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The influence of the modulus–density relationship and the material mapping method on the simulated mechanical response of the proximal femur in side-ways fall loading configuration

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ABSTRACT

Contributing to slow advance of finite element (FE) simulations for hip fracture risk prediction, into clinical practice, could be a lack of consensus in the biomechanics community on how to map properties to the models. Thus, the aim of the present study was first, to systematically quantify the influence of the modulus–density relationship (E–ρ) and the material mapping method (MMM) on the predicted mechanical response of the proximal femur in a side-ways fall (SWF) loading configuration and second, to perform a model-to-model comparison of the predicted mechanical response within the femoral neck for all the specimens tested in the present study, using three different modelling techniques that have yielded good validation outcome in terms of surface strain prediction and whole bone response according to the literature. We found the outcome to be highly dependent on both the E–ρ relationship and the MMM. In addition, we found that the three modelling techniques that have resulted in good validation outcome in the literature yielded different principal strain prediction both on the surface as well as internally in the femoral neck region of the specimens modelled in the present study. We conclude that there exists a need to carry out a more comprehensive validation study for the SWF loading mode to identify which combination of MMMs and E–ρ relationship leads to the best match for whole bone and local mechanical response. The MMMs tested in the present study have been made publicly available at https://simtk.org/home/mitk-gem.

1. Introduction

Since the pioneering work of Lotz et al. [1,2] was published, quantitative computed tomography (QCT) based finite element (FE) models of the proximal femur have been validated against in-vitro test results in numerous studies (Table 1). They differ in at least three important aspects: First, the loading mode (single leg stance (SLS) or sideways fall (SWF)); second, the modulus-density (E–ρ) relationships used to map calibrated CT based mechanical properties to the FE models; and third, the correction of partial volume artifacts implemented into the material mapping method (MMM), which influences the mechanical properties assigned to the bone surface.

In SLS mode, good correlation and good magnitude agreement between in-vitro experimental test results and predicted mechanical response were reported for local strains by [3–8], and whole bone stiffness or displacement by [7,8], and predicted fracture force by [3]. Yet the moduli resulting from the different E–ρ relationships used by these authors, differ as much as 80% in the cancellous bone range and as high as 40% in the cortical range (Fig. 1). The measures undertaken to correct partial volume artifacts in these studies ranged from no correction [5] to covering the surface of the FE models with a layer of shell elements and assigning cortical bone properties to them [3].

Using the same modelling technique as was presented by Schileo et al. [5], Grassi et al. [9], reported relatively good

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Table 1
A review of previous proximal femur validation studies in the literature where two or more specimens were used to investigate the mechanical response of the proximal femur. The E–ρ relationships are listed in Table 2. SLS, single leg stance; SWF, sideways fall; EXP, experimental results; FE, simulation results; bFEMs, finite element models based on accurate representation of the bone surface; voxel FEMs, finite element models based on a CT voxel to finite element conversion; F, fracture force; K, stiffness; C, compliance; u, displacement; ε, principal strain; σ, principal stress; P, principal strain and displacement data pooled together. (∗) The percentage RMS error was calculated based on the range of the measured values. (&) The percentage RMS error was calculated based on the maximum measured value (+) calculated by pooling data from the 18 specimens. The percentage RMS error was calculated based on the maximum measured value. (#): The prediction errors in the study were reported as −1.96SD, average, +1.96 SD where SD = standard deviation.

Study	Loading mode	Number of specimens	E–ρ relationship	Material mapping method	Model type	Correlation between experimental results and FEA	Correlation	Prediction error
[25]	SLS	18	IV	A	8 node voxel FEMs	$F_{EXP} = 1.66F_{FE} + 0.985$	$R = 0.867$	NA
	SWF	17				$F_{EXP} = 1.24F_{FE}^{1.22}$	$R = 0.949$	
	Pooled	35				$F_{EXP} = 1.29F_{FE}^{1.23}$	$R = 0.967$	
[26]	SLS	5	$E_{cort} = 15{,}000$ MPa	-	8 node voxel FEMs	$\sigma_{EXP} = 0.8431\sigma_{FE} - 0.7404$	$R^2 = 0.8541$	NA
			$E_{canc} = 1100$ MPa		10 node tetrahedral bFEMs	$\sigma_{EXP} = 0.8966\sigma_{FE} - 0.7554$	$R^2 = 0.8351$	
[27]	SLS	25	IX	A	8 node voxel FEMs	$F_{FE} = 0.8534F_{EXP} + 2.1648$	$R^2 = 0.8373$	NA
[23]	SLS	18	IV	A	8 node voxel FEMs	$F_{EXP} = 0.77F_{FE} + 1.15$	$R = 0.962$	13 %(∗)
						$C_{EXP} = 2.30C_{FE} + 0.017$	$R = 0.905$	NA
[3]	SLS	11	IV	E	10 node tetrahedral bFEMs covered with 6 node shell elements	$F_{EXP} = 0.936F_{FE} + 642$	$R = 0.979$	NA
						$\varepsilon_{EXP} = 0.912\varepsilon_{FE} - 16.7$	$R = 0.963$	NA
[4]	SLS	8	X	A	10 node tetrahedral bFEMs	$\varepsilon_{FE} = 1.43\varepsilon_{EXP} + 38.06$	$R^2 = 0.554$	42.3 %(&)
		8	VIII			$\varepsilon_{FE} = 1.89\varepsilon_{EXP} + 40.34$	$R^2 = 0.626$	53.5 %(&)
		8	II			$\varepsilon_{FE} = 1.01\varepsilon_{EXP} + 6.03$	$R^2 = 0.911$	9.8 %(&)
[5]	SLS	8	II	A	10 node tetrahedral bFEMs	$\varepsilon_{FE} = 0.97\varepsilon_{EXP} - 2$	$R^2 = 0.95$	7.2 %(&)
[28]	SLS	39	I	A	8 node hexahedral bFEMs	$F_{EXP} = 1.006F_{FE}$	$R^2 = 0.87$	NA
[29]	SLS	6	IV	B to C	p-formulation tetrahedral bFEMs	$u_{FE} = 0.987u_{EXP} - 89$	$R^2 = 0.871$	NA
						$K_{FE} = 1.367K_{EXP} + 77$	$R^2 = 0.619$	NA
						$\varepsilon_{FE} = 1.036\varepsilon_{EXP} + 30$	$R^2 = 0.951$	NA
[10]	SWF	2×9	II	A	10 node tetrahedral bFEMs	$K_{EXP} = 0.51K_{FE} + 648.75$	$R^2 = 0.87$	20.6 %(+)
						$K_{EXP} = 0.47K_{FE} + 764.49$	$R^2 = 0.87$	
						$F_{EXP} = 1.42F_{FE} - 995.87$	$R^2 = 0.93$	14.1 %(+)
						$F_{EXP} = 1.36F_{FE} - 580.04$	$R^2 = 0.86$	
[7]	SLS	2	IV	B to C	p-formulation tetrahedral bFEMs	$P_{EXP} = 0.961P_{FE} + 24.96$	$R^2 = 0.973$	NA
			III			$P_{EXP} = 1.003P_{FE} + 28.15$	$R^2 = 0.978$	
[30]	SWF	40	I	E	10 node tetrahedral bFEM covered with shell elements	$F_{FE} = 0.929F_{EXP} + 258$	$R = 0.931$	NA
[9]	SWF	3	II	A	10 node tetrahedral bFEMs	$\varepsilon_{FE} = 1.06\varepsilon_{EXP} - 6$	$R^2 = 0.91$	8.3 %(&)
						$u_{FE} = 0.87u_{EXP}$	$R^2 = 0.93$	11.0 %(&)
[31]	SLS	10	IV	A	10 node tetrahedral bFEMs	$F_{FE} = 0.9369F_{EXP}$	$R^2 = 0.9432$	NA
[11]	SLS	2×36	V	A	8 node voxel FEMs	$K_{EXP} = 0.6677K_{FE} + 1938.6$	$R^2 = 0.816$	NA
	SWF					$K_{EXP} = 0.47K_{FE} + 609.89$	$R^2 = 0.7437$	
	SLS					$F_{EXP} = 1.2886F_{FE} + 2472$	$R^2 = 0.8044$	
	SWF					$F_{EXP} = 0.9102F_{FE} + 713.26$	$R^2 = 0.8459$	
								−37.6%, −10.6%, +16.3% (ε)(#)
	SLS		II					−56.1%, −22.9%, +10.4% (u) (#)
								−10.3%, 22.6%, +55.5% (K) (#)
								−46.1%, −9.0%, +28.2% (ε)(#)
[8]	SLS	23	VI	C	10 node tetrahedral bFEMs	NA	NA	−56.4%, −20.9%, +14.6% (u) (#)
								−16.1%, +15.8%, +47.8% (K) (#)
								−55.4%, +7.9%, +71.3% (ε)(#)
	SLS		VII					−58.4%, +1.6%, +61.6% (u) (#)
								−46.7%, -9.6%, +27.4% (K) (#)
[32]	SWF	20	VIII	A	8 node voxel FEMs	$K_{FEA} = 1.07K_{EXP} - 505$	$R^2 = 0.89$	NA
						$F_{FE} = 0.68F_{EXP} + 156$	$R^2 = 0.81$	