A Parametric Model of the Human Knee for reduced simulation timeframes

Laurence Marks

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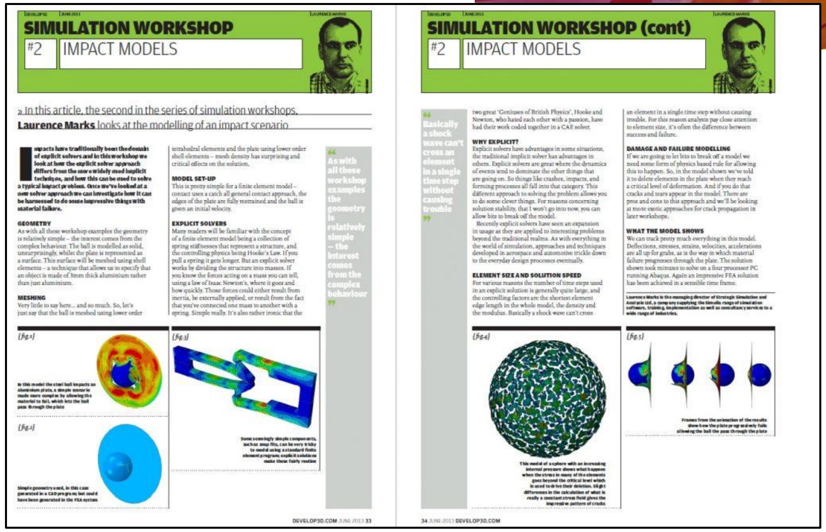
About me..

- 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


SIMULATION WORKSHOP
#2 IMPACT MODELS
» In this article, the second in the series of simulation workshops, Laurence Marks looks at the modelling of an impact scenario
SIMULATION WORKSHOP (cont)
#2 IMPACT MODELS

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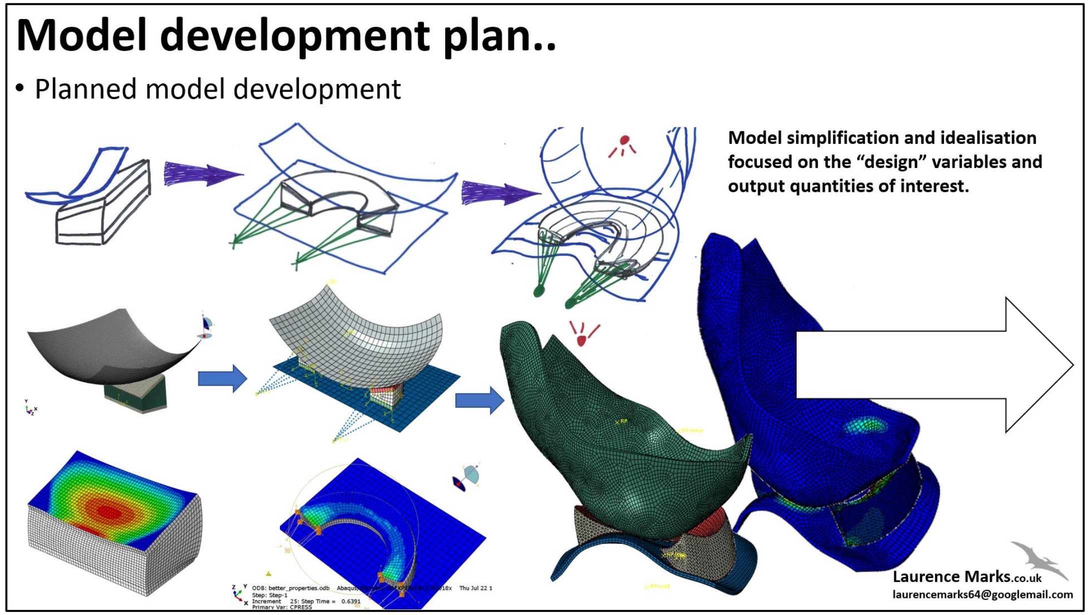
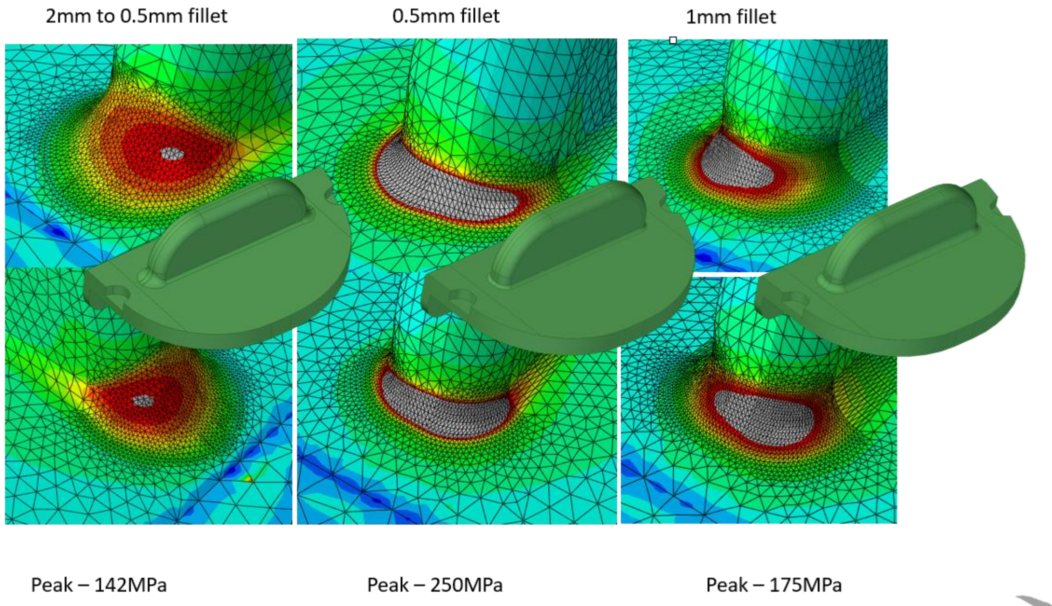
Some work in progress and a completed project..

- 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





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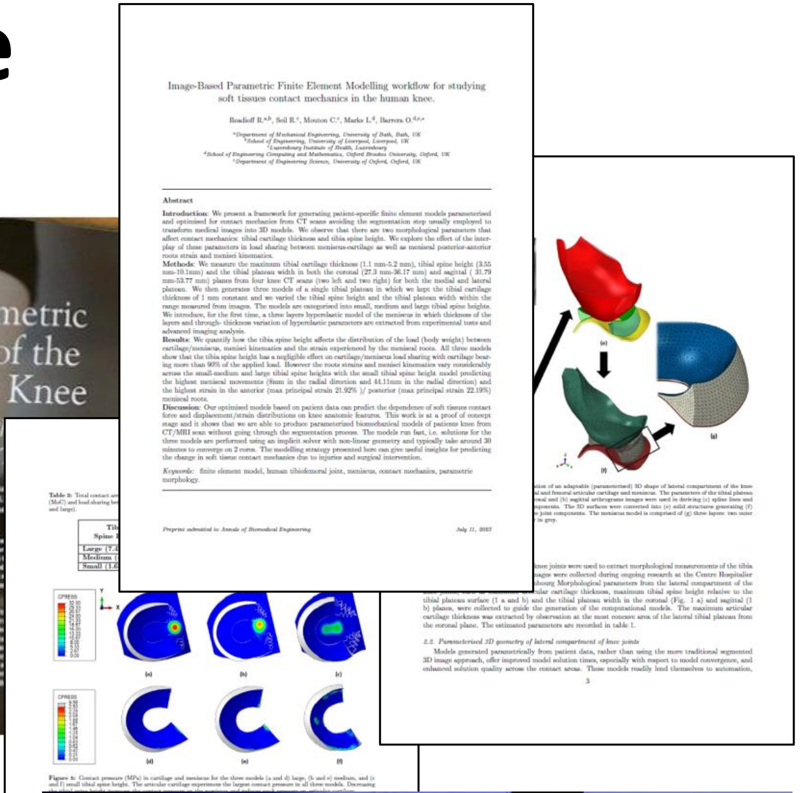
A parametric model of the human knee optimized for contact mechanics

- Olga Barrera



- Rapid assessment of the impact of variability of knee morphology across populations
- Rapid assessment of the impact of different clinical interventions
- A development framework for material model development

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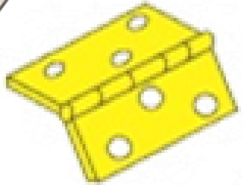
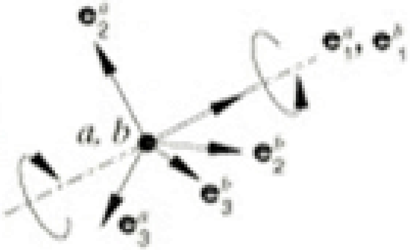
The human knee

- Easy to think of the knee as simple hinge





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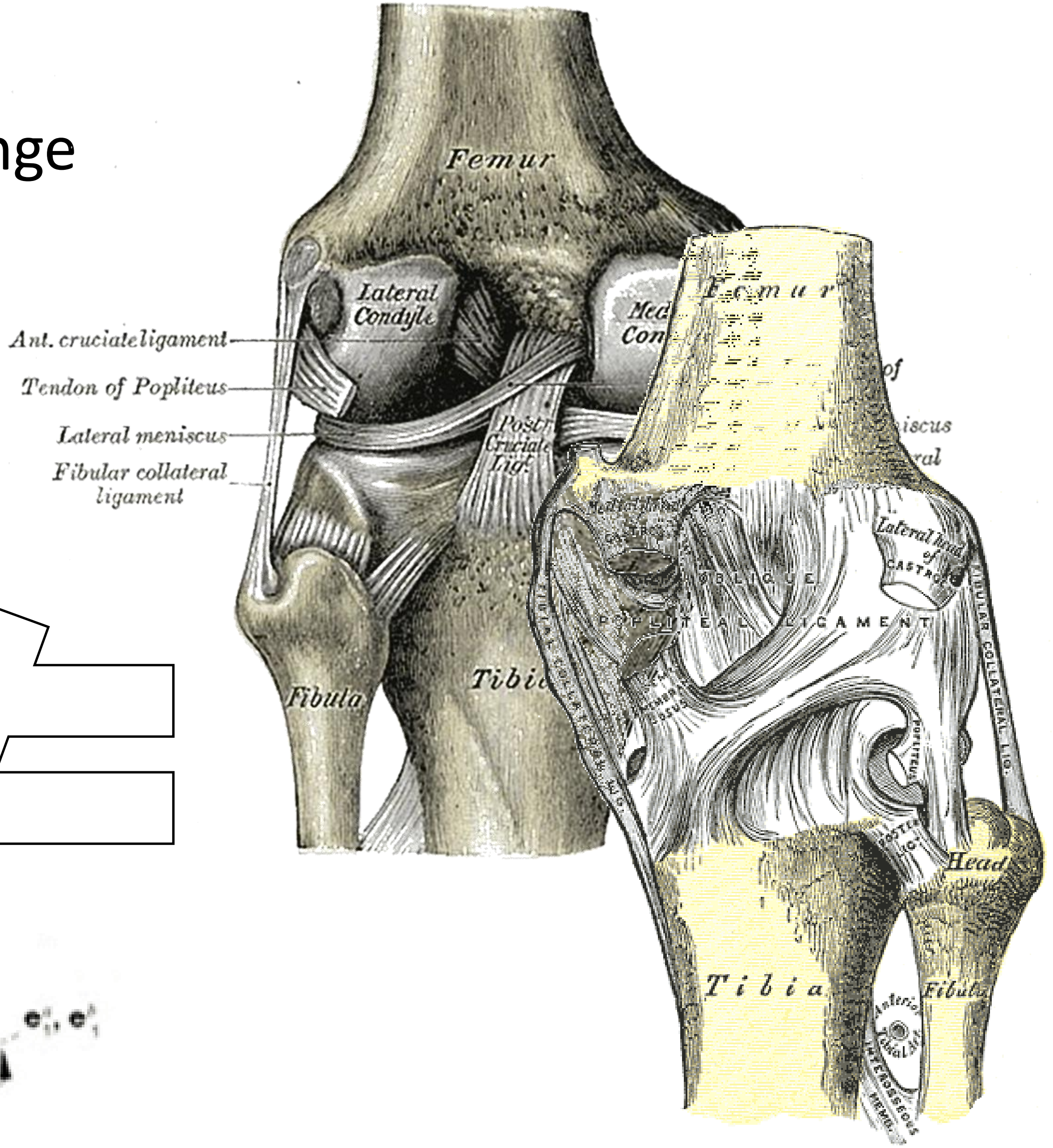

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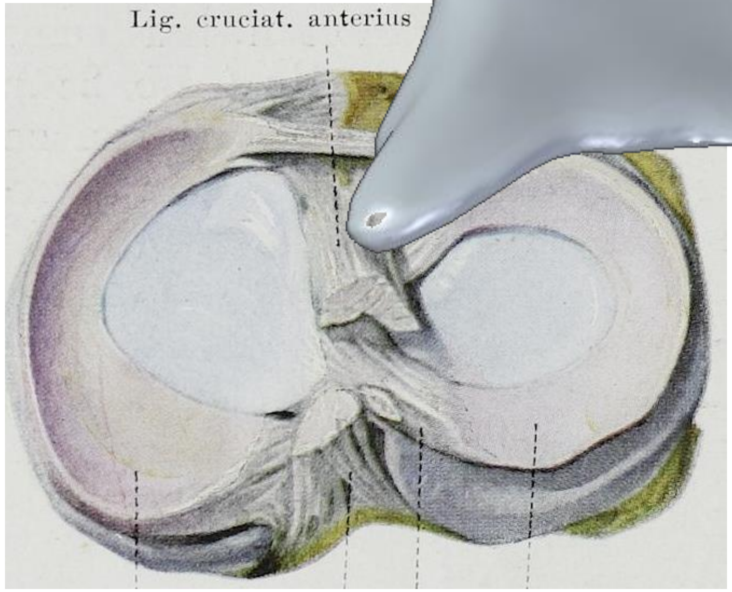
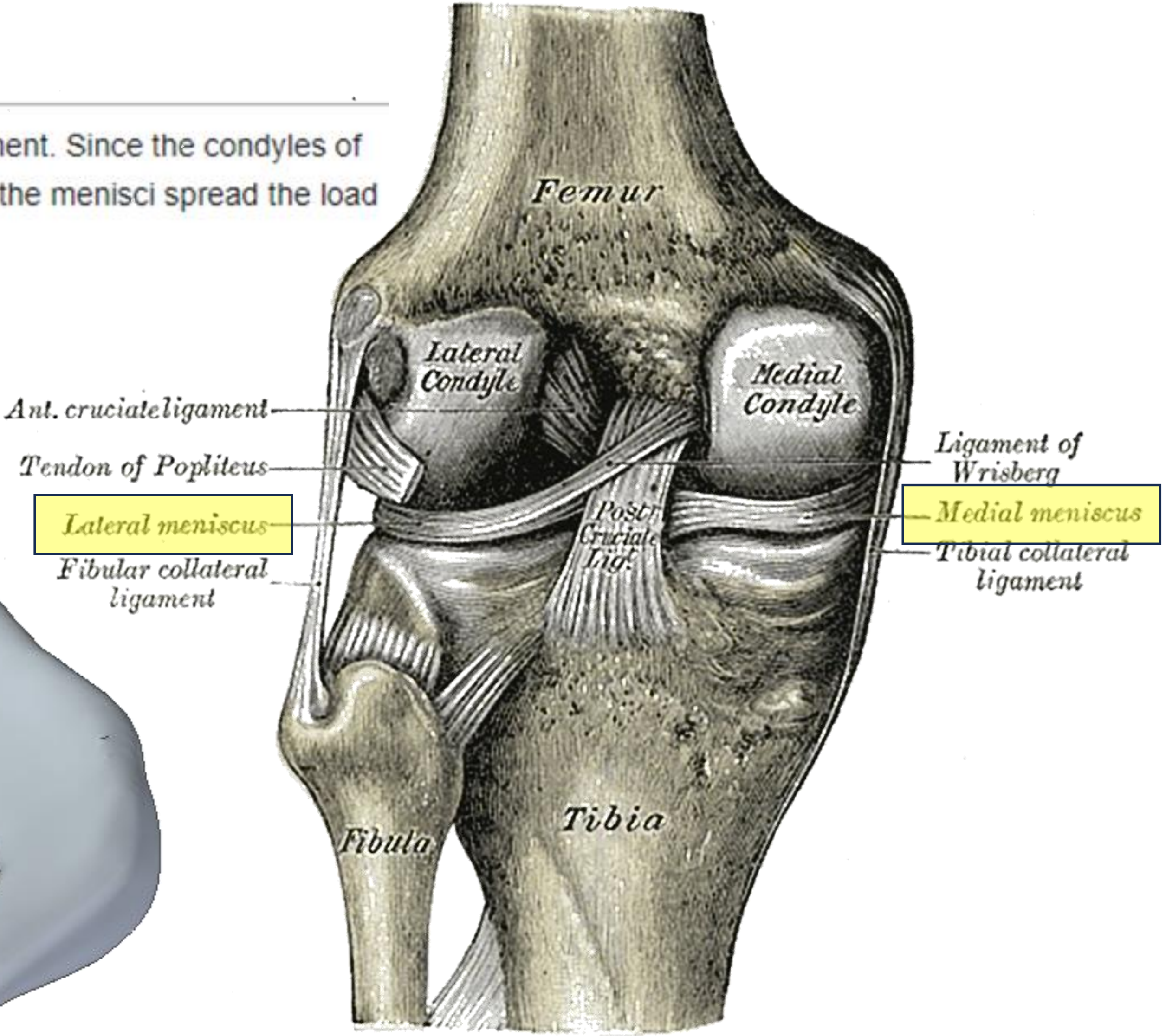
The meniscus

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]





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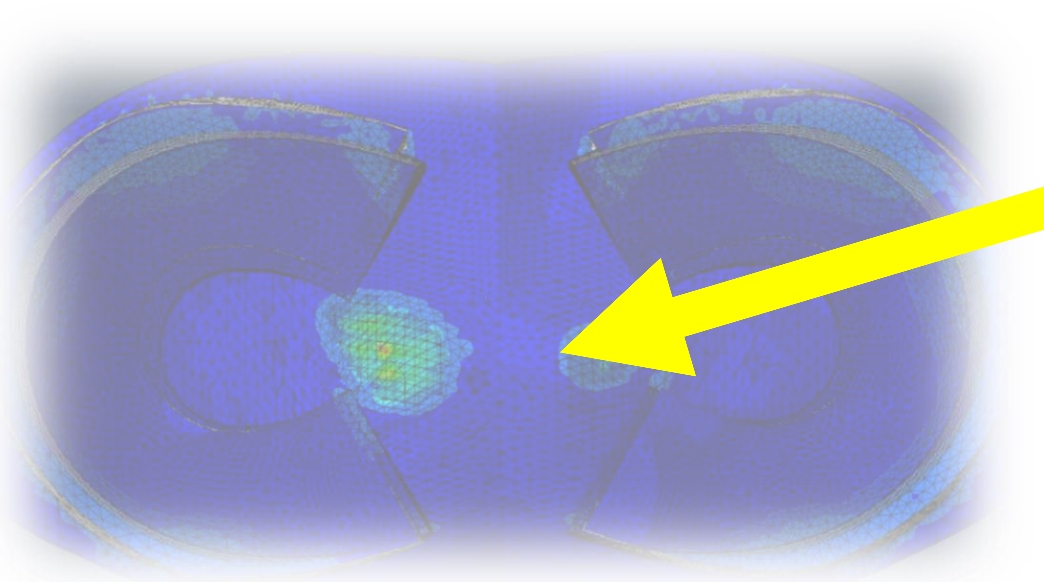
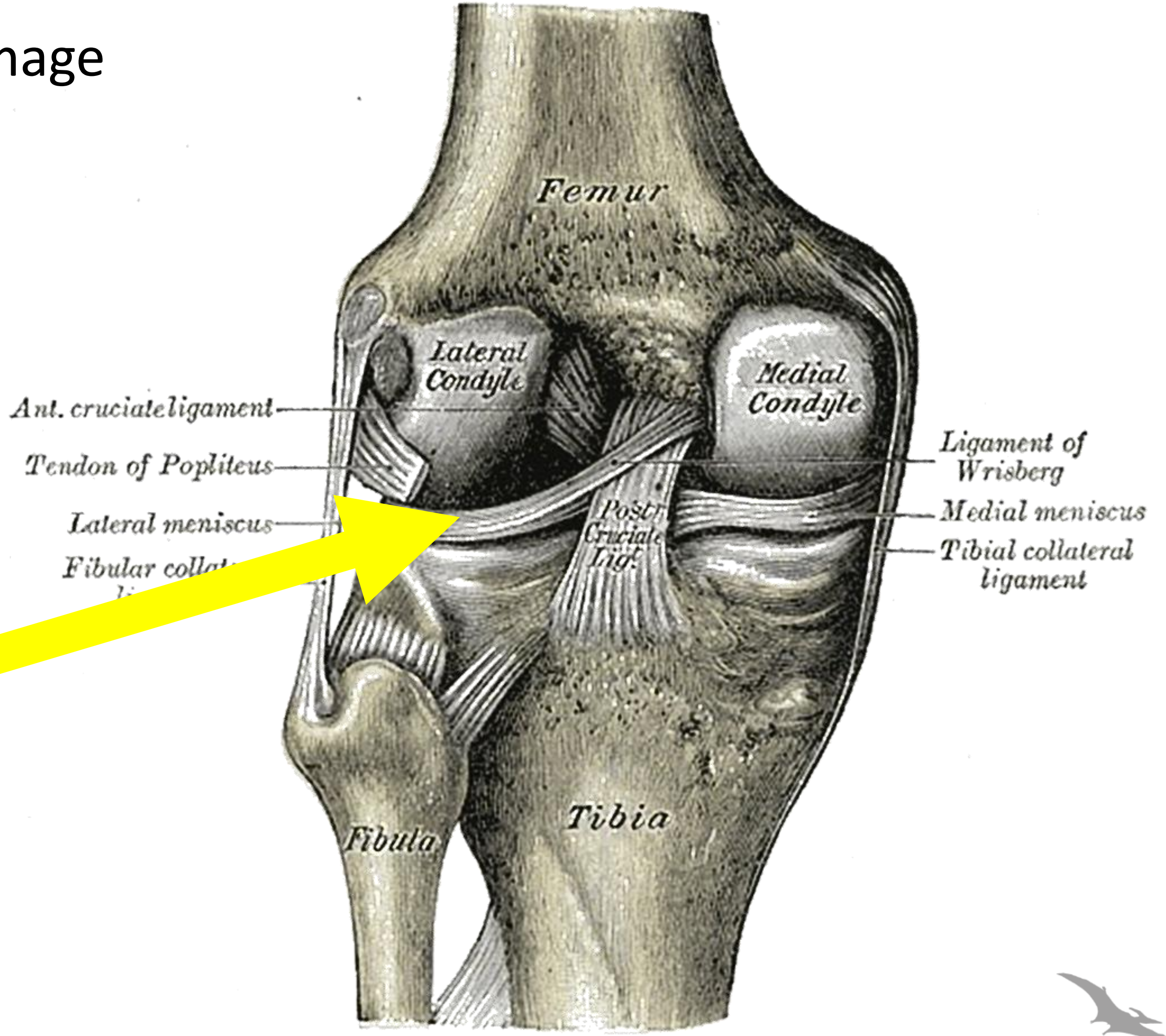
The meniscus – finite element modelling challenges

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





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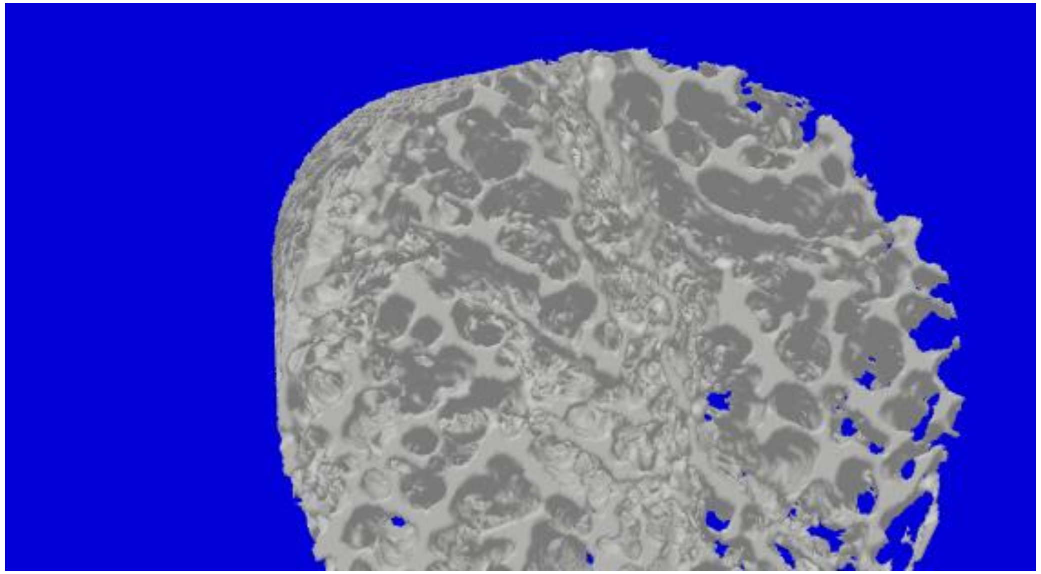
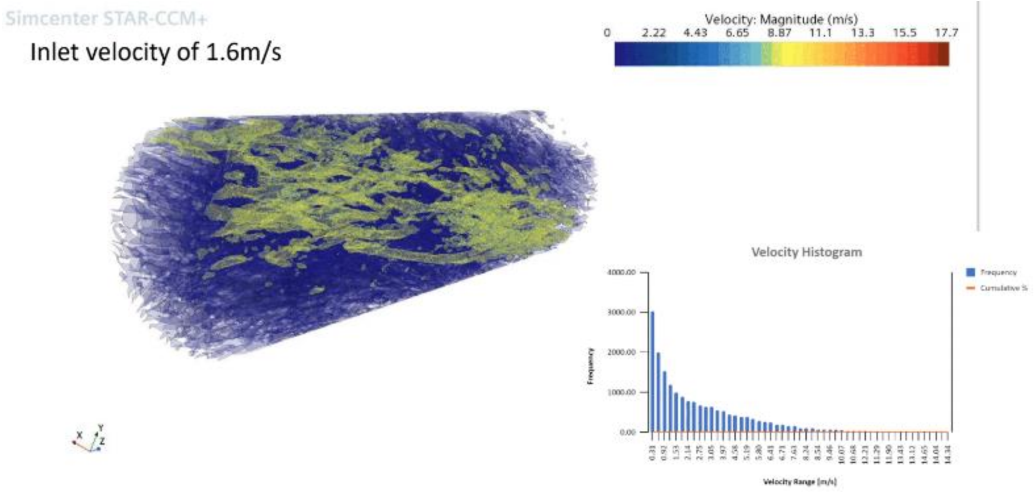
The meniscus – a materials challenge

- 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



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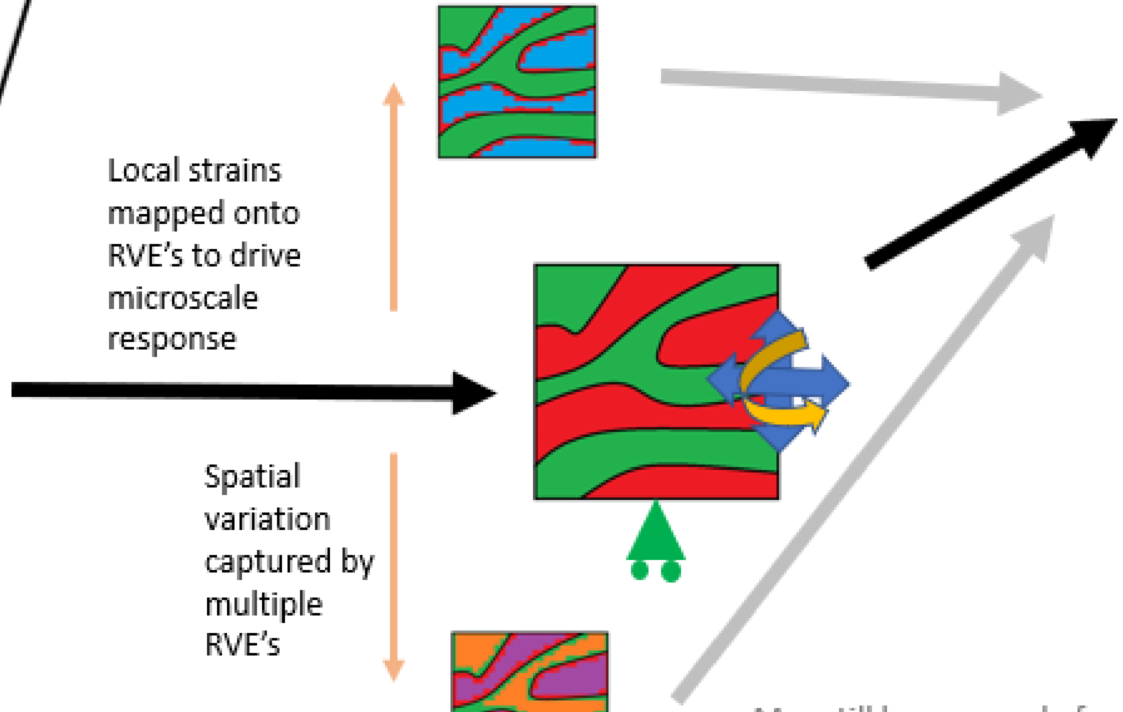
The meniscus – a multiscale challenge

Macro Scale

3d mapping of meniscus deformations and strains

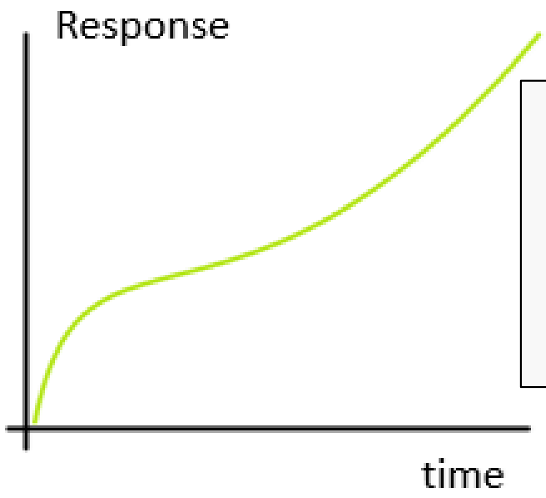
Could be backed up with FEA model

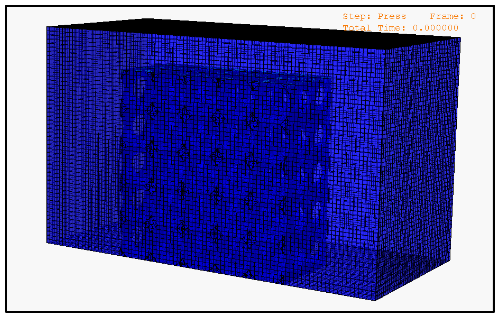
Micro Scale



Fluid Structural Interaction microscale models

May still be some role for a material model – but project more streamlined without it.





- Permeability
- Structural only response
- Coupled response
- Operating envelope

- Design parameter for replacement device

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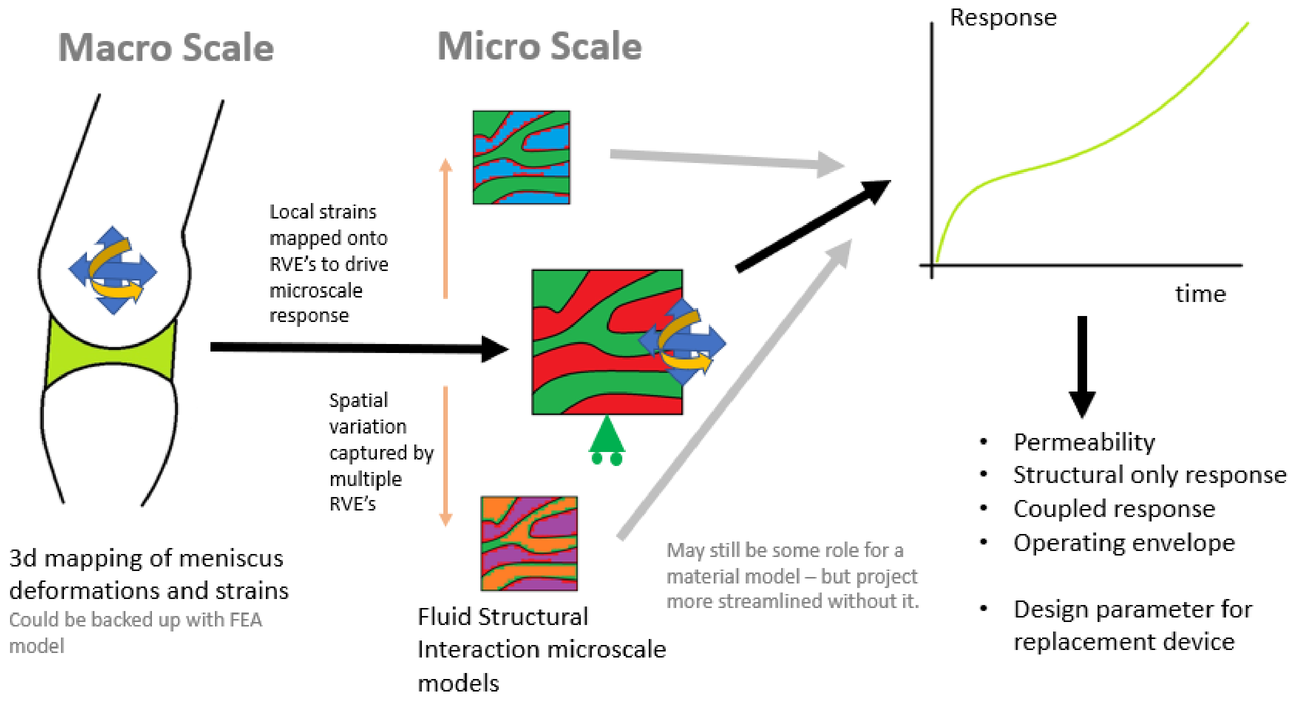
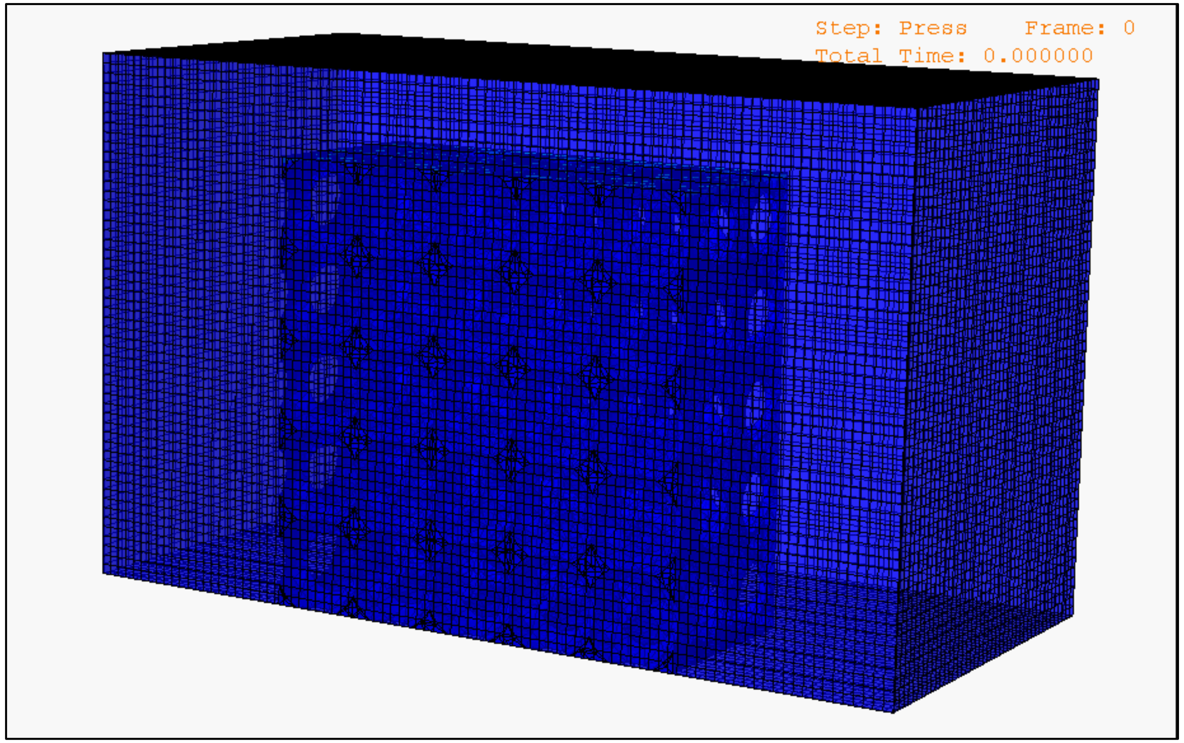
The meniscus – a multiphysics challenge

- FSI - **F**luid **S**tructural **I**nteraction
- RVE – **R**epresentative **V**olume **E**lement

- Definitely a work in progress..





Coupled **E**ulerian **L**agrangian model in Abaqus Explicit – other codes were tried with similar levels of success..

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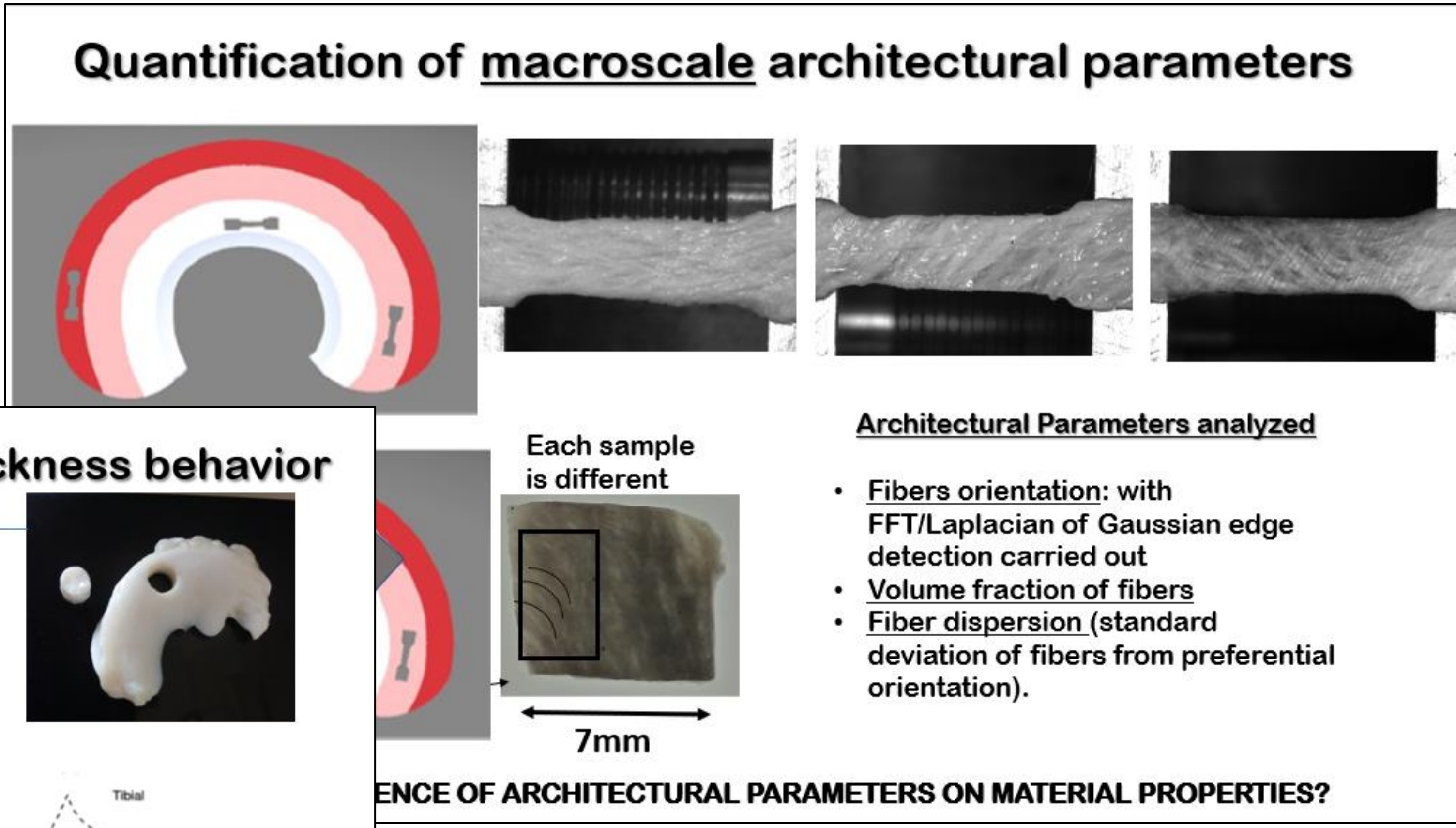
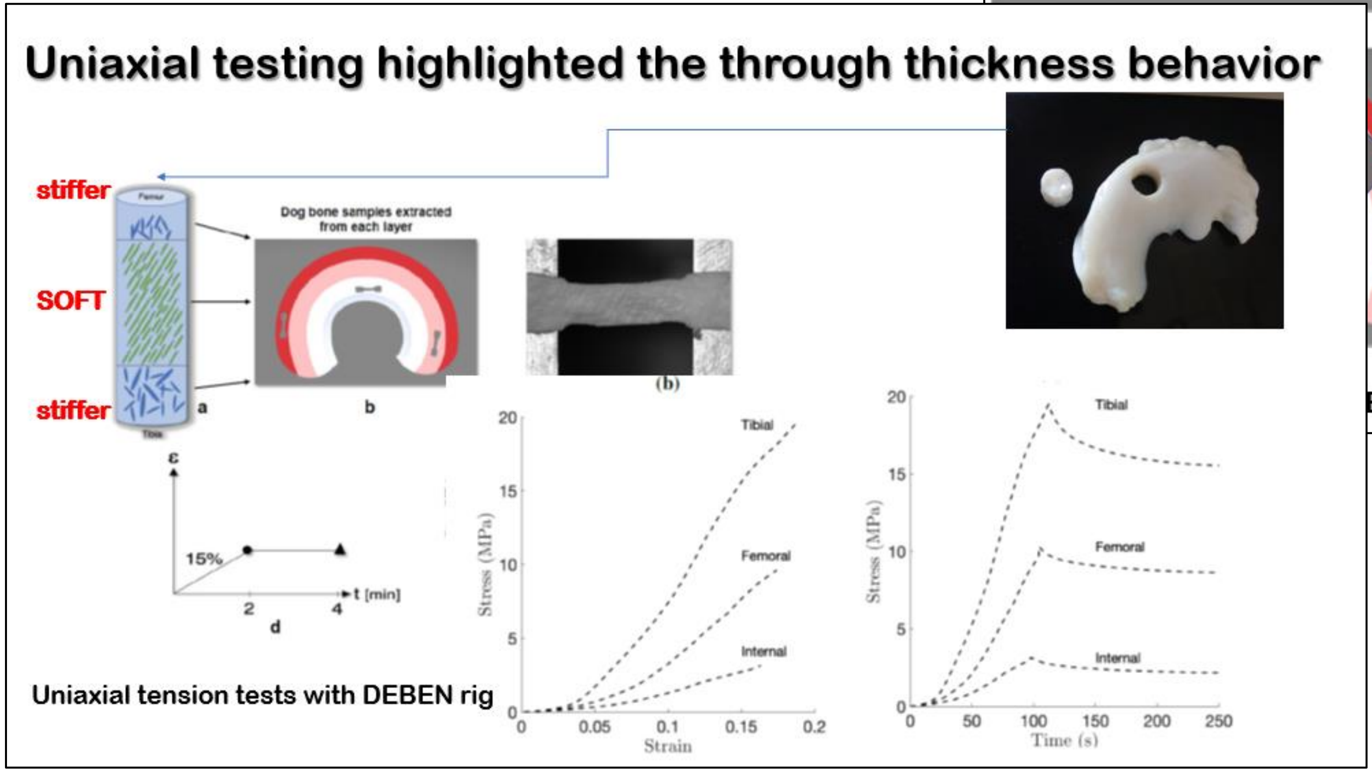
Meniscus – material approaches

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





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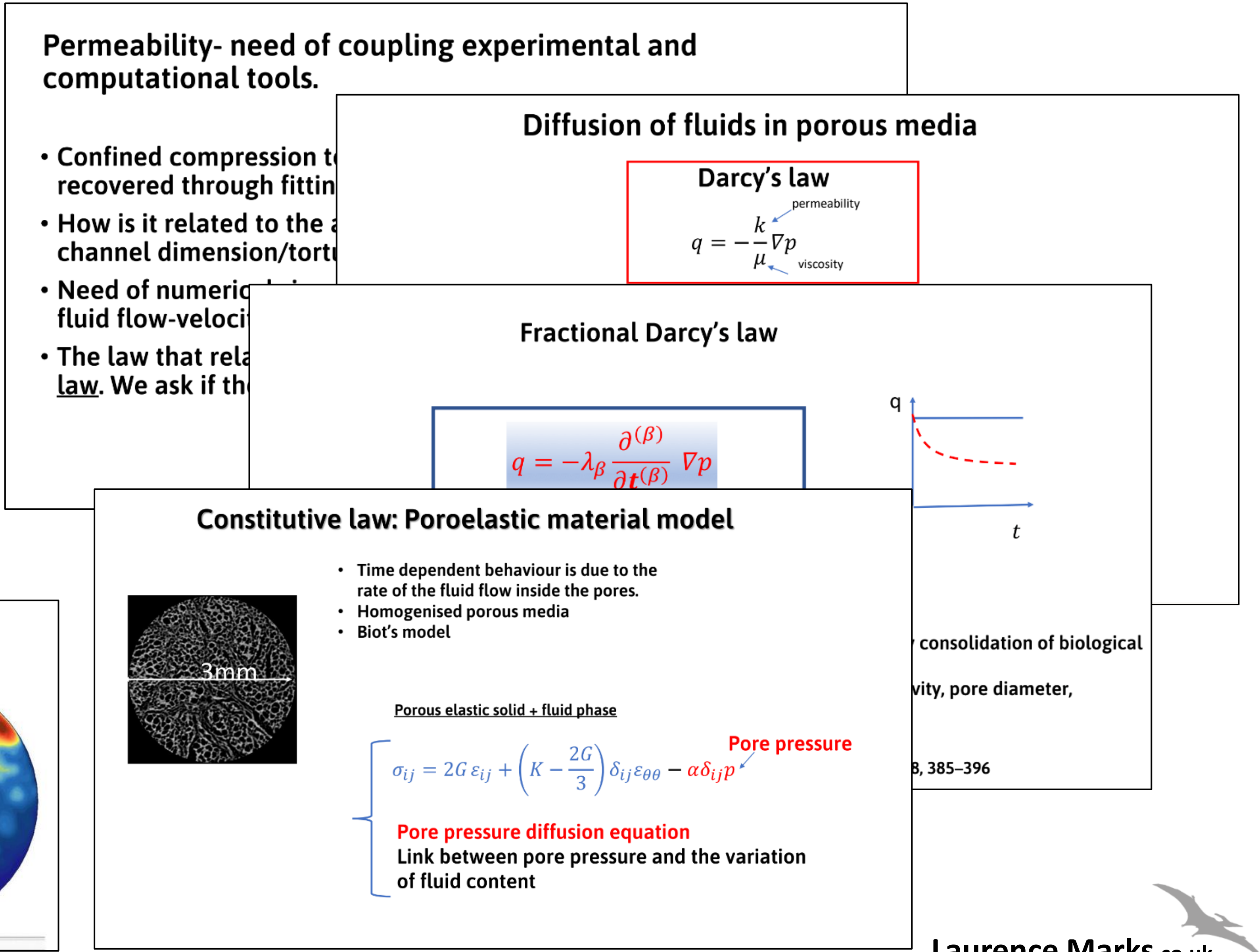

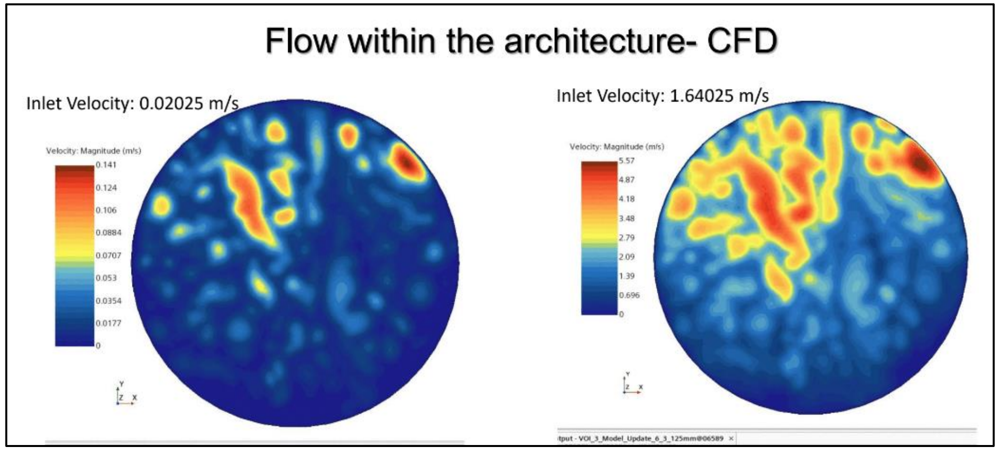

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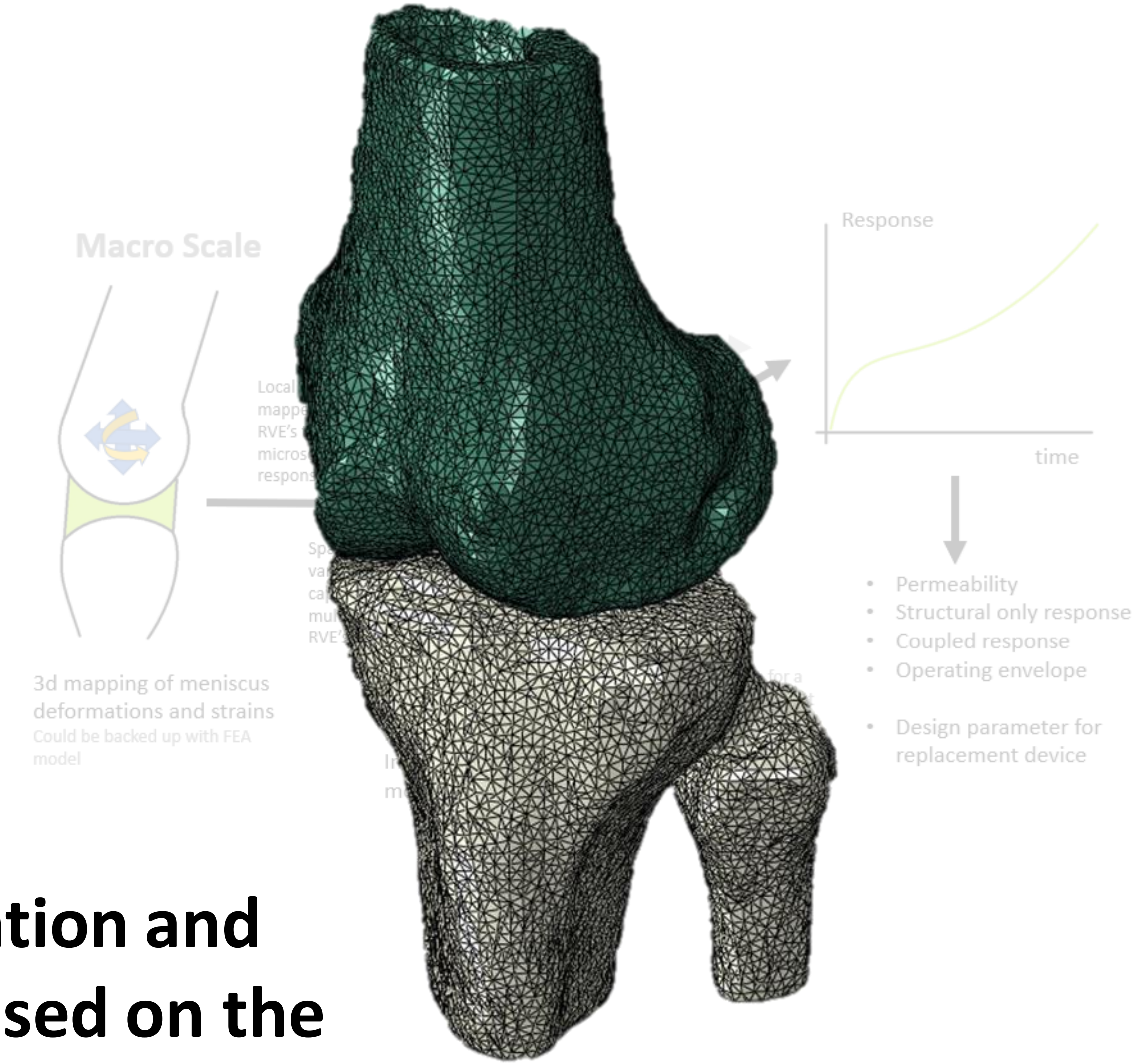
Contradictions towards a workflow..

- **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.

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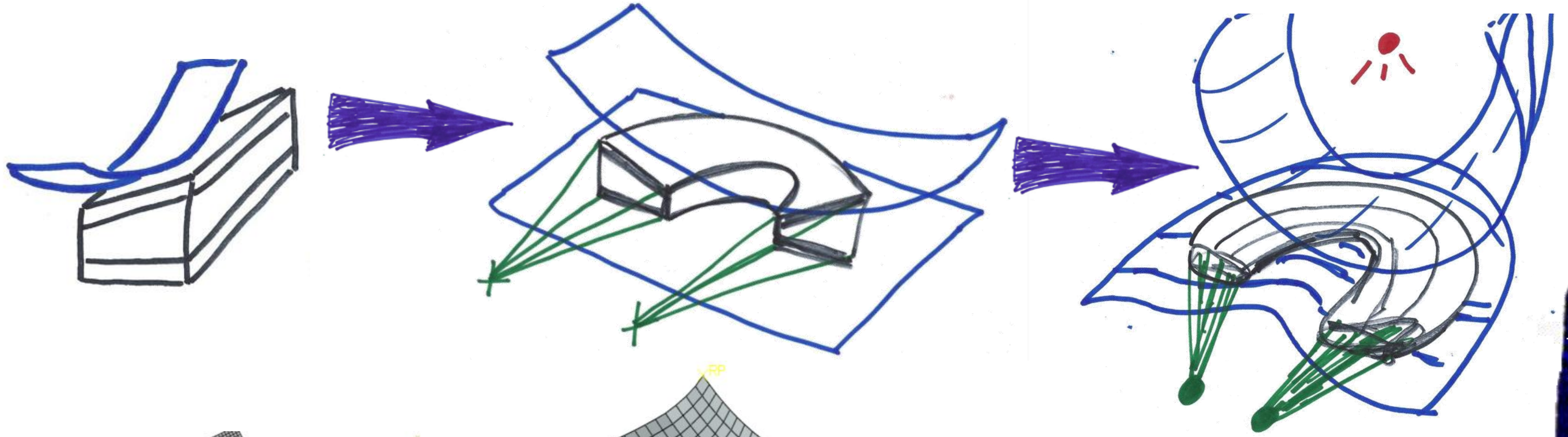
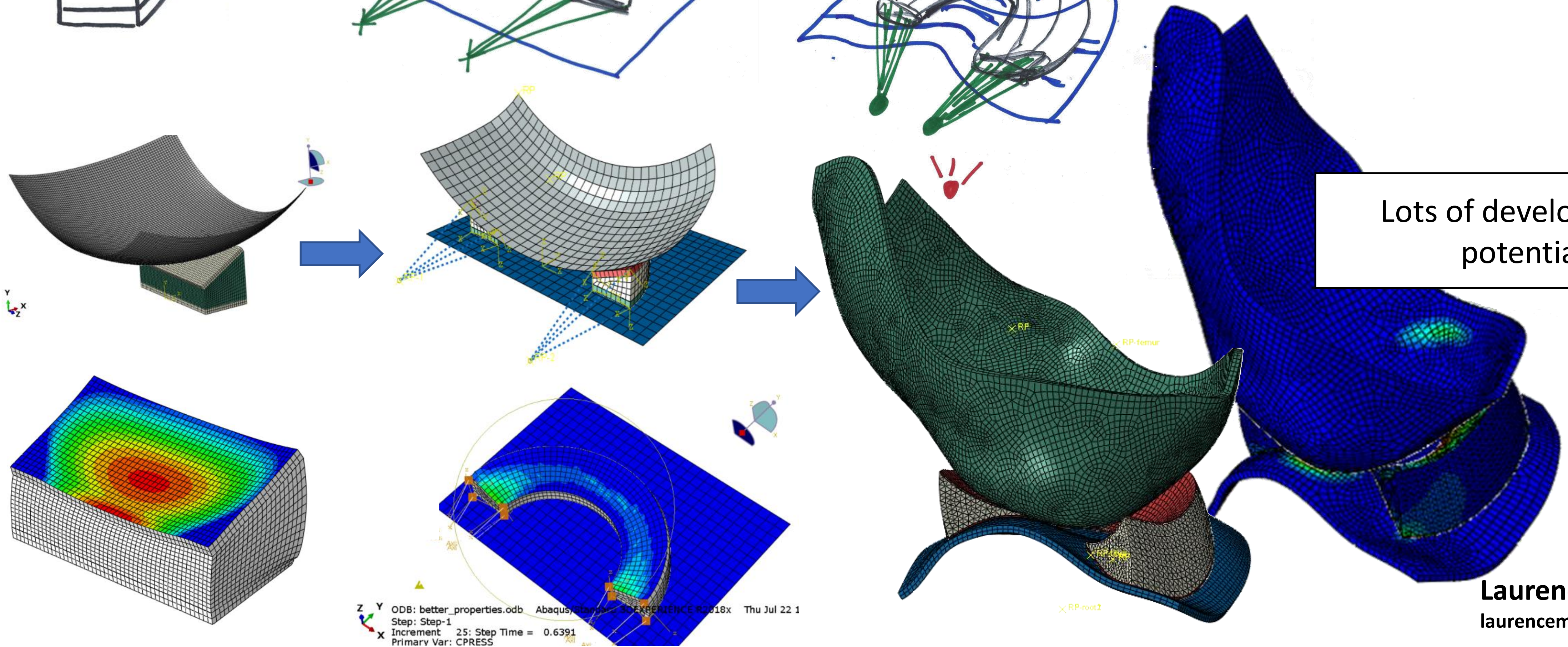
Model development plan..

- Planned model development





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

Lots of development potential

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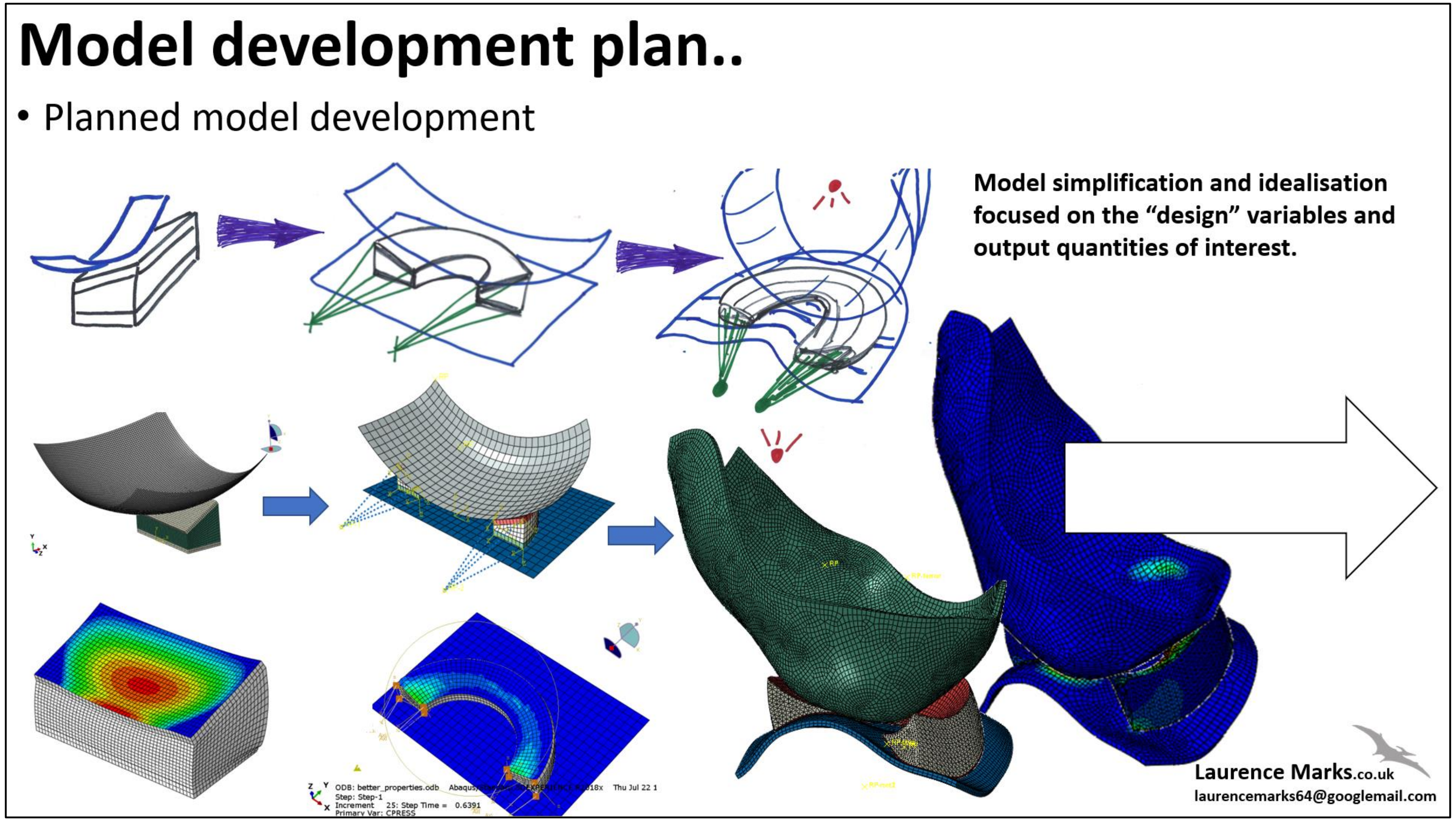
Something interesting happened on the way..

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



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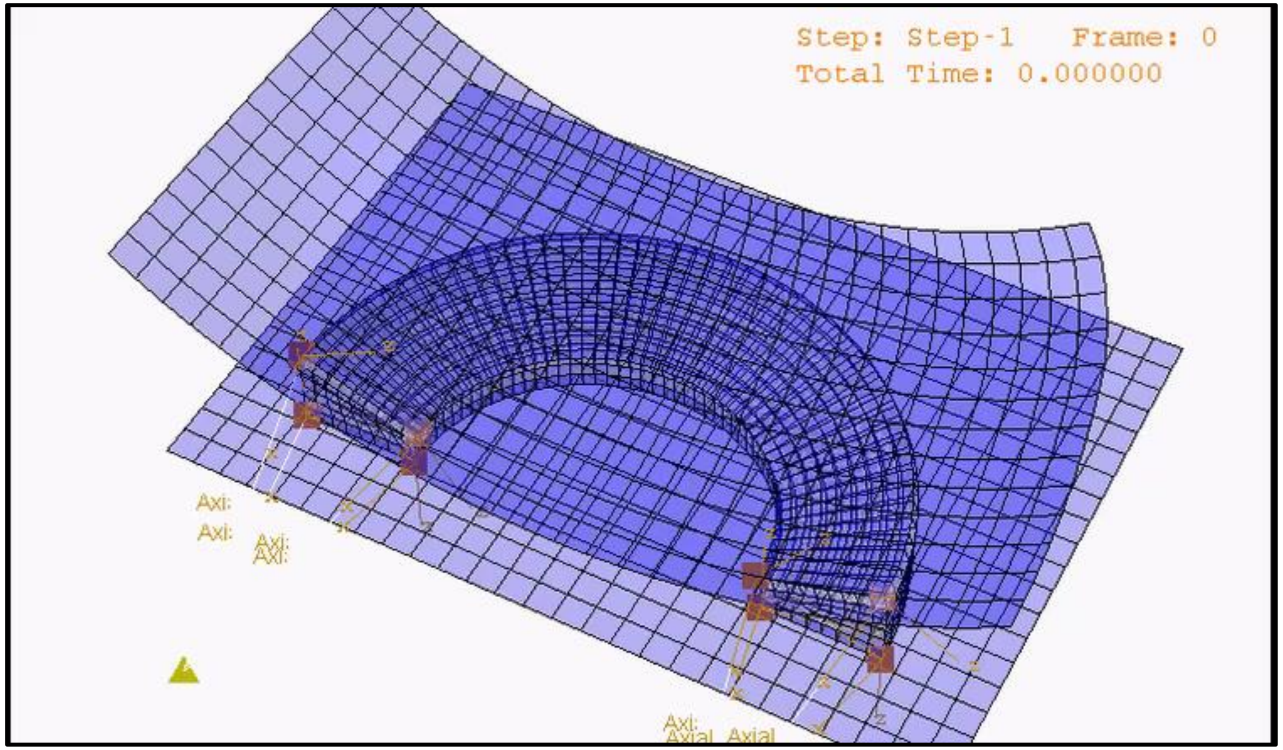
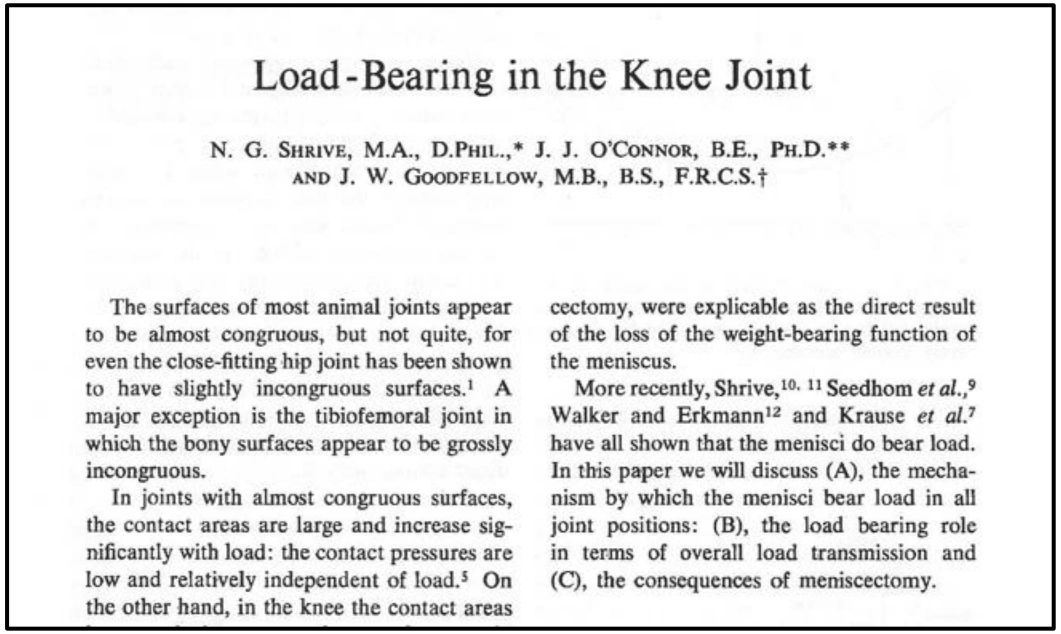
Something interesting happened on the way..

- 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 Erkmann[12] 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.

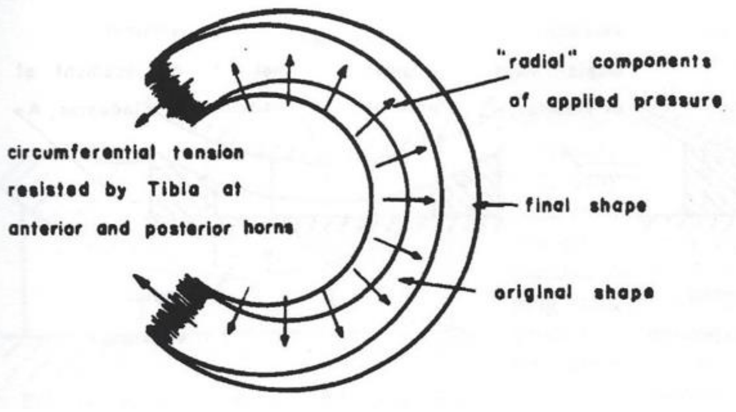


Fig. 4. Superior view of a meniscus showing deformation on loading, direction of 'radial' pressure and resistance of circumferential tension at tibia.

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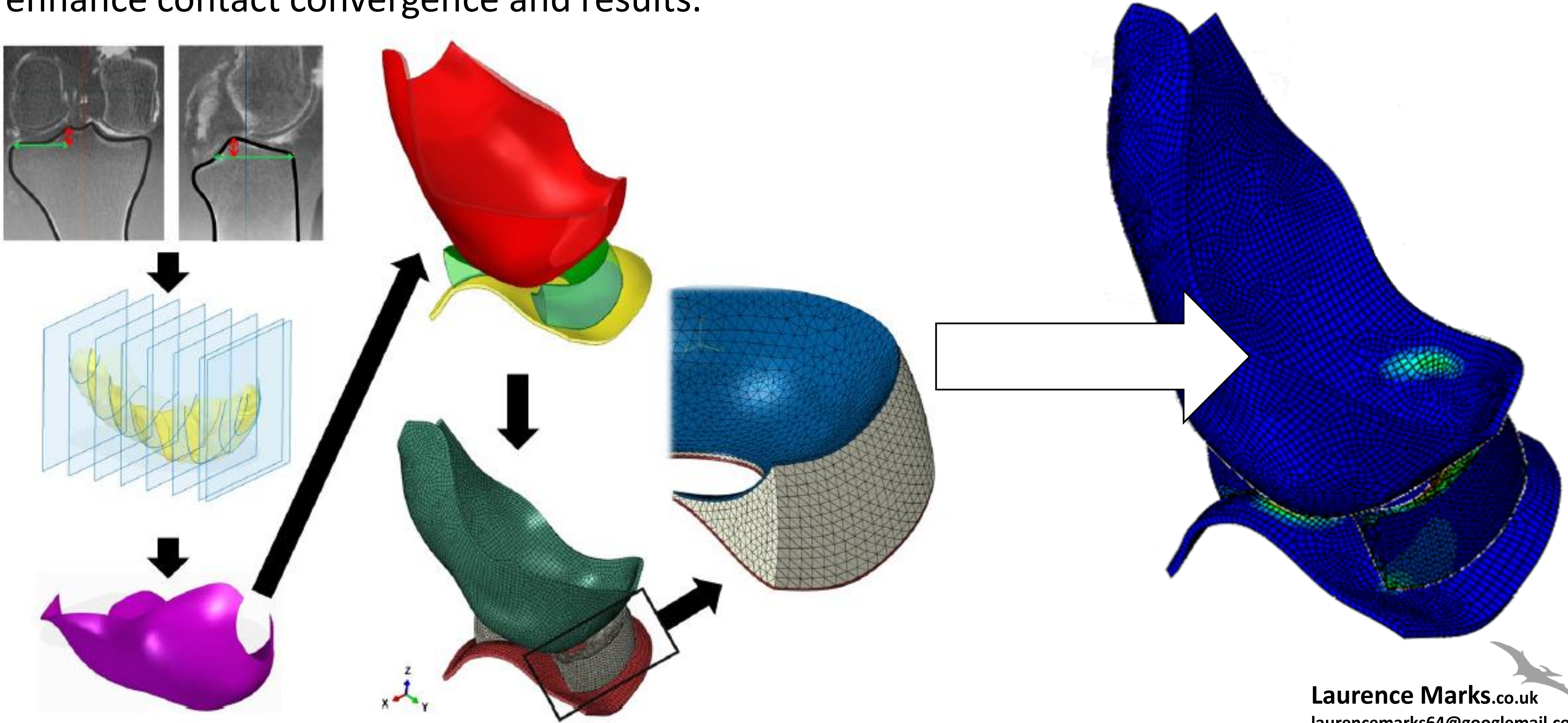
Modelling Workflow

- 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.



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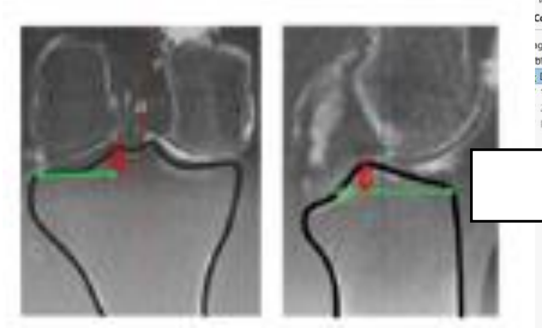

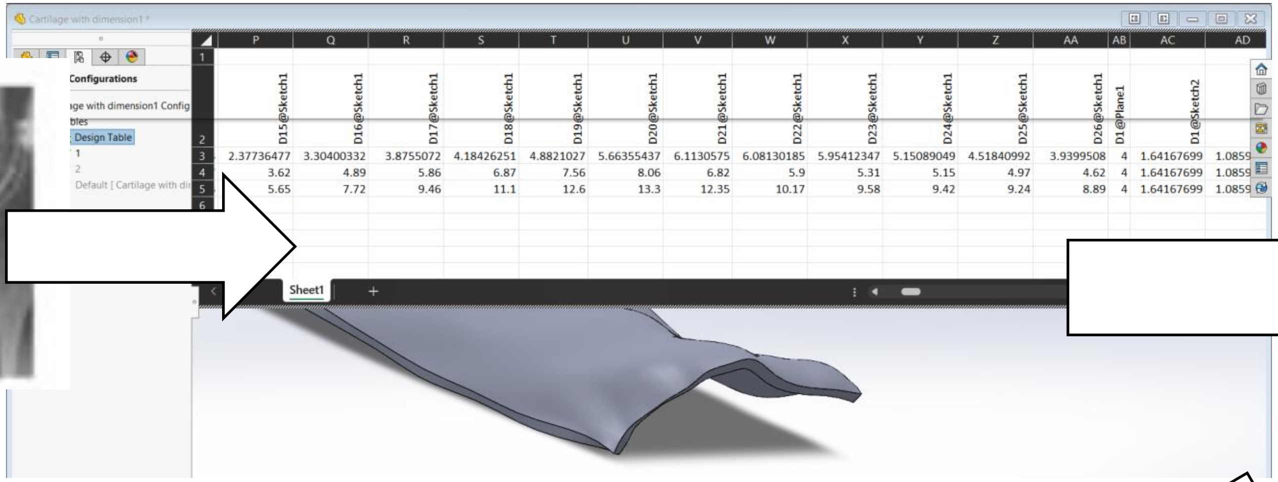

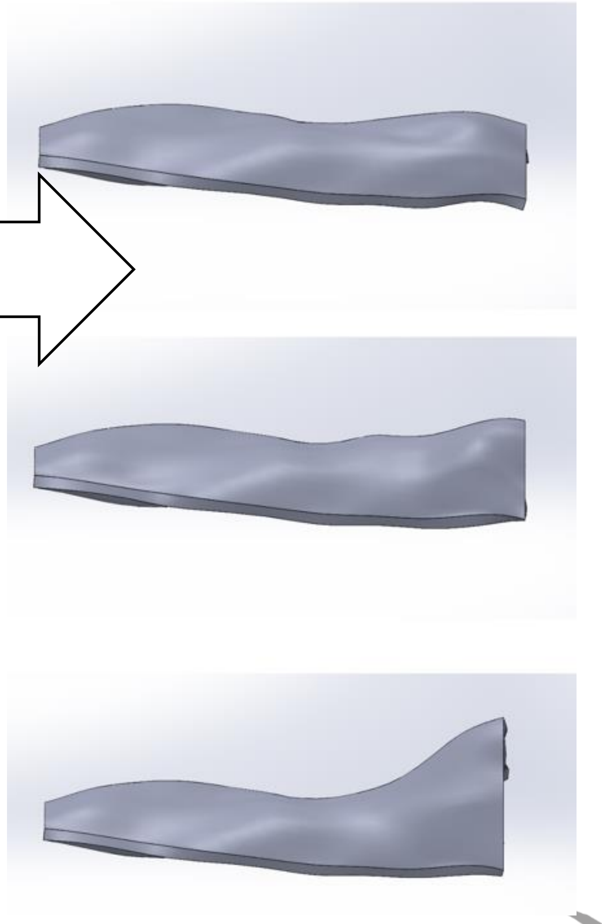

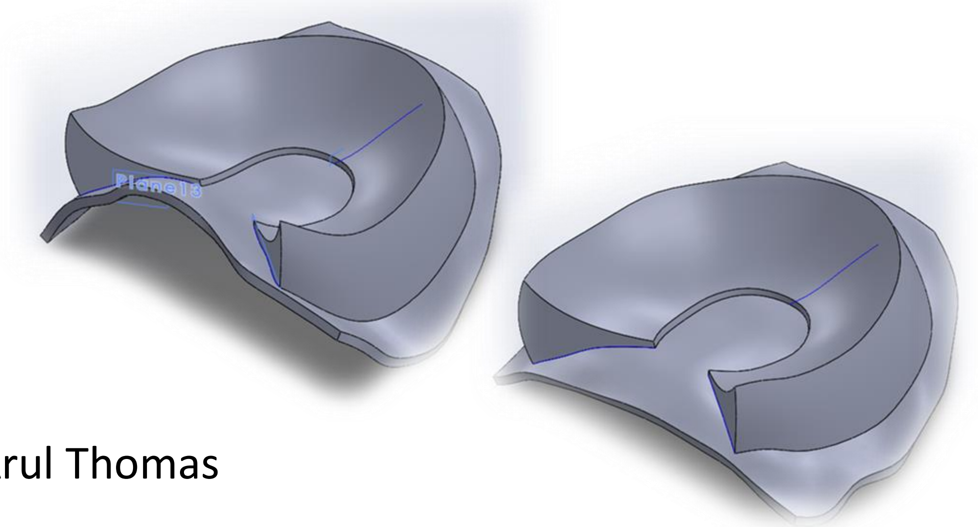

Work by: Bibin Arul Thomas

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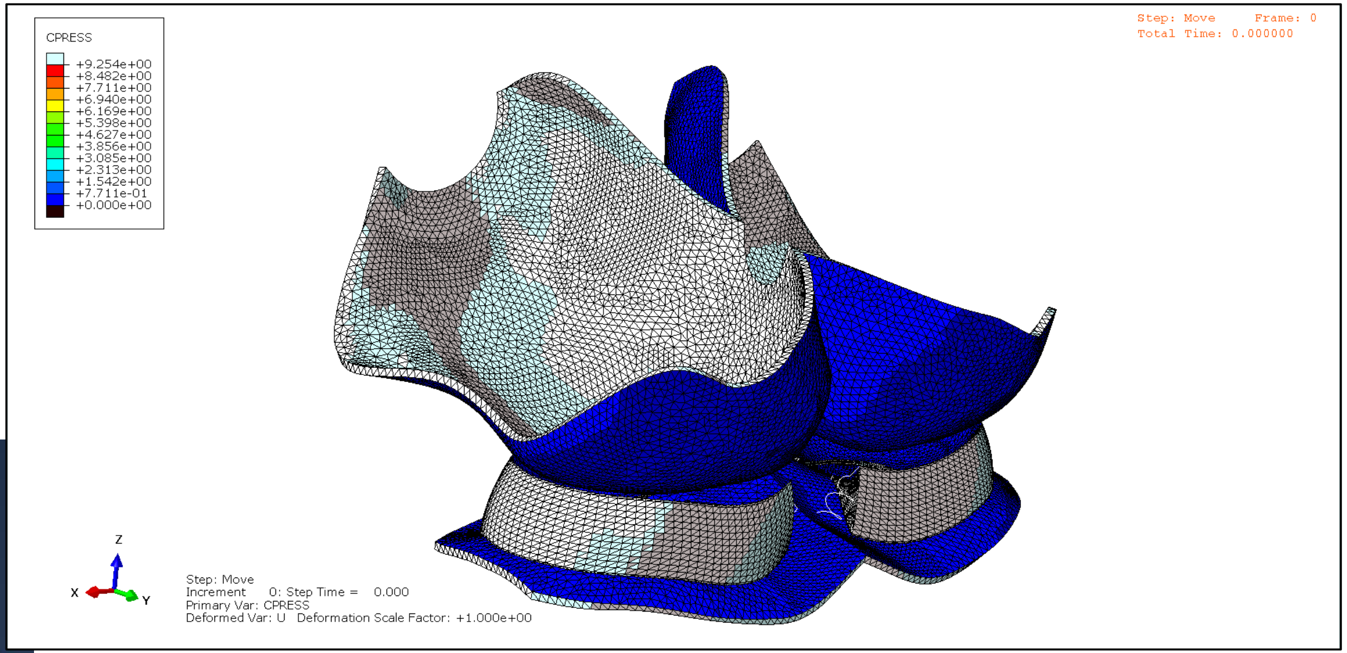
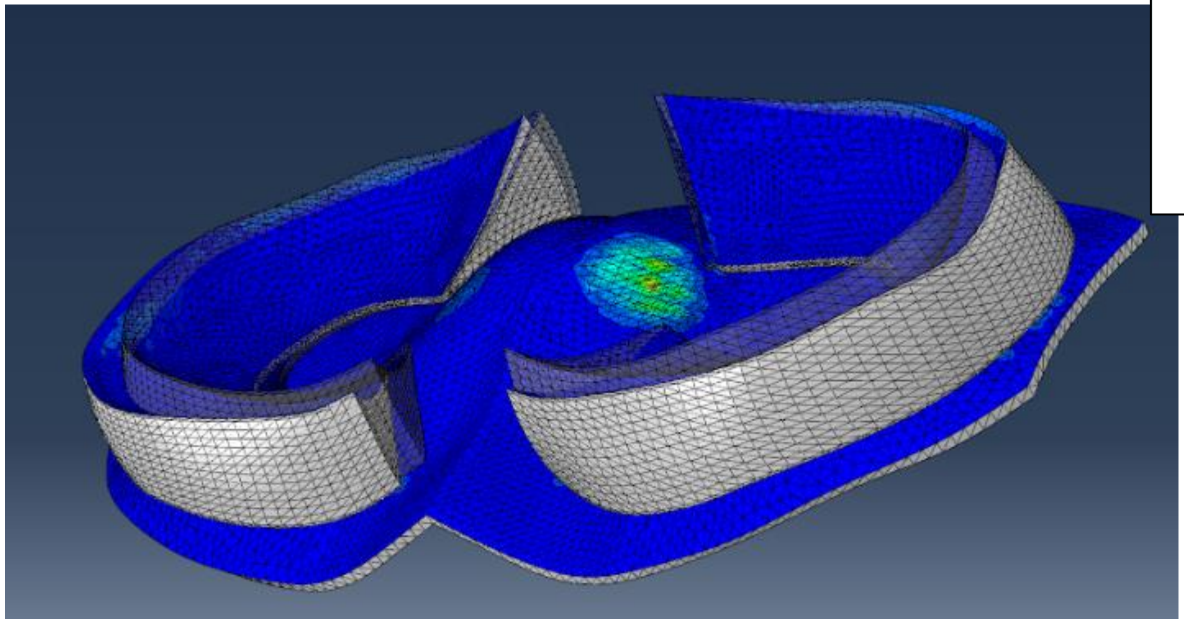
Adding the other condyle

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





Work by: Arjun Nair

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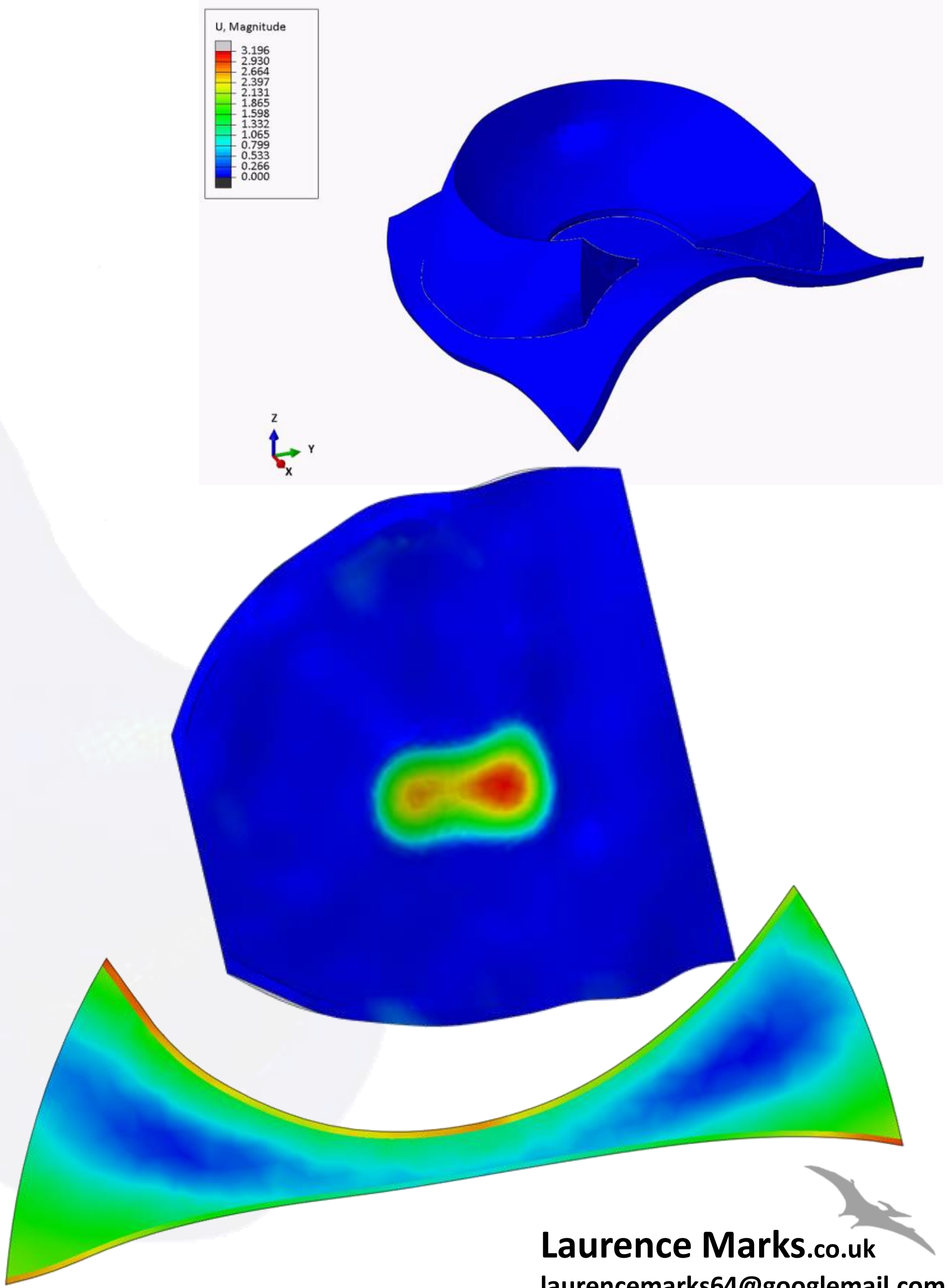
What we've achieved

- 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.



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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.

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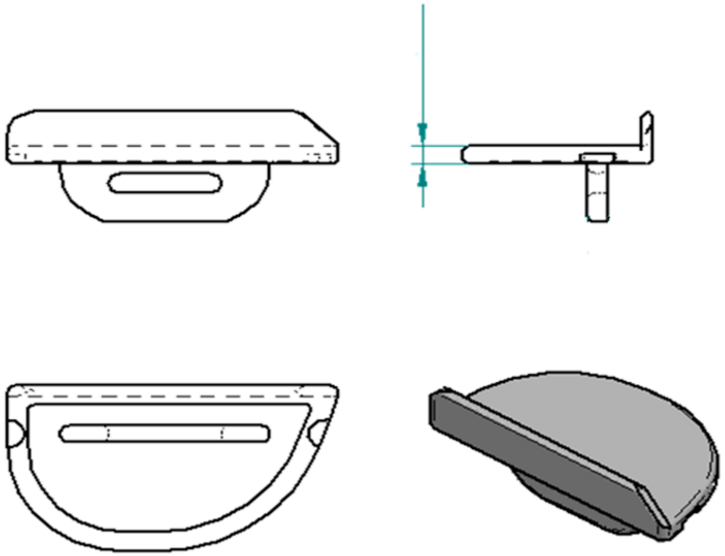
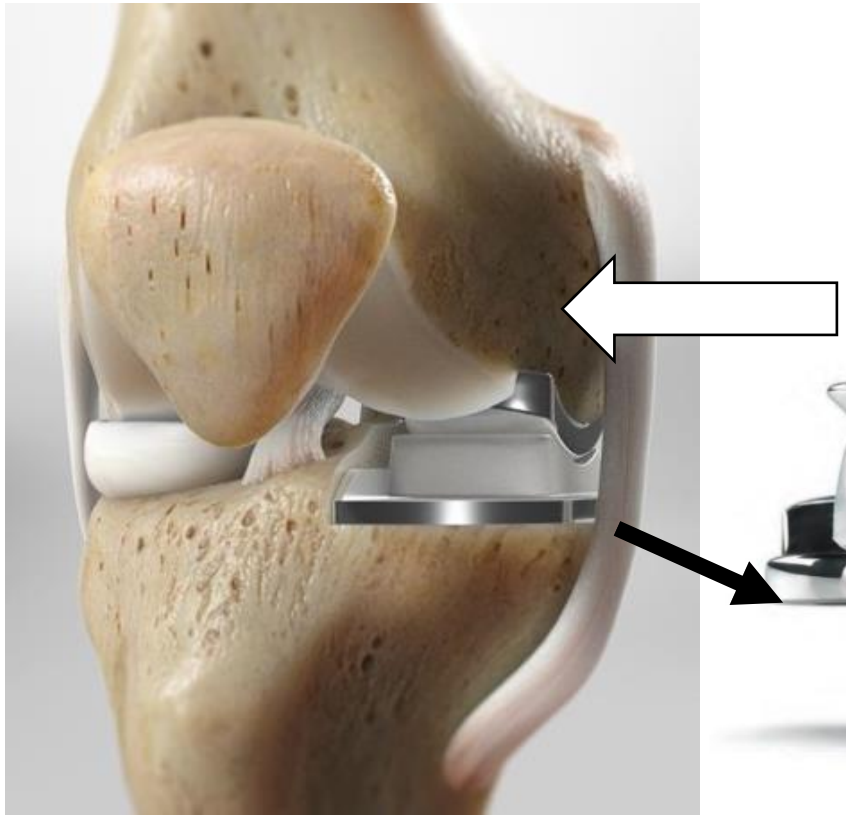
The Oxford Unicompartmental Knee replacement

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

Minimum bone resection is advantageous

This can be achieved through reducing the tray thickness





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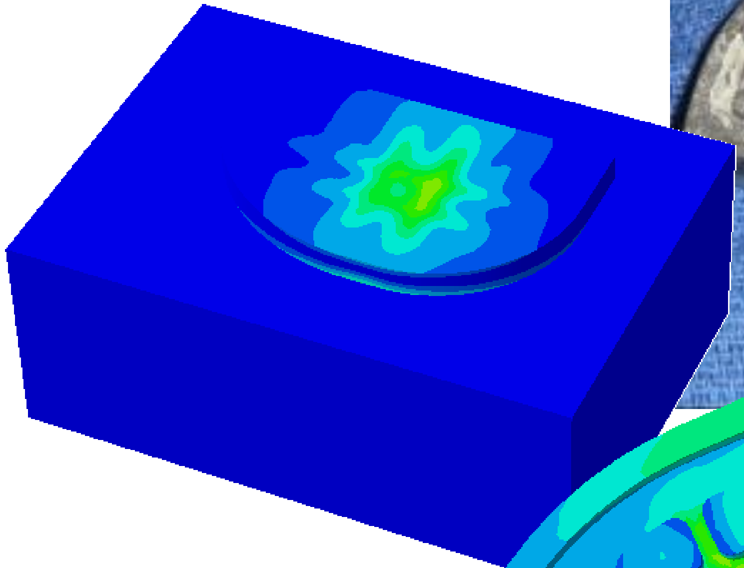
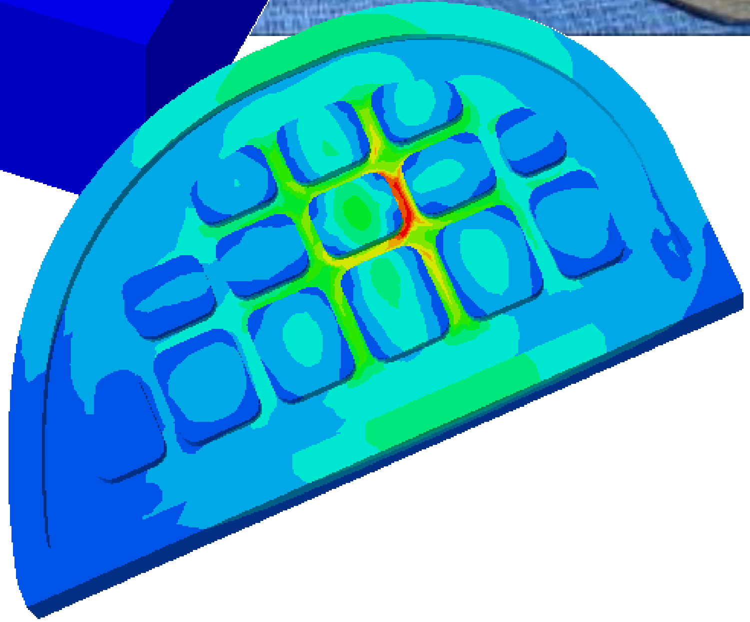
Tray Failure

- 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.

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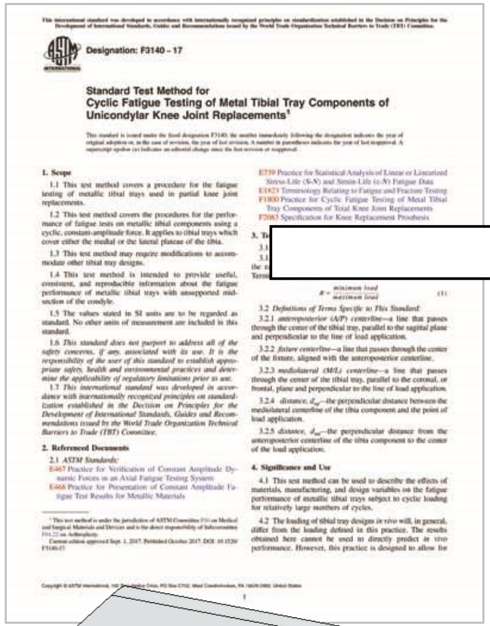
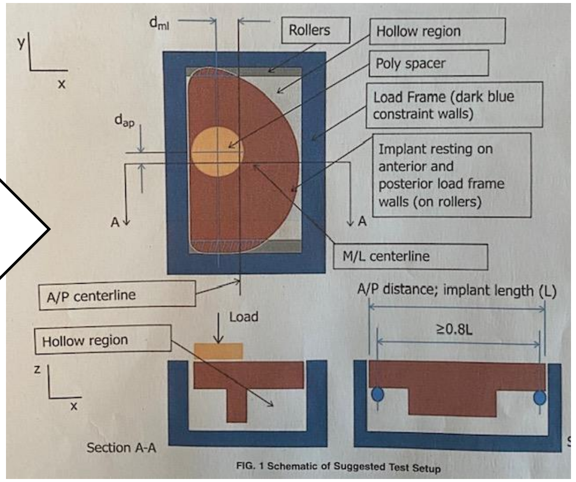
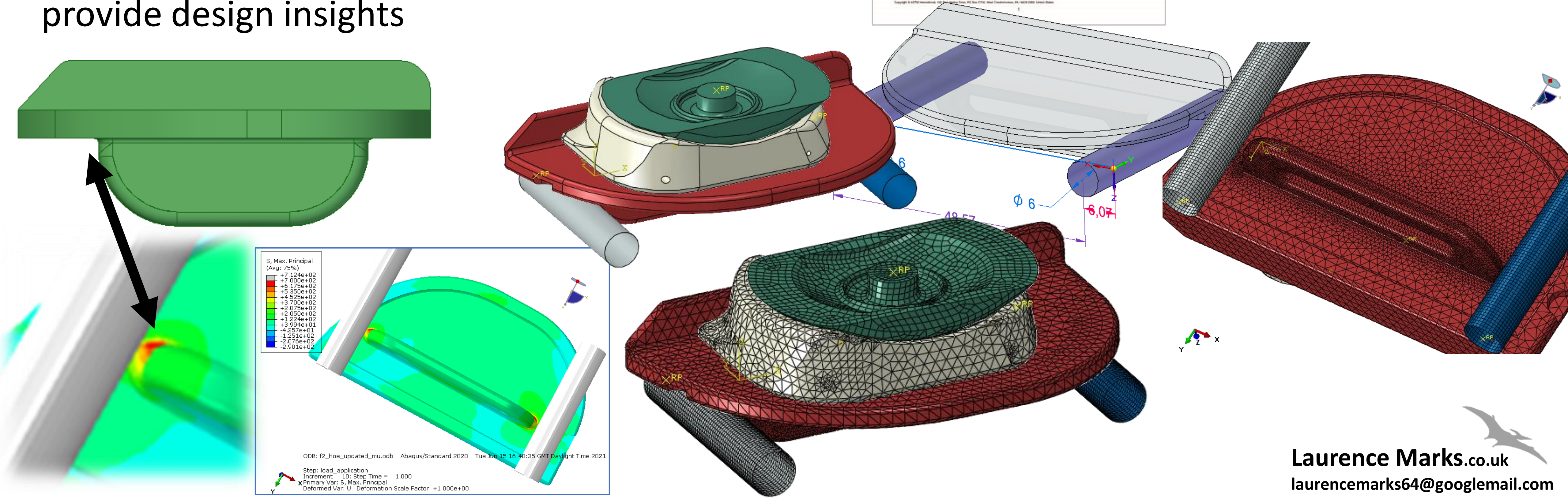
ASTM testing and simulation

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







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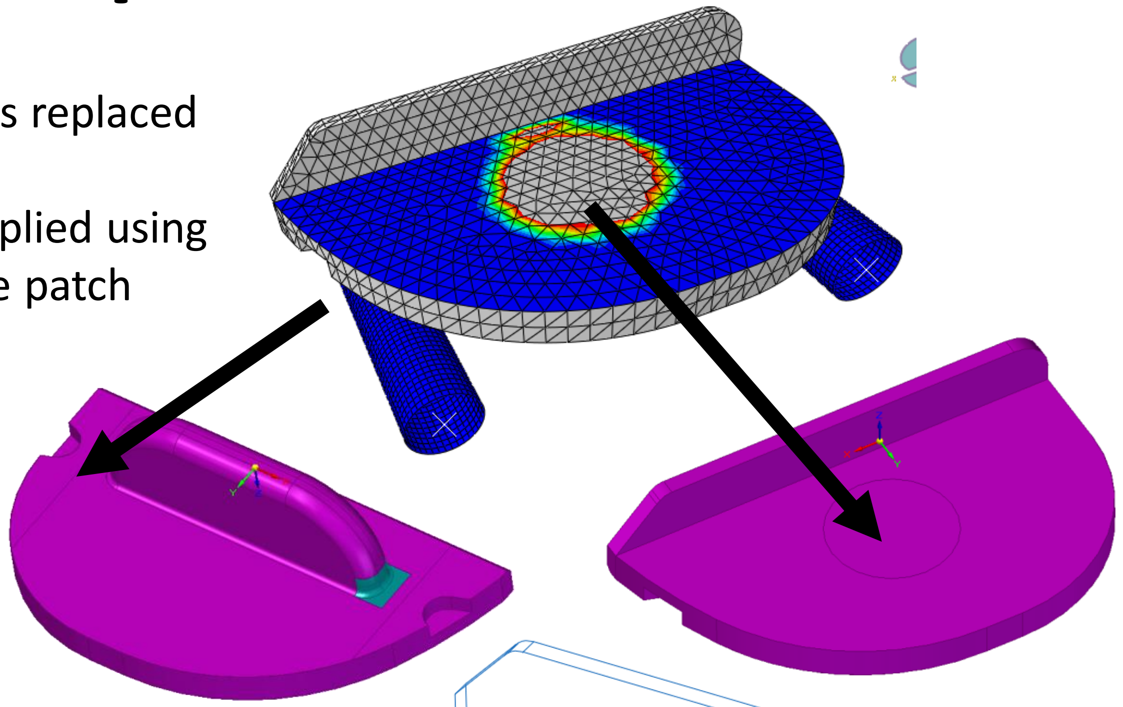
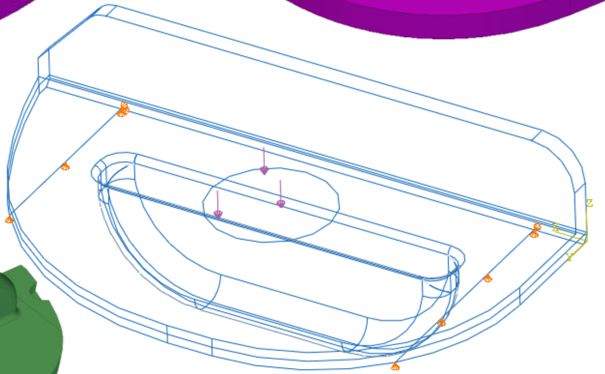
To optimise the design we need rapid solution

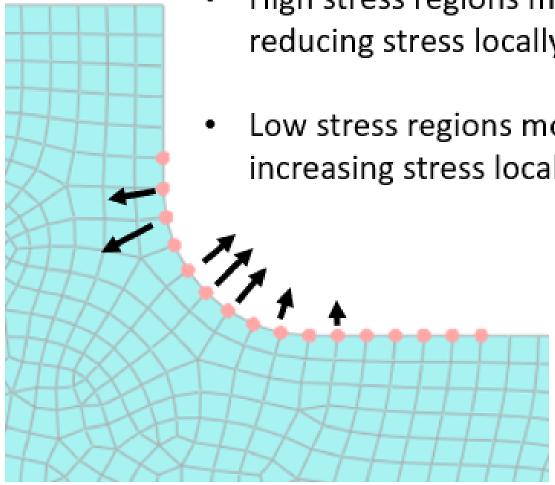
- Solution timescales fall from 4-24hrs to several minutes.
- Very small difference in results quality
- Which then allows us to use shape optimisation approaches (in this case non-parametric shape optimisation)

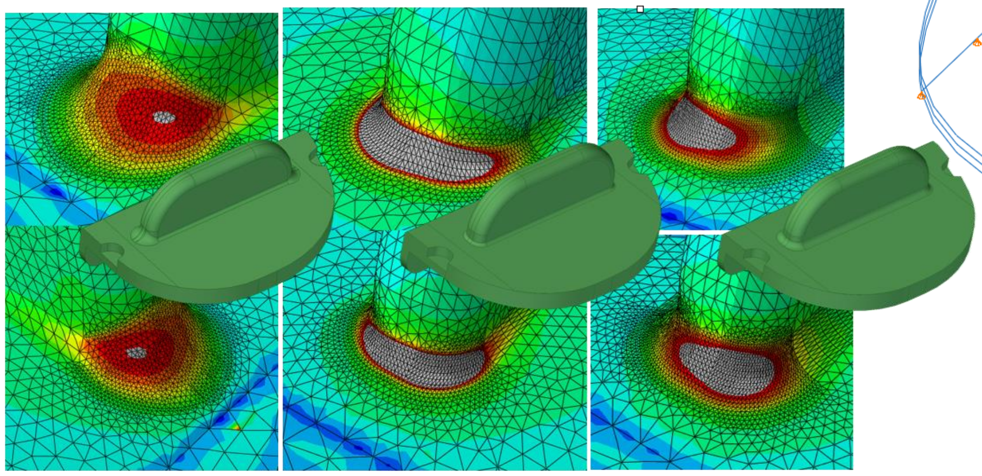
Supports replaced by BC's
Load applied using pressure patch





- High stress regions move out, reducing stress locally
- Low stress regions move in, increasing stress locally





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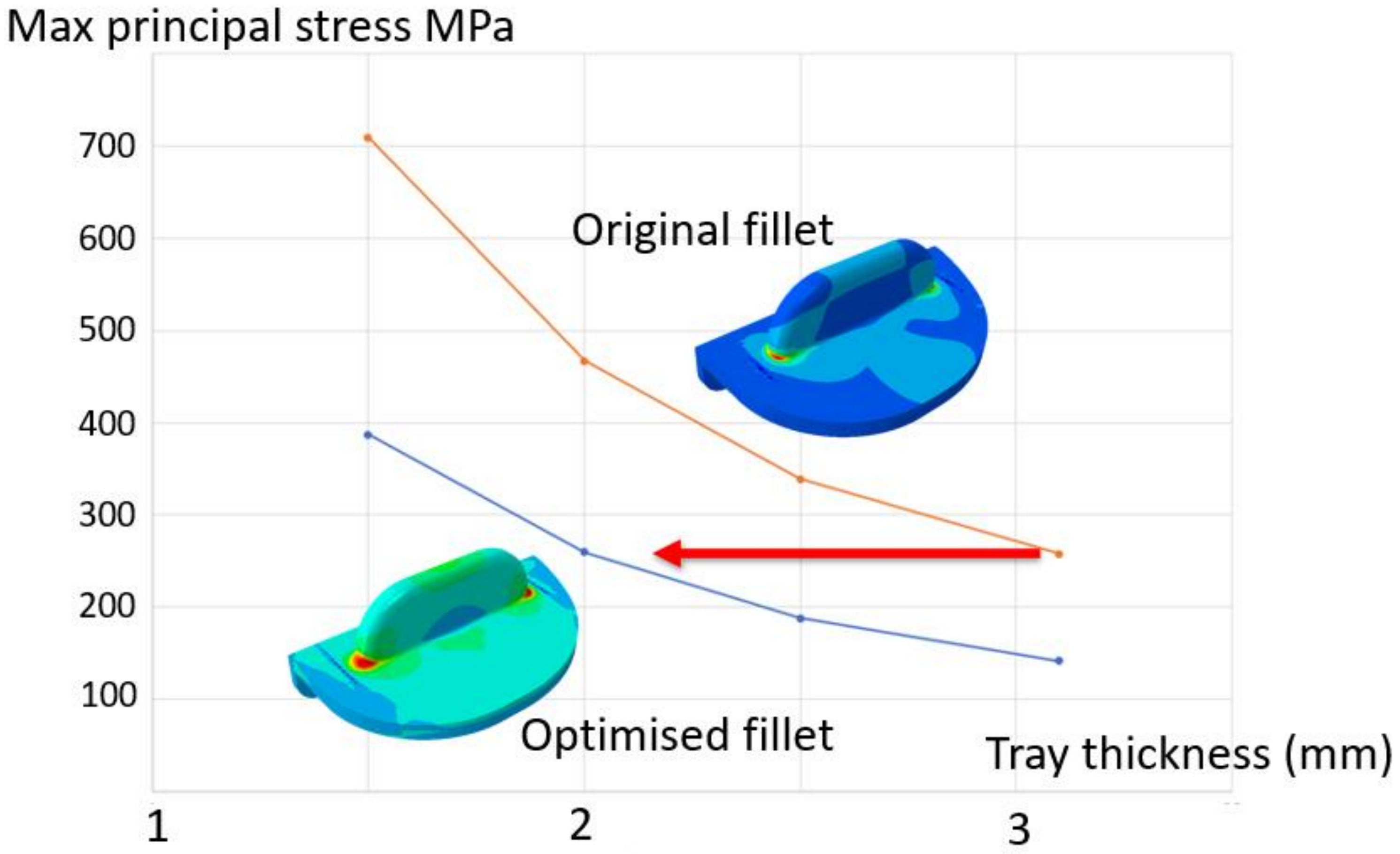
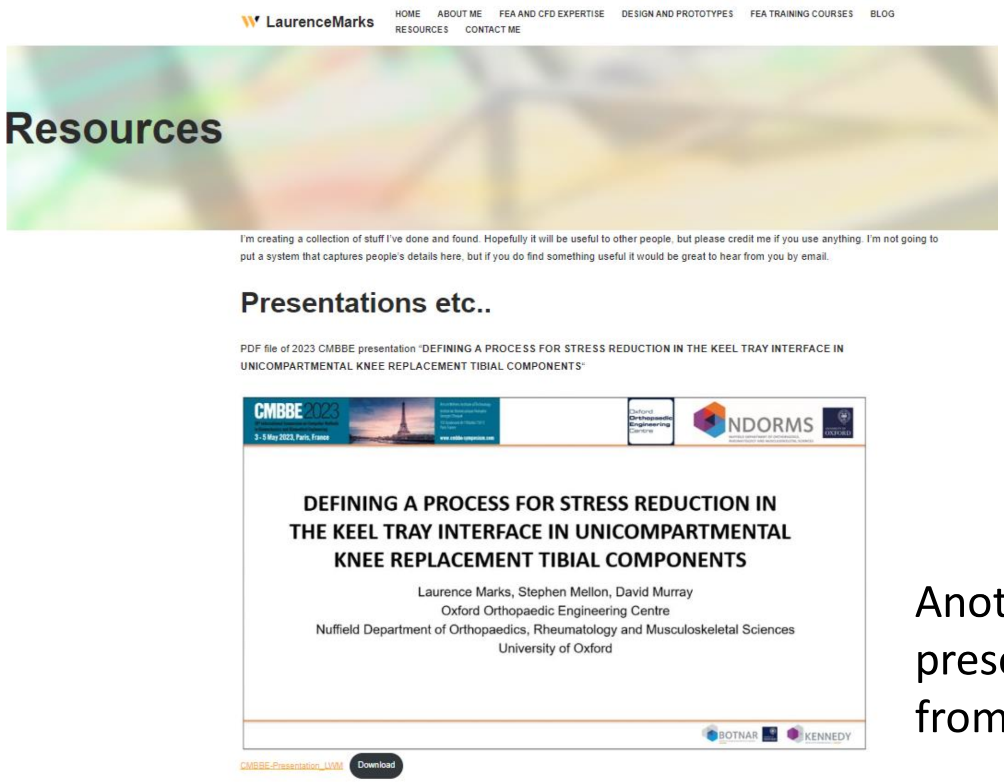
Modelling decisions have unlocked design variability

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





Another, more complete presentation is downloadable from my website.

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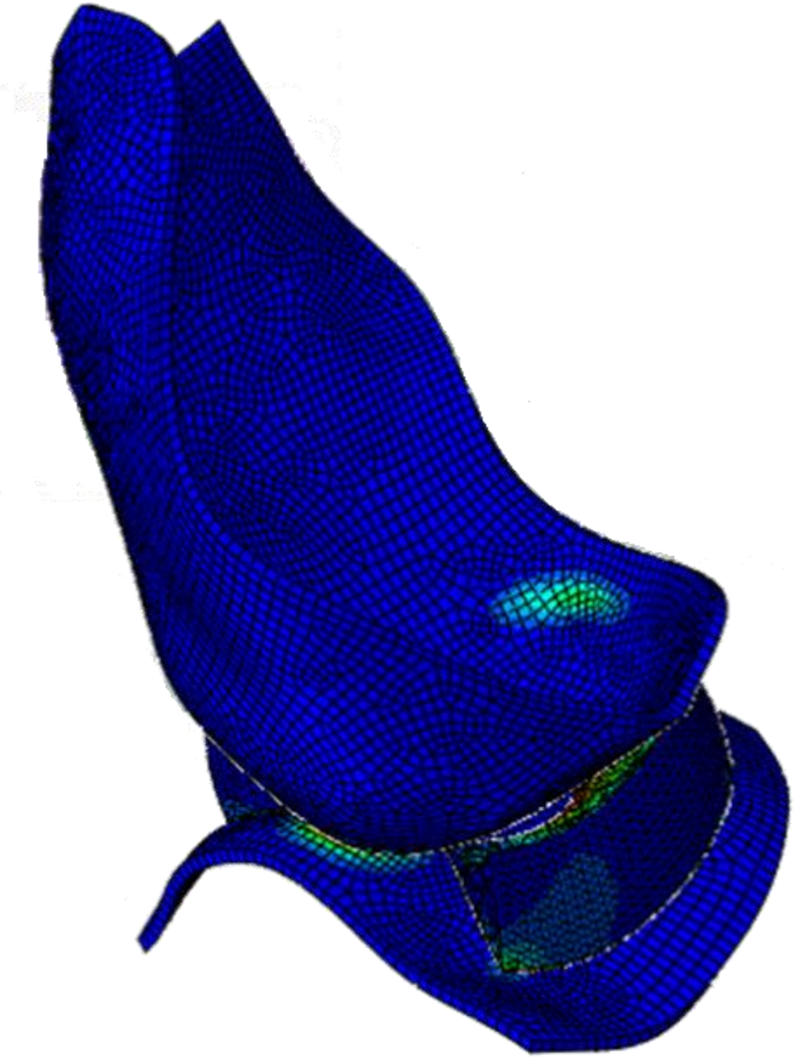
In summary

- 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…



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