A Parametric Model of the Human Knee for reduced simulation timeframes

Laurence Marks

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About me..

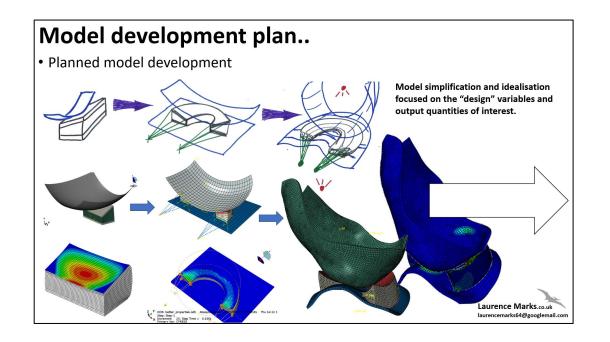
- FEA and CFD since 1987
- Several published papers on patient specific finite element modelling of tibial fractures and the healing process
- Founded Abaqus reseller SSA, sold to Technia in 2018
- Currently Visiting Research Fellow at Oxford Brookes working with Olga Barrera on models of the knee meniscus
- Work with a research group at Oxford University looking at knee joint replacement
- Consultancy projects in a range of fields
- Developing training material
- Sometimes write for Develop3D
- Hillclimb a Formula Ford

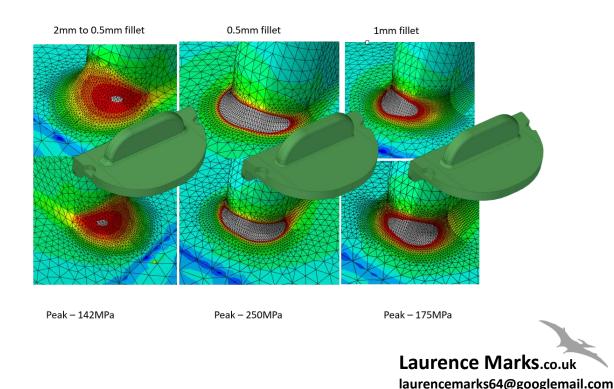


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Some work in progress and a completed project..

- The meniscus work is at a very early stage
- The shape optimisation work is a complete package
- But they do have some common theme's





A parametric model of the human knee optimized for contact mechanics

• Olga Barrera





Image-Based Parametric Finite Element Modelling workflow for studying soft tissues contact mechanics in the human knee.

> Beadioff R.^{a,b}, Seil R.^a, Monton C.^a, Marka L.⁴, Barrera O.⁴*p.s*</sub> ^aDepartment of Mechanical Engineering, Drinering of Both, Bath, 108 ^bSteheol of Dapasering, Deserving of Lowerpois, Lowenpoi, UK ^cLaurenburg: Institute of Studie, Laurenburg of Engineering Companying and Mathematics, Offend Booket, Dimering, Oxford, UR ^bDistances and Companying and Mathematics, Oxford Booket, Dimering, Oxford, UR ^bDistances and Deserving and Mathematics, Oxford Booket, Dimering, Oxford, UR ^bDistances and Deserving and Mathematics, Distances and Deserving, Defended Deserving, Deserving, Defended Deserving, Deserving, Defended Deserving, Deservi

betract

Introduction: We present a human-of lar gravening paired equify the finite denset models parameteriz and applicable for context remediates from CP states methods: the superstanding the usually randpartransform medical images into 3D models. We observe that there are two morphological parameters the plage of these parameters in load sharing between moritories entrings as well as manined posterior-anter record applies and methods without and the state of t

Methods: We measure the maximum field ordingst thickness (11 mm, 2 mm), this spin height (12 \text{ mm}, 2 \text{ mm}), this spin height (12 \text{ mm}, 2 \text{ mm}), this spin height (12 \text{ mm}, 2 \text{ mm}), this spin height (12 \text{ mm}) and (12 \text{ mm}) that the spin height (12 \text{ mm}) and (12 \text{ mm}) that the spin height (12 \text{ mm}) and (12 \text{ mm}) that the spin height (12 \text{ mm}) and (12 \text{ mm}) that the spin height (12 \text{ mm}) and (12 \text{ mm}) that the spin height (12 \text{ mm}) and (12 \text{ mm}) that the spin height (12 \text{ mm}) and (12 \text{ mm}) an

Beaultic We quantify how the title spins height affects the distribution of the height discrete method (second second sec

Discussion: Our capitalised models based on parisent data can predict the dynamics of the future rotates there and chaptenessing iteration distributions on howe assumes based models. This work is an pool of encours there are also approximately and the second stress of the second stress. This work is an pool of encours of the second stress stress are also approximately and the second stress of the second stress of the second stress and there models are preformed using an implicit solver with available stress stress stress and the second stress and and the second stress stress are also approximately the second and the second stress stress stress and the second stress stress and the second stress stress and stress st

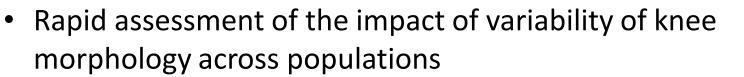
Keyaosele: finite element model, human tibiofemoral joint, noniscus, contact mochanics, paramotric morphology.



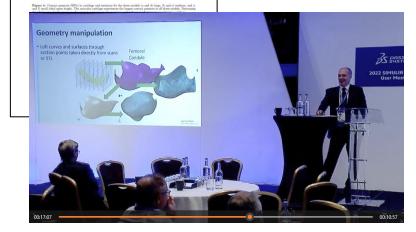


on software (1 a and by size bothing) indication, including the angles single values on the wave subjects to get the generation of the convention bothing. For this candid angle the bickness wave extracted by observation at the most encouve areas of the latered thial phases from a phase. The estimated parameters are recorded in table 1. accienced 2D generative g dilatered subgestment of dome points.

2.2. Parameteroid 20 generative of interial comparison of their justs Models generated parameterically from patient data, a table than using the more traditional segmented 20 image approach, offer improved model solution times, especially with respect to model convergence, and enhanced solution quality across the contact areas. These models ready lend themselves to automation, 3



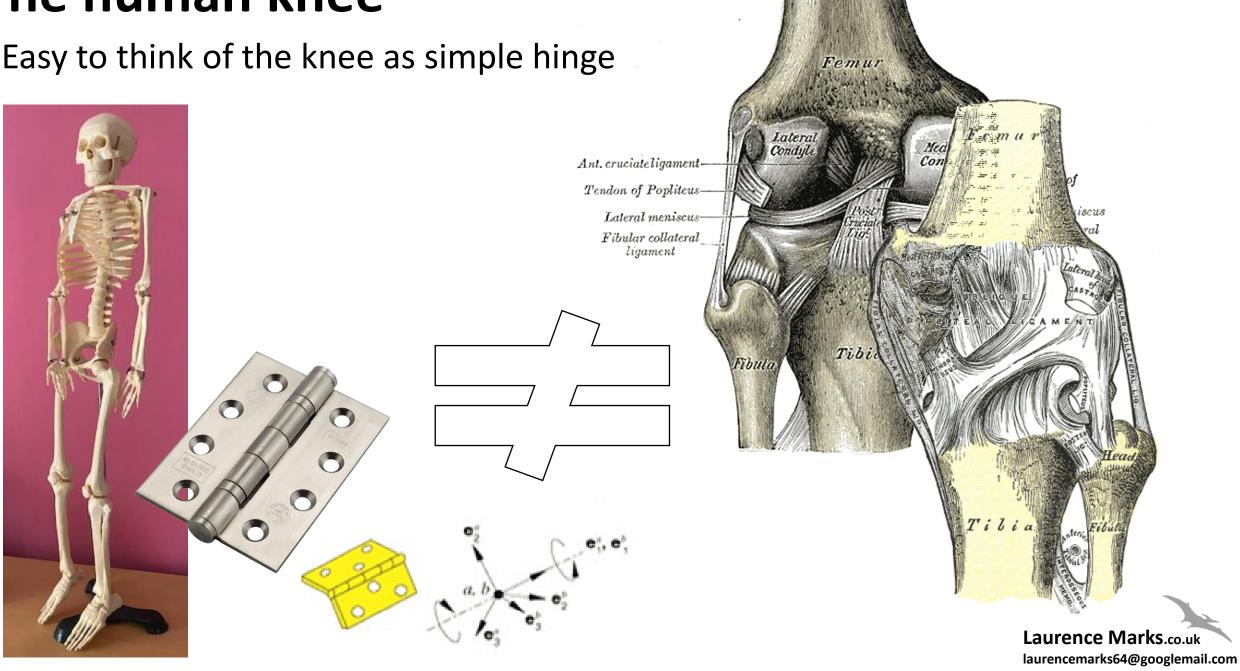
- Rapid assessment of the impact of different clinical interventions
- A development framework for material model development





The human knee

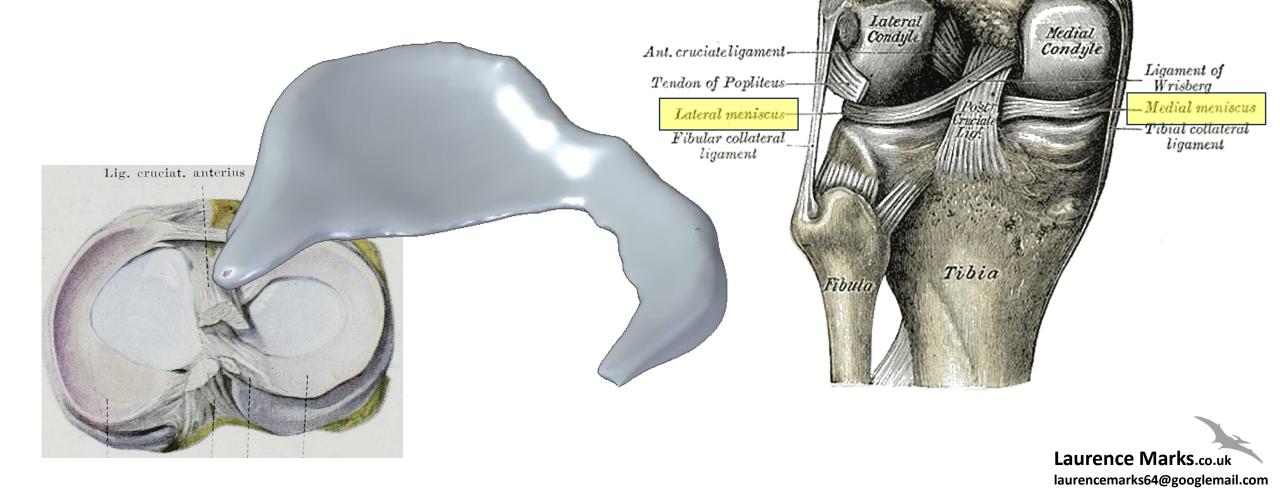
• Easy to think of the knee as simple hinge



The meniscus

Function [edit]

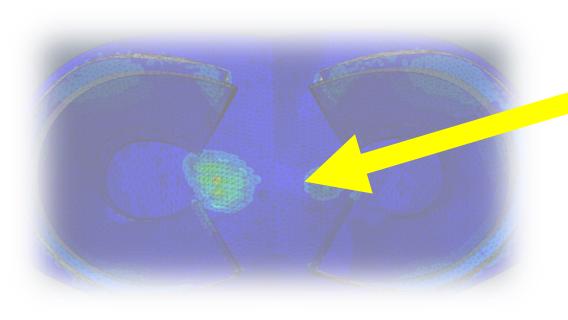
The menisci act to disperse the weight of the body and reduce friction during movement. Since the condyles of the femur and tibia meet at one point (which changes during flexion and extension), the menisci spread the load of the body's weight.^[6]

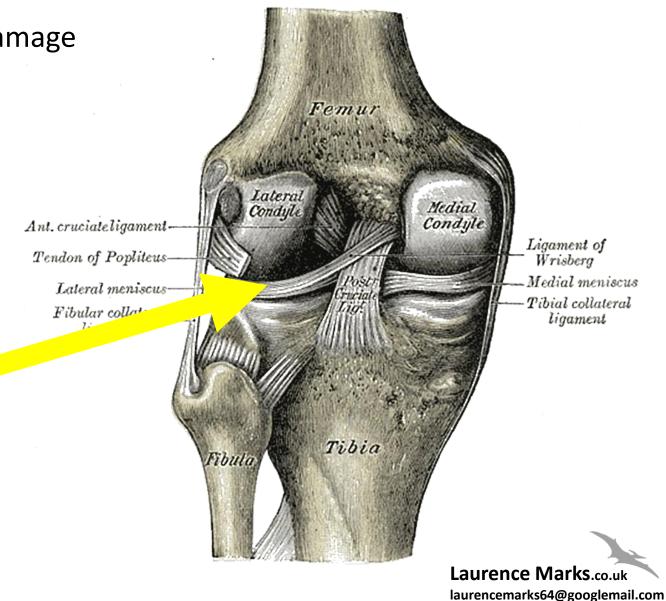


Femur

The meniscus – finite element modelling challenges

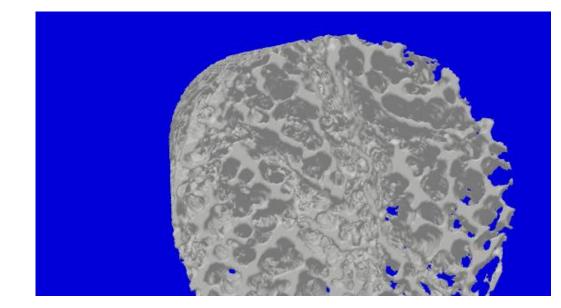
- Pressure distributions are important.
 - High local pressures result in cartilage damage

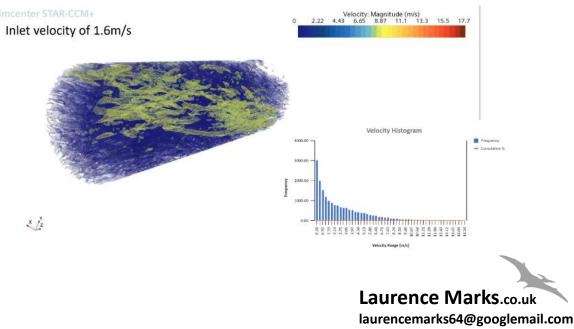




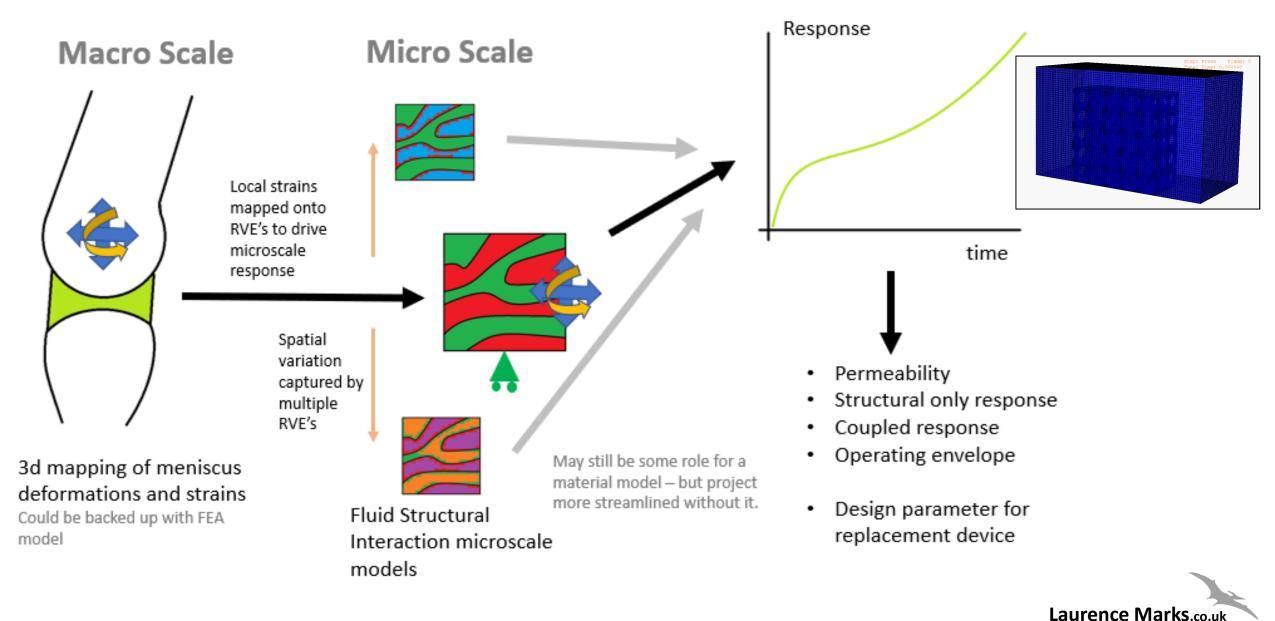
The meniscus – a materials challenge

- Not a simple structure
 - Was thought to be a continuous solid structure, it isn't
 - Was thought to contain just fibres it's a mixture of fibres and channels
- So what we have is a three layer structure (with thin outer layers)
- And the solid bits are really saturated cellular solids.
 - Meniscus is a highly complex porous "cushion" made of macro/micro/nano channels of collagen
 - Fluid flows inside the channels rules the time-dep behavior
 - CFD used to model the flow regime, and to help calibrate a time dependent model





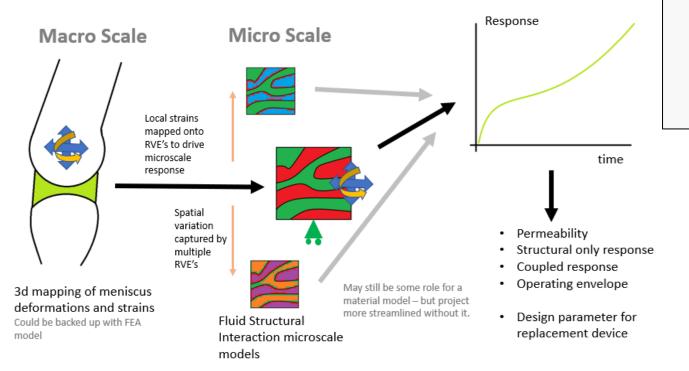
The meniscus – a multiscale challenge

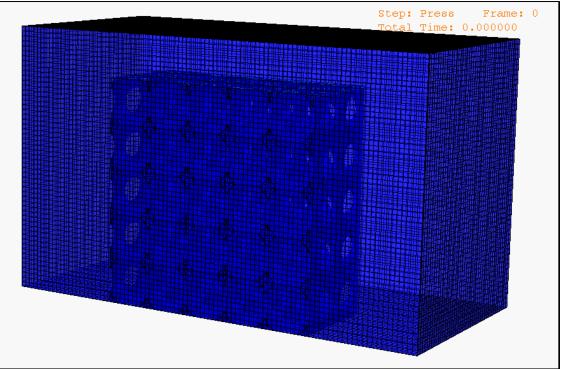


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The meniscus – a multiphysics challenge

- FSI Fluid Structural Interaction
- RVE Representative Volume Element
- Definitely a work in progress..





Coupled Eulerian Lagrangian model in Abaqus Explicit – other codes were tried with similar levels of success..

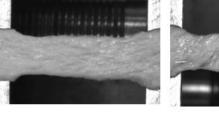


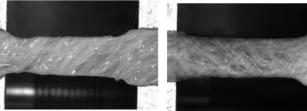
Meniscus – material approaches

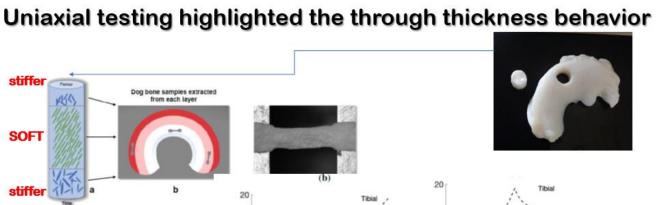
 An FSI RVE doesn't offer a sensible workflow.. So more conventional material characterisation

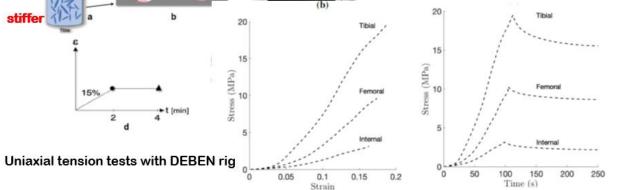
Quantification of macroscale architectural parameters











Each sample is different

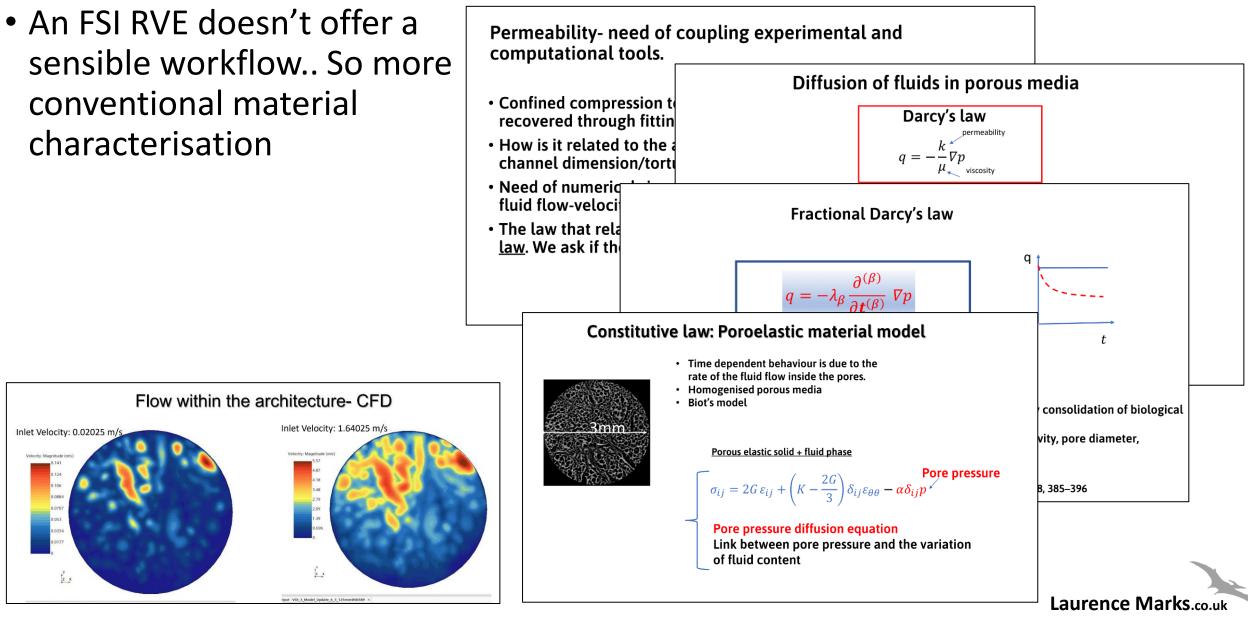
Architectural Parameters analyzed

- <u>Fibers orientation</u>: with FFT/Laplacian of Gaussian edge detection carried out
- Volume fraction of fibers
- <u>Fiber dispersion (standard</u> deviation of fibers from preferential orientation).

ENCE OF ARCHITECTURAL PARAMETERS ON MATERIAL PROPERTIES?



Meniscus – material approaches



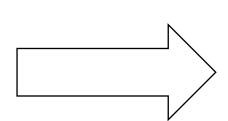
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Contradictions towards a workflow..

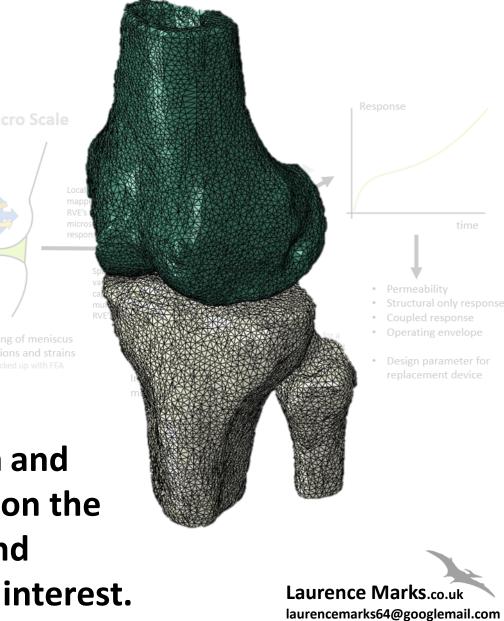
- So we would like..
 - Fast, accurate prediction of contact pressures
 - Rapid assessment of the impact of different clinical interventions
 - Rapid assessment of the impact of variability of knee morphology across populations
 - A framework for material model development

• But

- We have a geometrically complex multi-scale multi-physics problem
 - Models are often scanned from images, and solved using explicit solvers

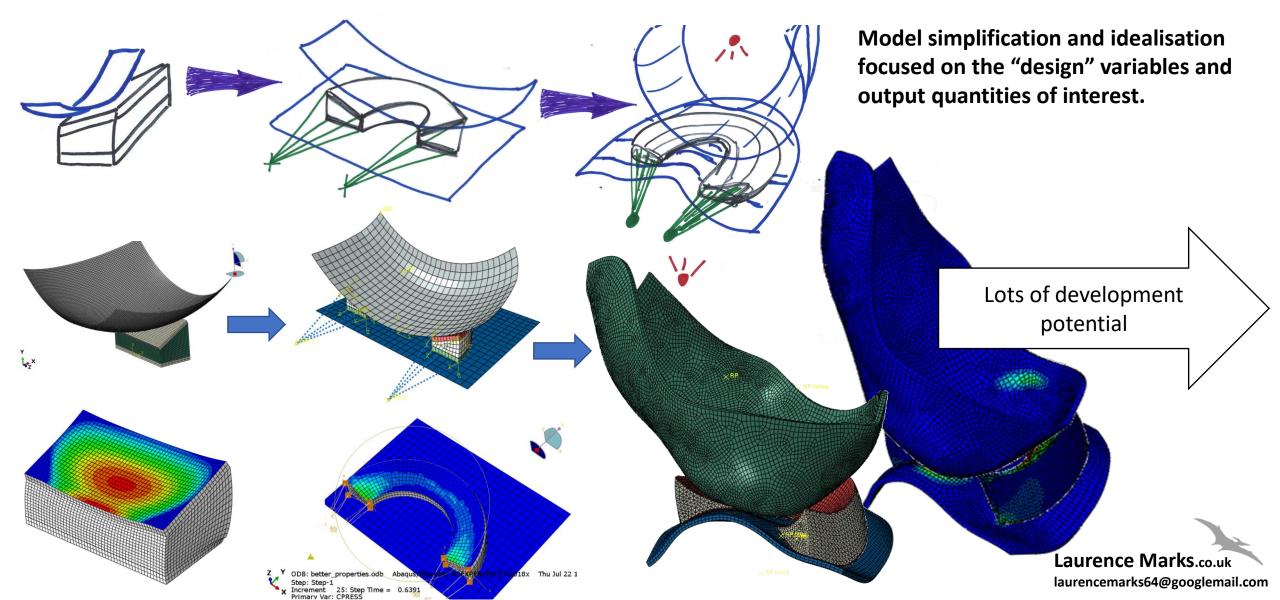


Model simplification and idealisation focused on the "design" variables and output quantities of interest.



Model development plan..

• Planned model development

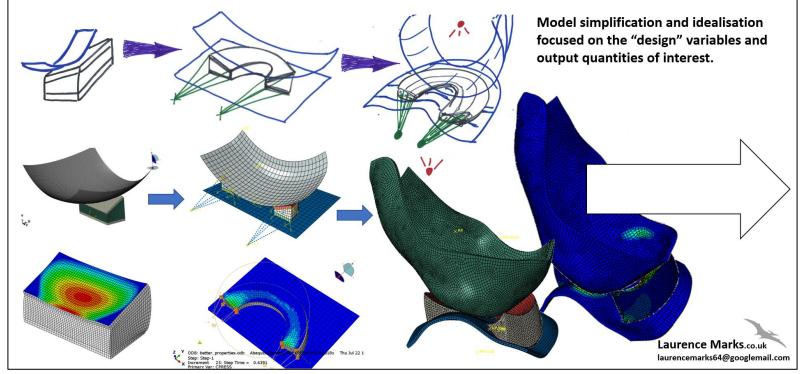


Something interesting happened on the way..

 At the second phase of model development something became obvious about the action of the meniscus.

Model development plan..

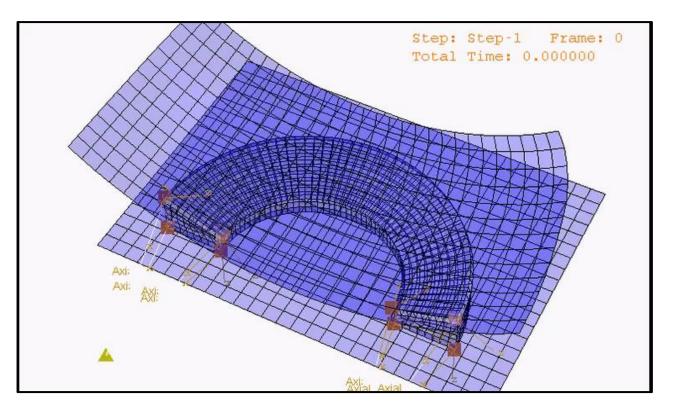
• Planned model development





Something interesting happened on the way..

 The model captured the self centring action and circumferential load reaction into the ligaments that is missing from many complex knee models.



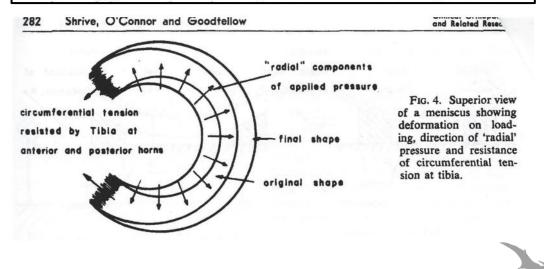
Load-Bearing in the Knee Joint

N. G. Shrive, M.A., D.Phil.,* J. J. O'Connor, B.E., Ph.D.** and J. W. Goodfellow, M.B., B.S., F.R.C.S.†

The surfaces of most animal joints appear to be almost congruous, but not quite, for even the close-fitting hip joint has been shown to have slightly incongruous surfaces.¹ A major exception is the tibiofemoral joint in which the bony surfaces appear to be grossly incongruous.

In joints with almost congruous surfaces, the contact areas are large and increase significantly with load: the contact pressures are low and relatively independent of load.⁵ On the other hand, in the knee the contact areas cectomy, were explicable as the direct result of the loss of the weight-bearing function of the meniscus.

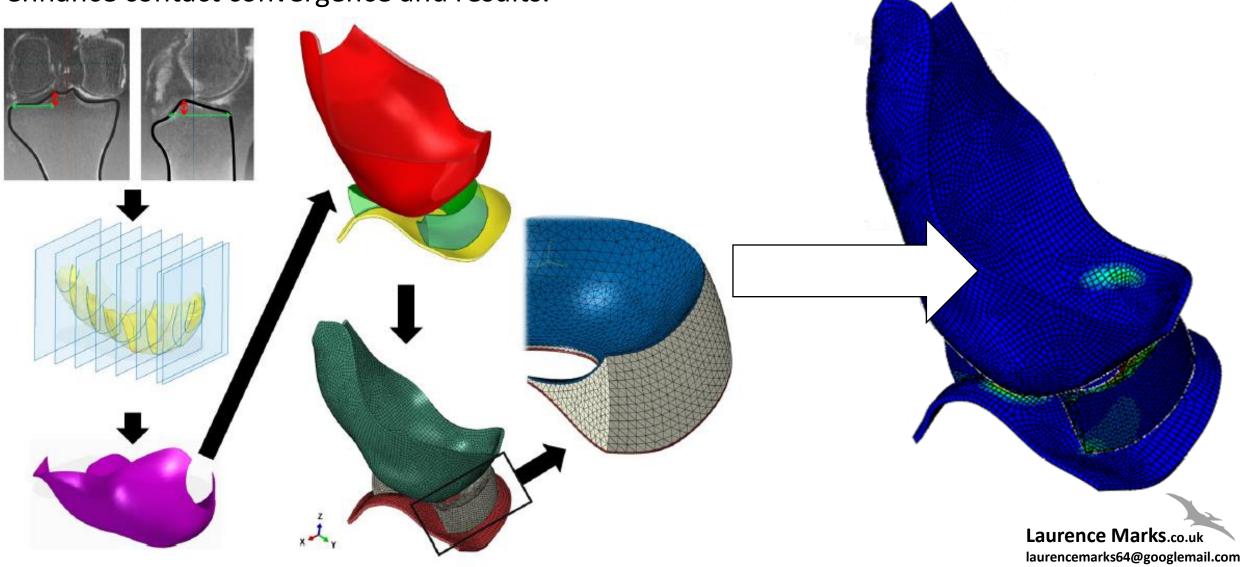
More recently, Shrive,^{10, 11} Seedhom *et al.*,⁹ Walker and Erkmann¹² and Krause *et al.*⁷ have all shown that the menisci do bear load. In this paper we will discuss (A), the mechanism by which the menisci bear load in all joint positions: (B), the load bearing role in terms of overall load transmission and (C), the consequences of meniscectomy.



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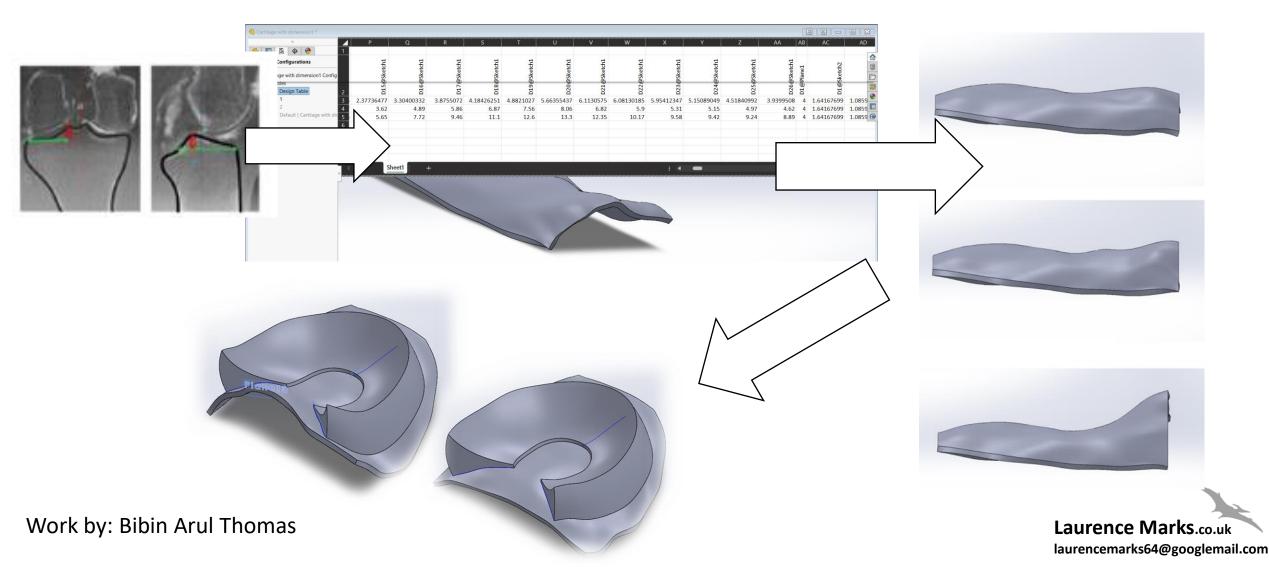
Modelling Workflow

• We use parametised surface definitions, from which rapidly meshable solid geometries are generated. The approach is optimised to create meshes which enhance contact convergence and results.



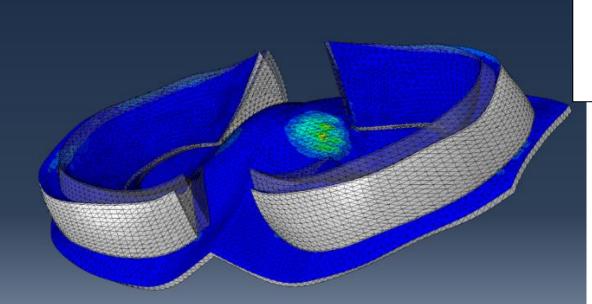
Modelling Workflow

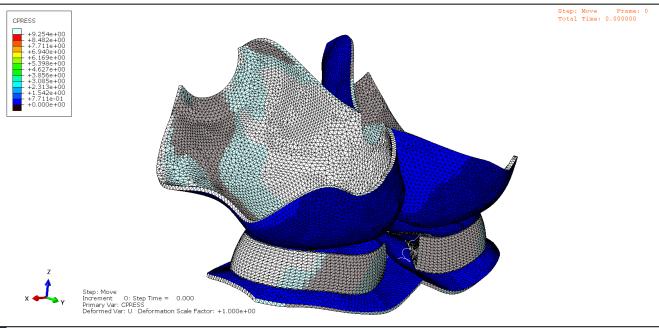
• We use parametised surface definitions, from which rapidly meshable solid geometries are generated. The approach is optimised to create meshes which enhance contact convergence and results.



Adding the other condyle

- Add another condyle. And the solution is still rapid and converges sensibly.
- And it's still an implicit solution.



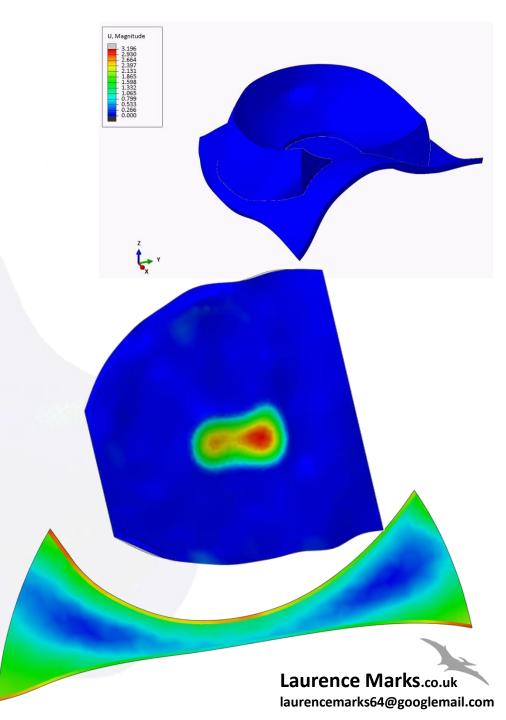




Work by: Arjun Nair

What we've achieved

- Parametrically variable models
 - We've started automating model creation
- Rapid solutions
 - 10 minutes vs 48hrs
- A series of models for material model development
 - We've used simpler models for material model development knowing where the model sits in terms of accuracy, relevance etc.
- A useful representation of contact stresses and variation of stresses through the 3 layer structure.
- In future we'll be extending the scope of the model to allow for more realistic loading cycles
- And we are aiming for a GUI to aid model generation so it could become a decision support tool for surgery.



A product optimisation example.

- This is work I've carried out with a group at Oxford University..
- Design improvement of the tibial section using finite element non-parametric shape optimisation.

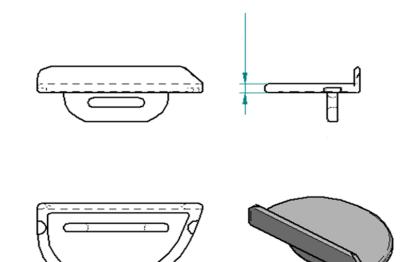


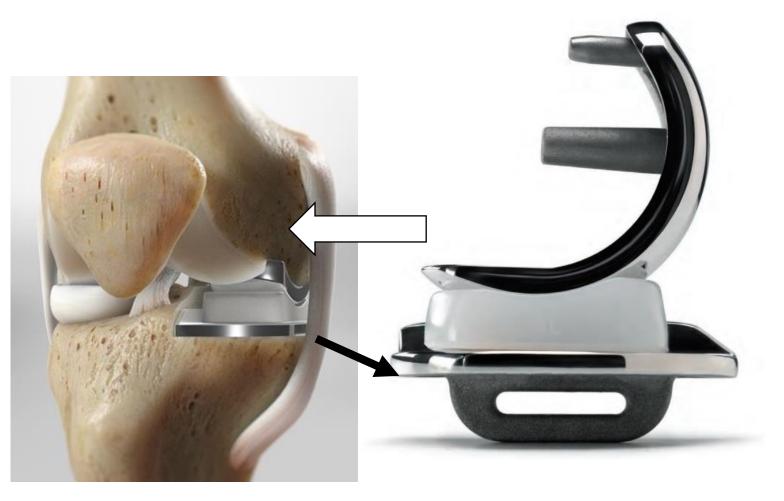
The Oxford Unicompartmental Knee replacement

- 3 Part device
 - Femoral component
 - Meniscal bearing
 - Tibial component

Minimum bone resection is advantageous

This can be achieved through reducing the tray thickness







Tray Failure

- Structural performance and durability constrain geometric design freedom
- Hasn't ever happened to an Oxford Unicompartmental Knee, but has happened with other devices.

Initial experience of the Journey-Deuce bicompartmental knee prosthesis. Palumbo BT, Henderson ER, Edwards PK, Burris RB, Gutiérrez S, Raterman SJ. *J Arthroplasty* 2011; 26 (6) Suppl 1: 40-45.

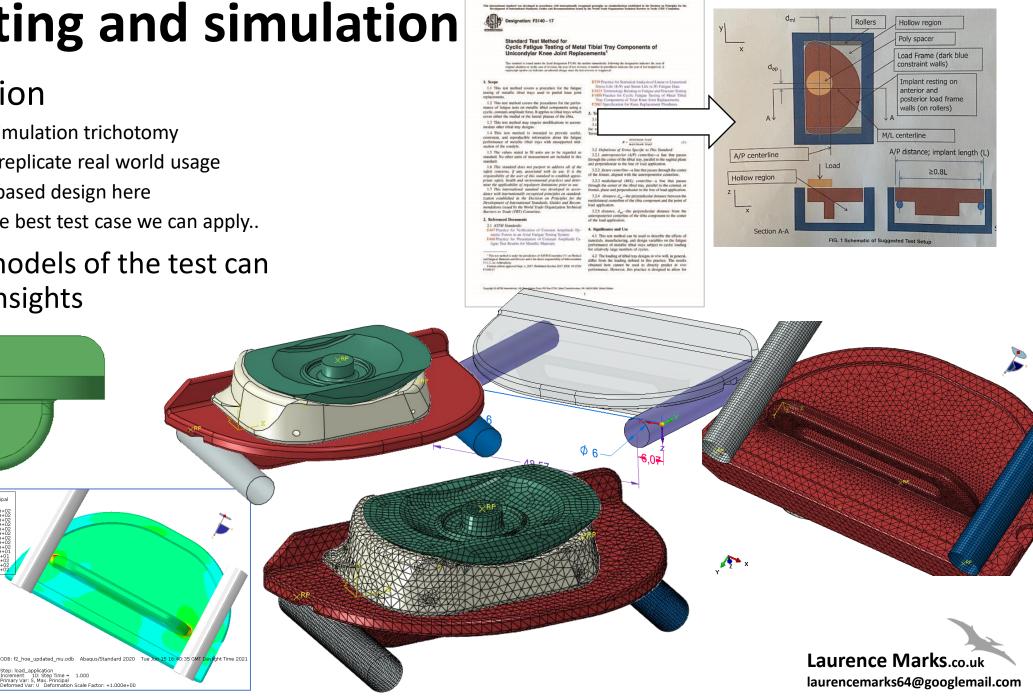




ASTM testing and simulation

• Test specification

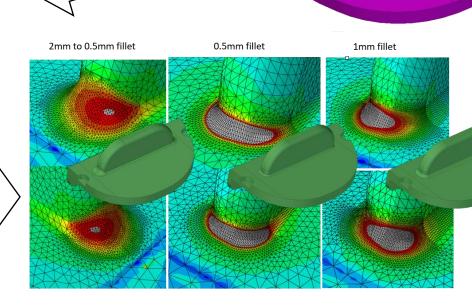
- Test vs real life vs simulation trichotomy
- ASTM test doesn't replicate real world usage •
- Almost into codes based design here ٠
- But it's probably the best test case we can apply. ٠
- Finite element models of the test can provide design insights



To optimise the design we need rapid solution

- Solution timescales fall from 4-24hrs to several minutes.
- Very small difference in results quality
- Which then allows us to use shape optimisation approaches (in this case non-parametric shape optimisation)
 - High stress regions move out, reducing stress locally
 - Low stress regions move in, increasing stress locally

111



Supports replaced

Load applied using

pressure patch

by BC's



Peak – 250MPa

Peak – 175MPa

Modelling decisions have unlocked design variability

- So by optimising the fillet profile we unlock areas of product performance.
- And we can only do that with efficient model definition.

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Resources

I'm creating a collection of stuff I've done and found. Hopefully it will be useful to other people, but please credit me if you use anything. I'm not going to put a system that captures people's defails here, but if you do find something useful it would be great to hear from you by email.

Presentations etc.

PDF file of 2023 CMBBE presentation "DEFINING A PROCESS FOR STRESS REDUCTION IN THE KEEL TRAY INTERFACE IN UNICOMPARTMENTAL KNEE REPLACEMENT TIBIAL COMPONENTS"

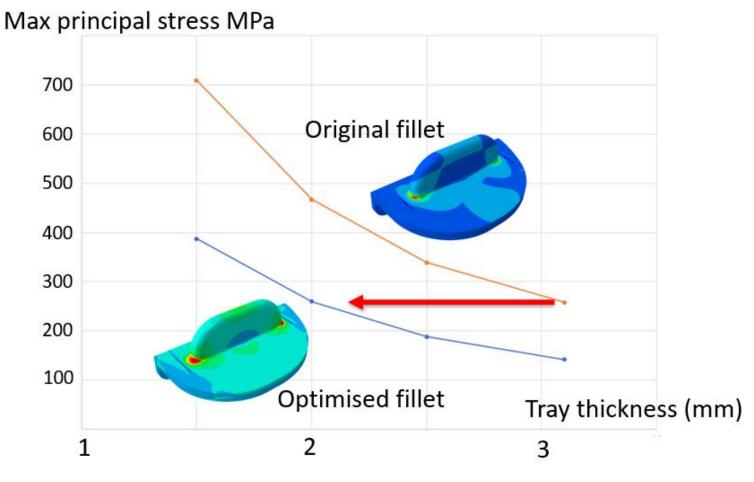


DEFINING A PROCESS FOR STRESS REDUCTION IN THE KEEL TRAY INTERFACE IN UNICOMPARTMENTAL KNEE REPLACEMENT TIBIAL COMPONENTS

Laurence Marks, Stephen Mellon, David Murray Oxford Orthopaedic Engineering Centre Nuffield Department of Orthopaedics, Rheumatology and Musculoskeletal Sciences University of Oxford

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Another, more complete presentation is downloadable from my website.



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In summary

- Sometimes using modelling simplifications can help provide useful design insights and design improvements, especially if you want to use optimisation or design space exploration.
- And sometimes you need the complex models...

