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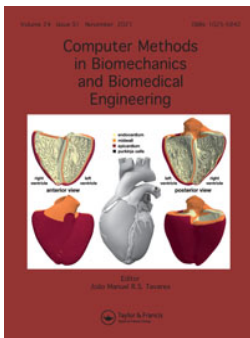
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Effect of density to mechanical properties relationships on simulated vertebral failure load

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1. Introduction

Vertebral fractures are frequent with the decrease of bone density due to age [1]. Finite element models of bone failure have been proposed to estimate failure load of single vertebrae including vertebral endplates e.g. [2, 3, 4, 5], but there is no international standard for these Finite Element (FE) models. Especially, many density to mechanical properties

Table 1. Density to Young's modulus relationships used in the current models ($\rho_{ash} = 0.6 * \rho_{app}$)

Studies	E (MPa)
Kopperdahl et al. (2002) [7]	$3230 \times \rho_{QCT} - 34,7$
Prado et al. (2021) [8]	$10494 \times \rho_{app}^{1,56}$
Morgan et al. (2003) [9]	$4730 \times \rho_{app}^{1,56}$
Keller (1994) [10]	$1890 \times \rho_{ash}^{1,92}$

relationships can be found in the literature and none has been significantly proven to be better than another to predict failure load on the same dataset. The aim of this study is to compare different density to mechanical properties relationships using a tetrahedral model using the same elasto-plastic model found in literature [2, 3, 4].

2. Methods

Seventeen L3 vertebrae without posterior arch (9 females, 8 males, 75.7 ± 11.2 y.o.) were mechanically tested under compression until failure as described in [7]. Image acquisitions before failure were performed using a High-Resolution peripheral Quantitative Computed Tomography (XtremeCT, Scanco Medical AG, Bassersdorf, Switzerland,) with an isotropic voxel size of $82 \mu\text{m}$.

For the modelling purpose, quadratic tetrahedron mesh were created by down sampling scan to $984 \mu\text{m}$ voxel size before segmentation done on 3D slicer (v4.10.2). A hydroxyapatite phantom composed of several known densities was used to calibrate grey levels into bone densities. Average grey levels for each element were assigned using Bonemat (v3.2, Bologna, Italy). Then the same relationships as the ones proposed in [7, 8, 9, 10] (Table 1) were used to attribute Young's modulus to each element leading to 4 different models for each vertebra. Specific yield stress was computed using a constant yield strain of 0.7% and the Young's modulus of each element. Perfect plasticity was given to each element once they reached their yield stress. Each vertebra was compressed

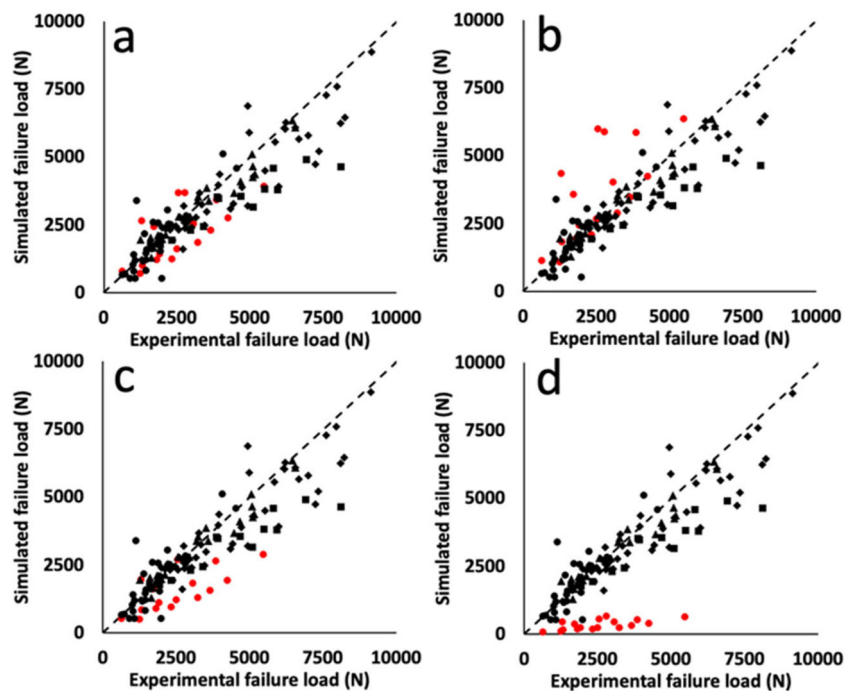


Figure 1. Simulated versus experimental failure load for different laws of the current study (in red) (a) [7]; (b) [8], (c) [9], (d) [10], in comparison to the literature in black (square) [2], (circle) [3], (diamond) [4], (triangle) [5].

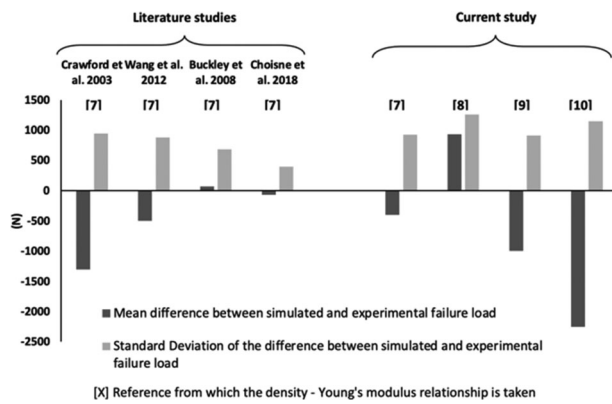


Figure 2. Differences between numerical and experimental failure loads, mean \pm SD, for studies in the literature (left) in comparison to the current study using four conversion's laws (right).

to reach a total strain of 1.9% according to failure criteria in [2, 3, 4]. Non-linear finite element analysis was performed with ANSYS (v19R1; Houston, USA).

3. Results and discussion

Simulated against experimental failure loads are presented in Figure 1. Scatter plots for the current study in red are similar to literature in black for (a, b, c) except for (d).

Figure 2 shows the difference between simulated and experimental failure load (mean \pm SD) for the different relationships. Models using laws of Kopperdahl et al. (2002) and Morgan et al. (2003) show a significantly smaller SD than the ones with Keller (1994) and Prado et al. (2020) (Figure 2). Furthermore, the law of Kopperdahl et al. (2002) displays a lower mean than the one of Morgan et al. (2003). The choice of Kopperdahl et al. (2002) [7] relationship is confirmed by the current study in comparison to studies [2, 3, 4, 5] using relationship from [7] as well.

The model proposed by Choisne et al. (2018) model displays a lower mean and SD of the difference between the simulated and experimental failure load than the current model using relationship from [7] as well. These discrepancies might be due to the following reasons. Poisson's coefficient in [5] is 0.4 while 0.3 was used in the current study; the failure criteria is based on total strain of a linear elastic perfectly plastic model while for [5] it was defined by a volume exceeding its yield strain in a linear elastic model. In addition, the mechanical properties attribution to elements and the number of materials considered for the simulation has not been detailed in literature which could induce uncertainties [11].

4. Conclusions

From this study, we can conclude that the Kopperdahl et al. (2002) relationship should be

considered to convert density to mechanical properties in model assessing failure load of a single vertebra. However, some models using the same relationship display better results and further studies should explore the influence of the operator and the uncertainties of the experimental data.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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