NDnano
Center for Nano Science and Technology

NDnano Summer Undergraduate Research
2017 Project Summary

1. Student name & university: Benjamin MacCurtain, Dublin City University

2. ND faculty name & department: Prof Glen Niebur, Prof Ryan Roeder, Aerospace & Mechanical Engineering

3. Project title: Analysis of porosity, mineralization, and damage as contributors to fracture risk.

4. Briefly describe new skills you acquired during your summer research:

Throughout my time in Notre Dame under Prof Niebur and Prof Roeder I developed a number of academic and professional skills. Being exposed to weekly meeting and daily conversations I was introduced to the process of developing a study for inclusion in academic publications. This has shown me the perseverance and intellectual problem solving that is required in order to conduct successful relevant research. On a technical level, my level of proficiency using MATLAB and Linux operating system has greatly increased as a result of being involved in the generation, running and editing of scripts used to post process finite element analysis data. Taking part in the poster session has, of course, improved my ability to convey the meaning and methodology of an idea as succinctly and clearly as possible.

5. Briefly share a practical application/end use of your research:

This research has the potential to increase the efficiency of pharmacological treatment development for metabolic bone diseases that may alter one's susceptibility to cortical bone fracture. As a result of this study, the relative effect of bone fatigue microdamage, porosity and mineralization can be observed as factors of cortical bone fracture susceptibility and as such treatment development can be adapted based on the effect each constituent of bone has. As well as this, since a micro-CT scan is used as the fundamental basis of analysis in this study, another possible application could be the development of a model that can predict if an individual is susceptible to cortical bone fracture based upon the levels of fatigue microdamage, porosity or mineralization levels observed in a CT scan of their bone.

6. 50- to 75-word abstract of your project:

This study utilized a combination of experimental and computational methods to develop a non-linear finite element model capable of predicting human cortical bone fractures based on the levels of fatigue microdamage, porosity and mineralization. Based on preliminary tests the non-linear model can predict a fracture during simulation based upon the above-mentioned bone characteristics with better than random probability. Additional steps are being taken to ensure the non-linear finite element model and the experimental model are demonstrating bone fracture initiation points in the same region.

7. References for papers, posters, or presentations of your research:

Baumann, A. The Relative Influence of Material and Architectural Properties on the Mechanical Behaviour of Bone Tissue. 2015 July; Dissertation submitted to the University of Notre Dame Graduate School

Turnbull TL, Baumann AP, Roeder RK. Fatigue microcracks that initiate fracture are located near elevated intracortical porosity but not elevated mineralization. Journal of biomechanics. 2014 Sep 22;47(12):3135-42.

One-page project summary that describes problem, project goal and your activities / results:

Age related and metabolic bone diseases can lead to altered mineralisation levels and por**e** structure of the bone. These factors have been reported to alter the mechanical properties of the bone itself [1-3]. These changes in mechanical properties can lead to a change in bone fracture susceptibility when subjected to cyclic loading in-vivo [4, 5]. As a result of the ongoing effects of osteoporosis and other metabolic bone diseases this project was undertaken in order to develop a non-linear finite element model capable of predicting human cortical bone fracture initiation point as a function of fatigue microdamage, cortical porosity and levels of mineralisation. This objective would be met with the completion of the following aims:

> To examine the effect of bone porosity and mineralisation on fracture initiation in cortical bone following fatigue loading.

> To correlate the finite element model fracture initiation site to an experimental model using 2-point correlation.

> To validate the accuracy of the finite element model by comparing the predicted fracture to experimental data.

Cortical bone specimens were harvested from a human femur and imaged using micro-computed tomography (μ-CT). Specimens were imaged before and after failure. The μ-CT images were then converted to a finite element mesh to ensure the computational model was a structural replica of the physical bone specimen analyzed. Linear finite element analysis (FEA) was used to determine the region with the largest von Mises stress magnitude in each sample. This region containing the largest amount high stress elements was then selected as the region of analysis for the non-linear analysis. A sub-volume was required as the computational cost of analyzing the entire bone sample was too great.

Non-linear FEA incorporating a Drucker-Prager yield criterion, linear hardening and element deletion was used to model failure under tension in each selected sub-volume for each specimen. The $1mm^2$ bone sub-volume was meshed using 20 μm hexahedral elements using custom scripts. Simulated uniaxial tension of these specimens was modelled to 1% strain using implicit quasi-static analysis. The FEA was completed using ABACUS by running custom Unix scripts in parallel with one another.

Spatial 2-point correlation functions were used to evaluate the correlation between fracture initiation and cortical features. The 2 features of interest in this case were (Damage Volumes) DV's and deleted elements in the model (simulated fracture). These correlation functions were calculated as displayed in Figure 1.

$$g(r)_{A-B} = \frac{\langle V_B(r) \rangle_A}{V_B}$$

Figure 1 2-Point Correlation Function

Where B is the feature of interest, $V_B(r)$ is the volume fraction of B within a spherical shell at radius, r, from the origin A and V_B is the total volume fraction. Considering Figure 2 an example of how the 2 Point Correlation Functions were calculated can be observed. Table 1 details the mathematical example of how the 2-point correlation functions for Figure 2 are calculated.

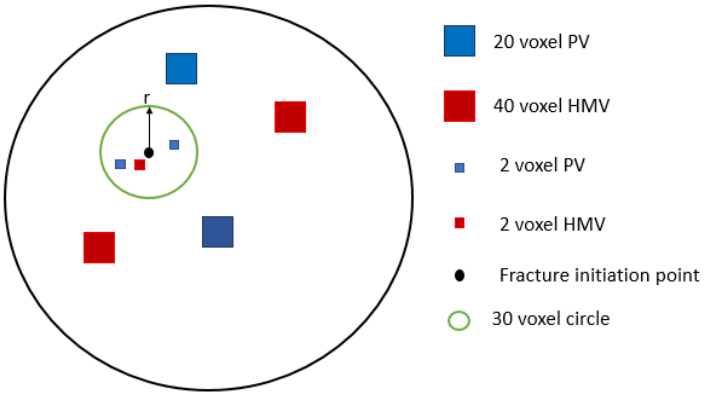

Figure 2 2-Point Correlation Example

Table 1 Correlation Calculation Example

	Location				PDF
	At r	***Perimeter***			
Voxels	30	400			
	Volume Fraction				
PV (Pore Volume)	4 / 30	44 / 400			
HMV (Hi. Min. Vol.)	2 / 30	82 / 400			
	PDF				
PV	(4 / 30)	/	(44 / 400)	=	1.21
HMV	(2 / 30)	/	(82 / 400)	=	0.33

2-point correlation functions were generated for 11 bone sub-volume specimens as displayed in Figure 3. These specimens were modelled using non-linear FEA and then quantitatively assessed in relation to fracture prediction using the 2-point correlation functions.

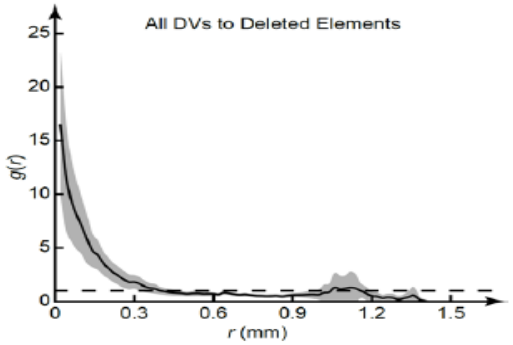

Figure 3 2-Point Correlation Function (G(r)), displaying the relative probability at radial distances from the DVs, of coming across deleted elements. Since the bone sub-volumes did not contain the fracture DV, all DVs were used to generate the spatial correlation function. The dark defined curve displays the mean correlation value while the shading displays the 95% confidence interval for the analyzed specimens. The dashed line represents random probability; or g(r) = 1.

Images were also created using custom MATLAB scripts in order to generate images that can be used to qualitatively assess the accuracy of the non-linear model. Figure 4 displays a sub-volume of the bone with the failed elements shown along the simulated path of crack propagation.

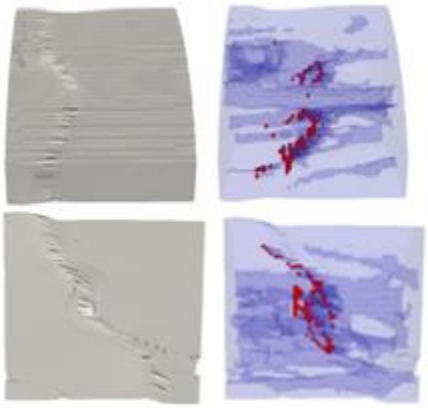

Figure 4 Finite element model output displaying the failed elements within a yielding sample.

As can be seen above in Figure 3 there is a greater than random probability of the non-linear FE model of accurately predicting a cortical bone fracture. It is also observed that the fracture initiation points were more likely to be in spatial proximity to a DV, hence prompting the conclusion that cortical bone fractures may be caused by inherent microcracks caused by fatigue damage. Examining the qualitative data generated in Figure 4, again it can be observed that the non-linear model generates results compliant with the experimental bone samples tested.

References

[1] Metzger TA, Vaughan TJ, McNamara LM, Niebur GL. Altered architecture and cell populations affect bone marrow mechanobiology in the osteoporotic human femur. Biomechanics and modeling in mechanobiology. 2017 Jun 1;16(3):841-50.
[2] Mashiatulla M, Ross RD, Sumner DR. Validation of cortical bone mineral density distribution using micro-computed tomography. Bone. 2017 Jun 30;99:53-61.
[3] Zioupos P, Wang XT, Currey JD. The accumulation of fatigue microdamage in human cortical bone of two different ages in vitro. Clinical Biomechanics. 1996 Oct 31;11(7):365-75.
[4] Timlin JA, Carden A, Morris MD, Rajachar RM, Kohn DH. Raman spectroscopic imaging markers for fatigue-related microdamage in bovine bone. Analytical Chemistry. 2000 May 15;72(10):2229-36.
[5] Wu B, Zhang C, Chen B, Zhang L, Dai R, Wu X, Jiang Y, Liao E. Self-repair of rat cortical bone microdamage after fatigue loading in vivo. International journal of endocrinology. 2013 Apr 10;2013.