and yield stress

An obvious shortcoming of this study was that it was applied to only two pairs of femora. To generalize the outcomes of this study, a larger number of femora should be assessed.

Conclusion

The results of this study verified the improved simulation of bone failure using the DP criterion relative to the VM criterion. Moreover, the fracture location showed to be sensitive to variations in yield asymmetry; whereas the failure force was very sensitive to variations in the defined initial yield stress.

References

- [1] Keyak et al., Clin Orthop Rel Res 437:219-28, 2005.
- [2] Bessho et al., J Biomech 40:1745-53, 2007.
- [3] Bayraktar et al., J Biomech 37:27-35, 2004.
- [4] Kopperdahl et al., J Biomech 31:601-8, 1998.
- [5] Mullins et al., J Mech Behav Biom Mater 2:460-70, 2009.