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# Simulation based upon medical data offers a fast and robust method for the prediction of fracture risk

Nicholas J. Emerson[a*], Matt J. Carré[a], Gwendolen C. Reilly[b], Amaka C. Offiah[c]

[a]*ACES, Sheffield Hallam University, Sheaf Sreet, Sheffield, S1 1WB, UK*
[b]*Dept. of Engineering Materials, Kroto Research Institute, University of Sheffield, Broad Lane, Sheffield, S3 7HQ, UK*
[c]*Academic Unit of Child Health, Sheffield Children's NHS Foundation Trust, Western Bank, Sheffield, S10 2TH, UK*

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**Abstract**

The accurate estimation of activation forces remains a significant challenge in the field of injury prediction and simulation in sports. Precision in the field of biomechanical simulation has been improved through the use of medical data such as Computed Tomography (CT) and Magnetic Resonance Imaging (MRI). These have the added benefit of providing simulation that is patient-specific. As a developing research technique, the absolute accuracy of biomechanical simulation has been improved in line with the development of both imaging and simulation technology. Cutting-edge simulation methods are now able to describe the minutiae of biomechanical systems with ever-increasing complexity. As the complexity of progressive biomechanical simulation increases, research is being undertaken to determine if more simplistic methods may now be considered for the robust and accurate portrayal of general bone behaviour and fracture prediction. In this paper, the Computed Tomography based Finite Element (CT-FE) simulation process is examined and its application with regards to Sports Engineering is discussed. It is proposed that this method of patient-specific and geometrically-accurate simulation would provide an excellent tool for the investigation of injury mechanisms and equipment design, allowing a wide array of operating conditions to be simulated without the need for physical testing, which can be complex to the extent of unfeasible.


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*Keywords:* Finite element; mechanical model; torsion; compression; simulation; bone; porcine; femur

* Corresponding author. Tel.: +44 114 2252085.
*E-mail address*: n.emerson@shu.ac.uk.


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## 1. Introduction

Accurately assessing the performance of bone and other biological tissues under load poses a significant challenge and has been the subject of many investigations. The majority of structural-based bone assessments ultimately aim to determine fracture risk for a given environment or condition. Structural studies have been completed using a number of techniques, from simplified beam-based mechanical models, assessment of generalised and averaged bone geometry, to complex computational simulation. The development of simulation techniques has allowed high resolution three-dimensional models of biological tissues to be created directly from medical images such as Computed Tomography (CT) and Magnetic Resonance Imaging (MRI). CT is preferable to MRI for bone-based studies as, in addition to the accurate geometrical replication of bone tissues, the greyscale attenuation response of the scan directly correlates with the relative density of the item being scanned. Through appropriate formulation, this figure can be used to compute the material information (specifically Young's Modulus) of the sample. This combination of accurate geometrical representation and accurate material information provides a true 'patient-specific' simulation that can be implemented for fracture assessment on a case by case and highly-automated basis. The development of this type of simulation has been considered for some time, and has been used to assess a number of biomechanical parameters from general bone behaviour to high-resolution micro-architectural studies.

Crucially CT based Finite Element (FE) simulation has thus far focussed (perhaps justifiably) in a clinical context. In this environment, estimations of bone strength have historically been examined using standardised measures of bone 'quality', thereby omitting geometrical information. CT-FE simulation has focussed almost exclusively on the older population and expansion into other disciplines such as Sports Engineering remains limited. Perhaps as a result of this clinical interest, research typically considers validation of the CT-FE process in general, forgoing the opportunity to assess the application of the process for fracture prediction or the assessment of equipment etc.

## 2. General methodology

### *2.1. Simulation*

#### *2.1.1 Geometry production*

The first stage in the general CT-FE methodology is data capture. CT is preferable in structural studies of bone, providing greater clarity in calcified structures and allowing the calculation of material properties. MRI may be more applicable for soft tissue simulation and the two may be overlaid for a single athlete should resources allow.

The geometry is typically selected using a semi-automated technique known as 'thresholding'. This is a process in which regions of interest within the CT data set are selected based upon greyscale attenuation (the relative brightness of the image). These values correlate with the apparent density of the subject and thus, by this method, regions pertaining to hard calcified tissue can be selected separately from softer tissues such as muscle, fat etc. The geometry selection process stage requires validation (literature shows physical measuring of the samples and comparing to the simulated geometry) [1]. However, once this is complete, the geometry production process can be undertaken rapidly.

### 2.1.2 Material Parameters

As mentioned, there is a relationship between the greyscale attenuation of a CT scan and apparent bone mineral density (BMD). This has been shown to be linear and is commonly used by clinicians to determine the density of a bone sample under review, thereby estimating a sample's material quality. In simulation, samples are typically scanned using volumetric CT which captures geometry and density data throughout the volume of the scan. The relationship between greyscale attenuation and apparent density has been under investigation for some time and a number of relationships are proposed. Investigation has shown variation >8% between relationships when plotting at high densities for a single bone sample [2].

Once BMD has been calculated for each pixel in the image, a second relationship relates this value to Young's Modulus. This density-elasticity (E-BMD) relationship has been extensively investigated, culminating in a review paper in 2008 [3], in which relationships from 23 different studies were analysed. The relationship selected for a given study should be considered carefully, particularly when moving away from the commonly-simulated older adult field. Fig. 1 and Table 1 show three relationships from literature, the field in which they were derived and the variation in predicted material properties predicted.

Table 1. Three Elasticity-Density (E-BMD) relationships from literature and the field in which they were each derived.

| Paper / Author | Relationship | Field |
|---|---|---|
| Mechanical Properties of Trabecular Bone from the Proximal Femur: A Quantitative CT Study, Lotz et al [4] | $E = -13.43 + 14.261\rho_{app}$ | Proximal femur, trabecular bone |
| Trabecular bone modulus–density relationships depend on anatomic site, Morgan et al. [5] | $E = 6.850\rho_{app}^{1.49}$ | Various locations, all samples trabecular bone |
| Predicting the compressive mechanical behaviour of bone, Keller et al [6] | $E = 10.5\rho_{ash}^{2.57}$ | Lumbar/femoral samples, in compression |

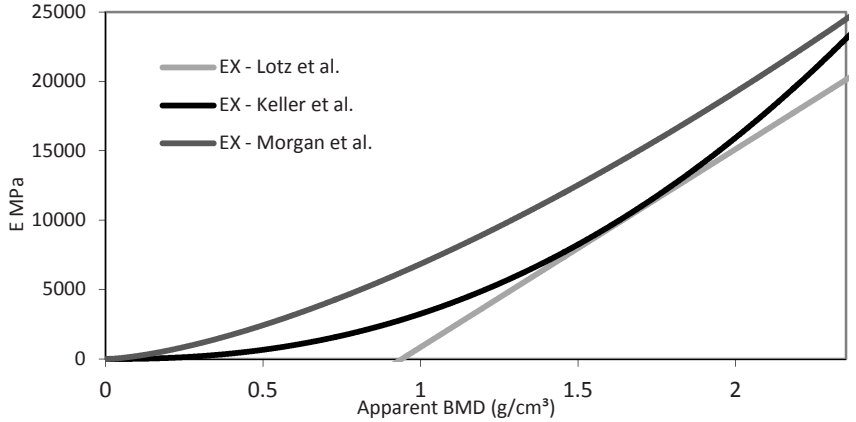


Fig. 1. The behaviour of three Elasticity-Density (E-BMD) relationships from literature as apparent BMD increases.

### 2.1.2 Meshing

As with all simulation, the accuracy of CT-FE is fundamentally a product of the resolution and quality of the mesh of elements. More recent studies typically utilise geometry produced and meshed through automated algorithms. The accuracy of these automated techniques has been investigated, comparing the

results observed with manual meshing procedures. Comparison with physically-derived results demonstrates that both manual and automated meshing is viable, whilst automated tetrahedral and hexahedral meshing, which are the most commonly used CT-FE meshing methods, are shown to provide the most accurate results for simulation.

### *2.2. Physical validation*

Determining the true accuracy of biomechanical simulation is inherently difficult. Validation through physical testing is preferred; however, this often leads to difficulties in fracture prediction for patient-specific studies. The confirmation of a predicted fracture load cannot be undertaken without fracturing the simulated sample. Consequently, confirming predictions in fracture tests is limited to the sample size available, and ultimately unlikely in *in vivo* studies.

Studies typically favour sub-maximal (non-fractured) validation techniques, primarily utilising *ex vivo* bone samples mounted with strain gauges. Taddei et al. were amongst the first to use this technique and proposed the general methodology that is most commonly used for strain data gathering. Principal strain correlation between predicted and observed results has been demonstrated effectively at the bone surface using this type of testing arrangement [7, 8] (Fig. 2).

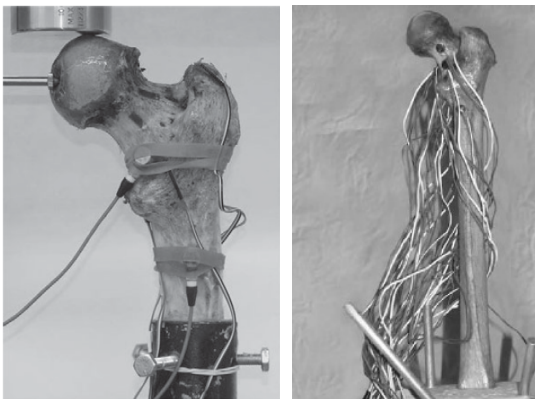

Fig. 2. General testing arrangement in two strain-gauged studies of the proximal femur [7, 8].

Whilst more feasible than *in vivo* validation, the complexity of the human skeleton and the soft tissue interactions at the bone surfaces often reduce *ex vivo* validation to discrete sections of a structure or lead to simplification in the 'as tested' boundary conditions.

To date, validation of human simulation has primarily been undertaken using samples from the older population. This is undoubtedly a function of the availability of bone samples, but poses questions with respect to how well these results can be compared across age groups. Other solutions such as animal substitution have been implemented and demonstrated to be accurate [1, 2]

In addition to strain correlation, strain data from gauged samples can be used to perform stress correlation once the local material condition is known beneath the strain gauge. This material value is typically defined through analysis of the CT data, a process that highlights the requirement for accurate spatial resolution throughout simulation and renders other strain sampling solutions such as Digital Image Correlation (DIC) inaccurate. Stress correlation is typically preferred in validation studies, being dependent upon both material and strain data and thus providing a better estimation of the overall simulation accuracy.

## 3. Results and accuracy

### *3.1. Validation accuracy*

As discussed, stress-based correlation is preferred in most studies. Accuracy is therefore determined on the basis of comparing observed results (those measured in the laboratory using strain gauges) with those predicted (through simulation). This allows for a direct comparison between differing samples and studies, in which the ideal set of results plots to a line passing through 0,0 of equation $x=y$ (Fig. 3).

Table 2. A comparison of simulation accuracy for two recent studies that implemented stress correlation [1, 8].

| | Taddei et al. | Emerson et al. |
|---|---|---|
| Agreement ($R^2$) | 0.91 | 0.95 |
| RMSE (MPa) | 2.6 | 3.4 |
| RMSE (%) | 8.6% | 8.4% |
| Max. error (MPa) | 8.3 | 9.77 |
| Max. error (%) | 27% | 24% |

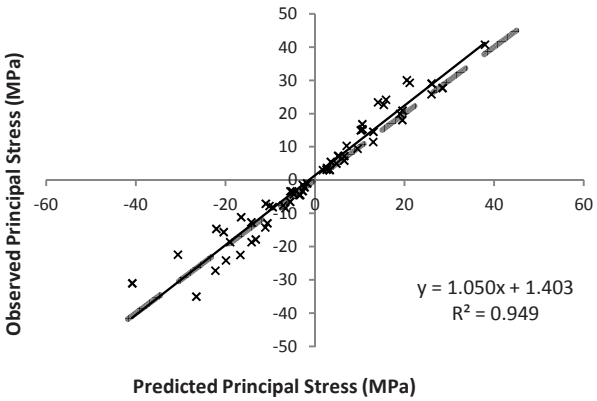


Fig. 3. Results plot demonstrates typical method of stress correlation in CT-FE simulation (torsional loading of porcine samples) [2].

### *3.2. Fracture prediction*

Whilst the general accuracy of the CT-FE process has been demonstrated through sub-maximal validation procedures, there are significantly fewer papers that consider the application of the CT-FE technique through fracture prediction. As with most simulation, the selection of the failure criteria is a key step in these predictions. Both limiting maximum stress [9] and limiting maximum strain [10] have been implemented in literature. Whilst a stress-based criteria has been shown to be applicable, papers comparing the accuracy of prediction techniques typically show an improved accuracy in fracture

prediction when implementing a strain limiting criterion [11]. Mapping linear elastic material models with strain based failure has been demonstrated to be both rapid to implement and accurate.

Table 3. Accuracy output for three studies that implemented using CT-FE for fracture prediction [9, 12, 13].

| | Accuracy Reported by Keyak et al. | Accuracy Reported by Lotz et al. | Accuracy Reported by Emerson et al. |
|---|---|---|---|
| Pearson's (r) | 0.867 | - | 0.806 |
| P Score | P < 0.001 | - | P = 0.003 |
| RMSE (%) | 19.5% | - | 8.4% |
| Max. error (%) | - | 4 and 22 % | 13.9 % |
| Prediction precision | -40% / +60% | | -30.8% /+35.4% |

As with stress correlation, data can be compared on the basis of predicted vs. observed values. Research has demonstrated greater correlation using yield load rather than absolute failure load, which corresponds with the linear nature of most CT-FE simulation and the brittle nature of whole bone samples [12].

## 4. Extending CT-FE simulation into a sporting environment

Although *ex vivo*, bone-only studies have been successfully demonstrated to be valid, there is no common methodology in the assessment of fracture in combination with muscular forces and meaningful soft tissue interaction. This is due, in part, to the complexities of providing appropriate boundary conditions in physical testing, and in part to a lack of availability of tissue samples. Isolated physical tests have shown an improvement in the accuracy of strain correlation when muscular forces are considered (in this case muscular forces were estimated through the inclusion of nylon straps) [14]. Other studies have applied the CT-FE procedure for the simulation of soft tissue (ligament) behaviour, notably within the knee [15] and foot but have omitted meaningful validation, rendering the results somewhat limited. The selection of boundary conditions and simplification in simulation remains the most significant challenge to using widely using CT-FE in a sporting context. One solution may be the implementation of multi-scale modelling. Majumder et al. effectively demonstrated this technique, using highly detailed CT-FE simulation of the pelvic region and simplifying bodily forces away from this area [16]. The focus of the study was falls within the ageing population, however the techniques are applicable in other contexts.

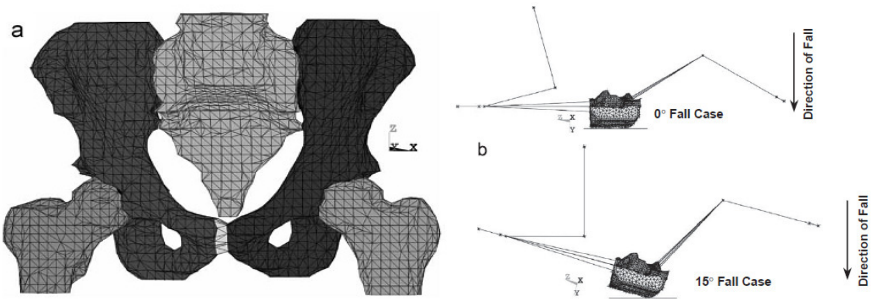


Fig. 4. Multi-scale modeling showing areas of high resolution and general body kinematics [16].

Large-scale projects are currently in progress to create fully-validated musculoskeletal models of the entire human body. This represents a significant challenge, with many considerations and limitations for each constitutive aspect of the overall process. These studies are typically clinically focused, but have highlighted the current limitations in research, namely a lack of data and accuracy in simulating muscular force interaction [17].

## 5. Summary

Developments in CT-FE simulation have shown that highly accurate and robust fracture prediction may now be completed using rapidly-solving linear simulation and simple failure criterion. Soft tissue interaction and validation remain significant challenges, but CT-FE may represent an excellent tool for the investigation of injury mechanisms and equipment design on an athlete-specific basis in the future.

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