An Investigation of the Fluid Structure Interaction in Articular Cartilage across Disparate Scales

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Clinical Background

- **Articular cartilage (AC)** is found at opposing surfaces in mammalian joints. It provides a **smooth bearing surface**, promoting **low friction articulation,** facilitating continuous operation under relative motion.
- A lack of cells within AC renders a **low capacity for intrinsic healing** or repair, leaving it prone to **degeneration**.
- High clinical demand for cartilage repair, with **8.75 million people** aged 45 and over having sought treatment for osteoarthritis (a disease developed when cartilage breaks down) in the UK [1]. Which is predicted to **cost the NHS around £118.6 billion** in the next decade [2].
- Despite this, a lack of understanding of the tissue renders **successful repair techniques elusive**.

Modelling Articular Cartilage

- AC has a **biphasic structure**, with a deformable **matrix of collagen**, immersed in an **interstitial fluid**. The complex tissue composition spans **a range of length scales** (Fig.1).
- The micro-structure of the tissue contains a **collagenous network of cells** with variable **permeability** across a **stratified composition**.

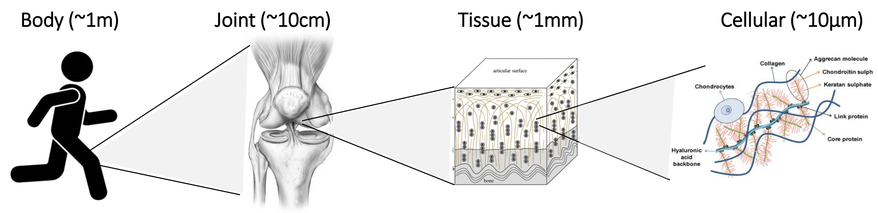


Fig.1: Multi-scale structure of AC (adapted from [3]).

- Current **single-scale** constitutive models do not capture the physical interactions at both the fibre and material scale.
- This project aims to create a **coupling** between the micro- and macro-scales to map the pore-scale effects onto the material-scale response.

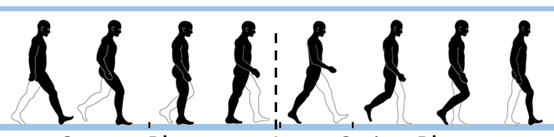
Scientific Aims and Objectives

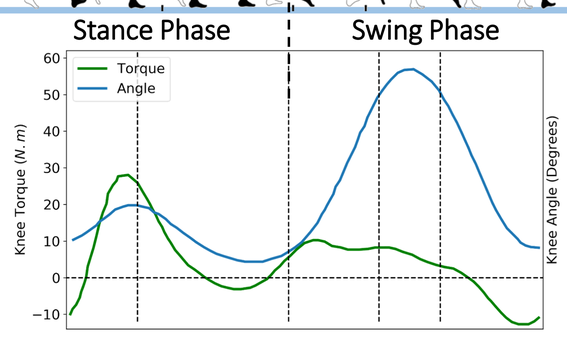
Project Aim

Couple **an immersed fibre network** (micro-scale) model with a **poroelastic continuum mechanical** (macro-scale) model to create a novel multi-scale model of articular cartilage and its mechanical response.

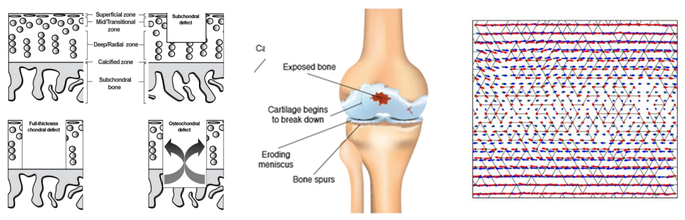
Objectives:

- Refine computational set up to create an **efficient, accurate multi-scale solver**.
- Complexify the model to incorporate **a stratified composition** and **damage modelling** to improve clinical understanding of **damaged tissue**.
- **Validate** model against **controlled experiments** using bovine and human (subject to ethics) cartilage.



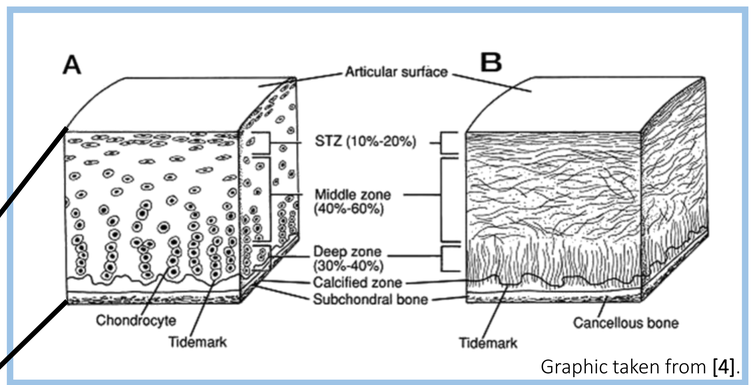


Gait Cycle Analysis



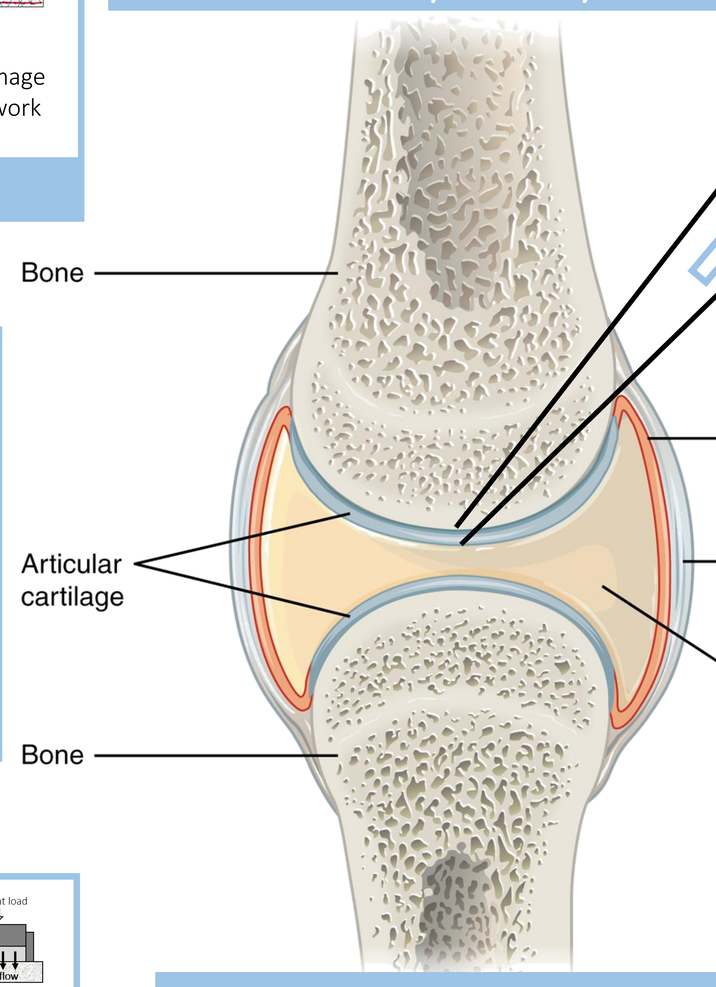
Degeneration of lesions → Osteoarthritis of the knee joint → Introduce damage in spring network

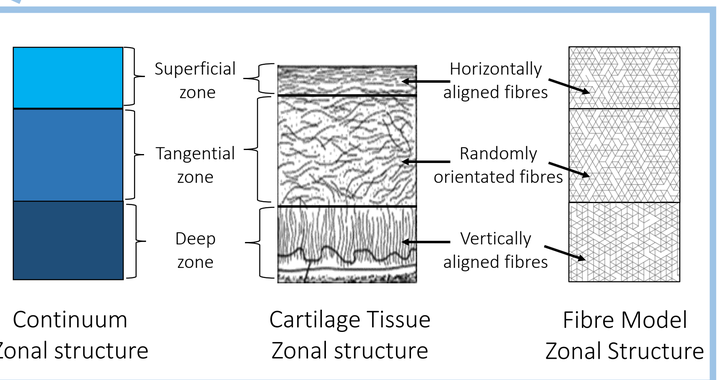
Damage Modelling



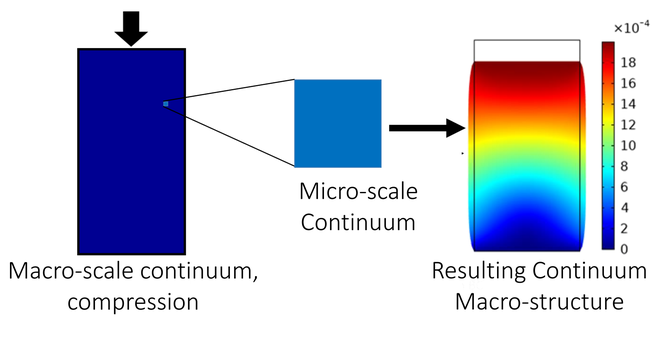
Graphic taken from [4].

Articular Cartilage Tissue Structure





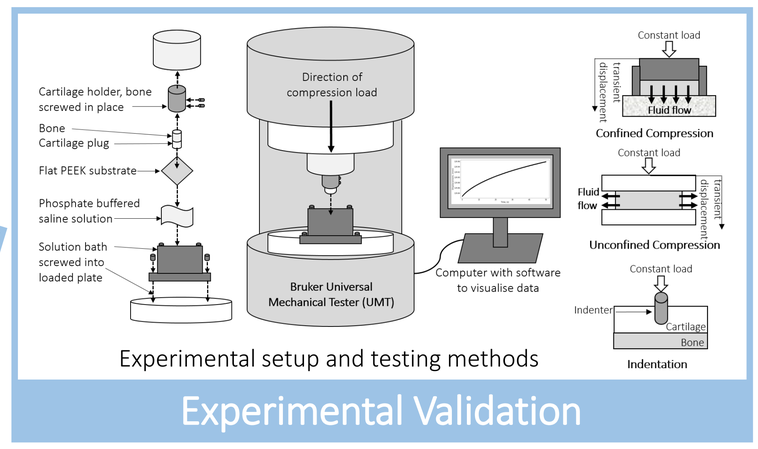
Zonal Structuring



Continuum-continuum Model

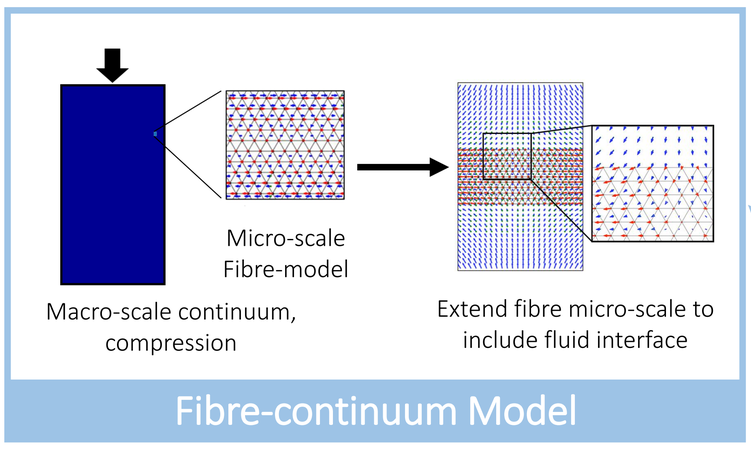
Research Gap

Complete **multi-phase, multi-scale** representation of Articular Cartilage.



Experimental setup and testing methods

Experimental Validation



Fibre-continuum Model

Representative Computational Results

- Multi-scale model uses **COMSOL-MATLAB Live Link**. Micro- and Macro-scales coupled using **Heterogeneous Multi-scale Methods.**
- Currently, the continuum-continuum macro-scale model undergoes a **1D, unconfined compression** in the negative y-direction (Fig2a).

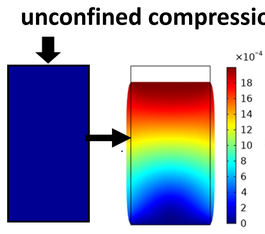


Fig.2a: 2D compression

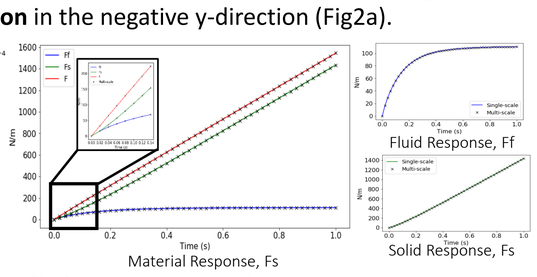
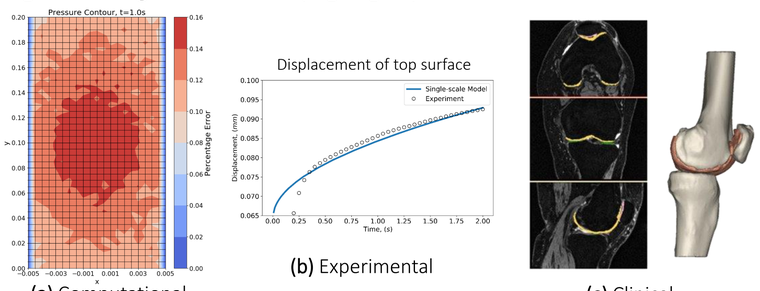


Fig.2b: Resulting solid, fluid and material response

- Next, include **fibrous network micro-scale model** using extensional shear.
- Replace continuum solid with a bond-diluted triangular **spring network**.
- **Challenges: fibre model is** inherently **oscillatory,** calculating non-constant parameters, e.g. the **Biot Willis coefficient**.

Model Validation

- Current **multi-scale continuum-continuum model** has been validated against a **single scale model** (e.g. Fig 3a).



(a) Computational **(b)** Experimental **(c)** Clinical

Fig.3 Types of validation for the multi-scale model.

- **Experimental compression** and **indentation** testing of cartilage samples will be used to validate the model (Fig 3b).
- **Atomic Force Microscopy** to understand the fibre-structure of the tissue for validation and improvement of the fibre-model
- **Clinical Collaboration** will be used to optimize a biological model (Fig 3c).

Model Refinement and Optimization

- **Increasing model complexity** will require computational **optimization**.
- **Meta-modelling,** for example GPTIPS is being explored to speed up multi-scale model simulations.
- **Machine Learning** implemented to select the most pertinent data points.
- **Model efficiency** will be improved with efficient data storage.

References

[1] Christopher J.L. Murray et al. "UK health performance: Findings of the Global Burden of Disease Study 2010". DOI 10.1016/S0140-6736(13)60355-4.
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[3] Wang, X., Neu, C.P. and Pierce, D.M., 2019. Advances toward multiscale computational models of cartilage mechanics and mechanobiology. *Current Opinion in Biomedical Engineering*, *11*, pp.51-57.
[4] Fox, A.S. and Bedi, A., 2009. ja SA Rodeo. *The basic science of articular cartilage: Structure, composition, and function Sports Health*, *1*, pp.461-468.