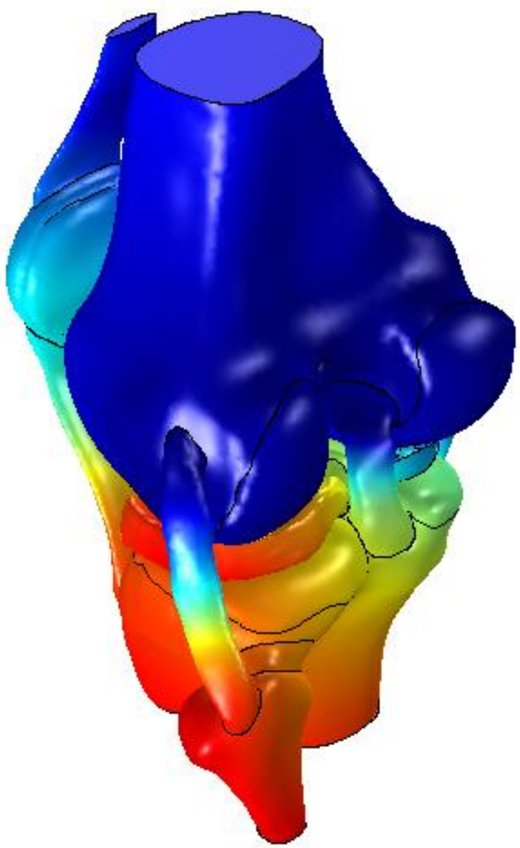
COMSOL CONFERENCE
2017 ROTTERDAM

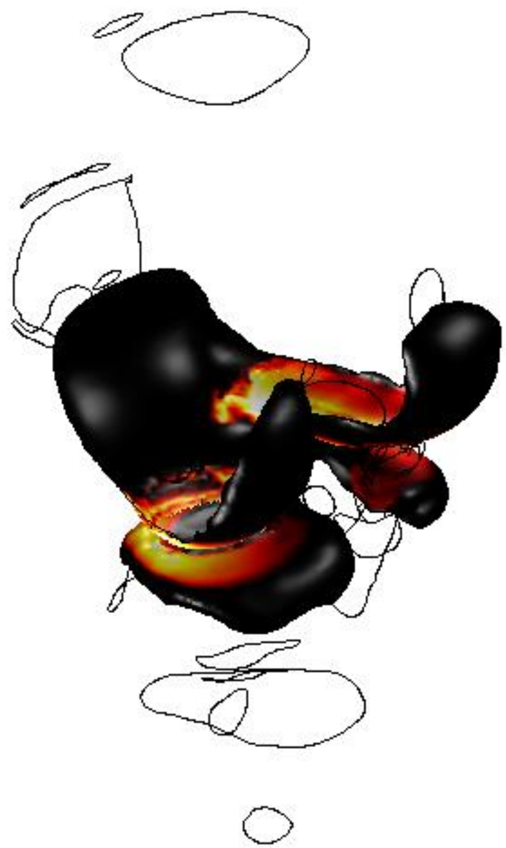
Investigating the loading behaviour of intact & meniscectomy knee joints & the impact on surgical decisions

M S Yeoman PhD[1]
1. Continuum Blue Limited, One Caspian Point, Caspian Way, CF10 4DQ, United Kingdom

Presenter: Mark Yeoman PhD

Date: 19 October 2017





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Address: 1 Caspian Point
Caspian Way
Cardiff Bay
Cardiff
CF10 4DQ
United Kingdom

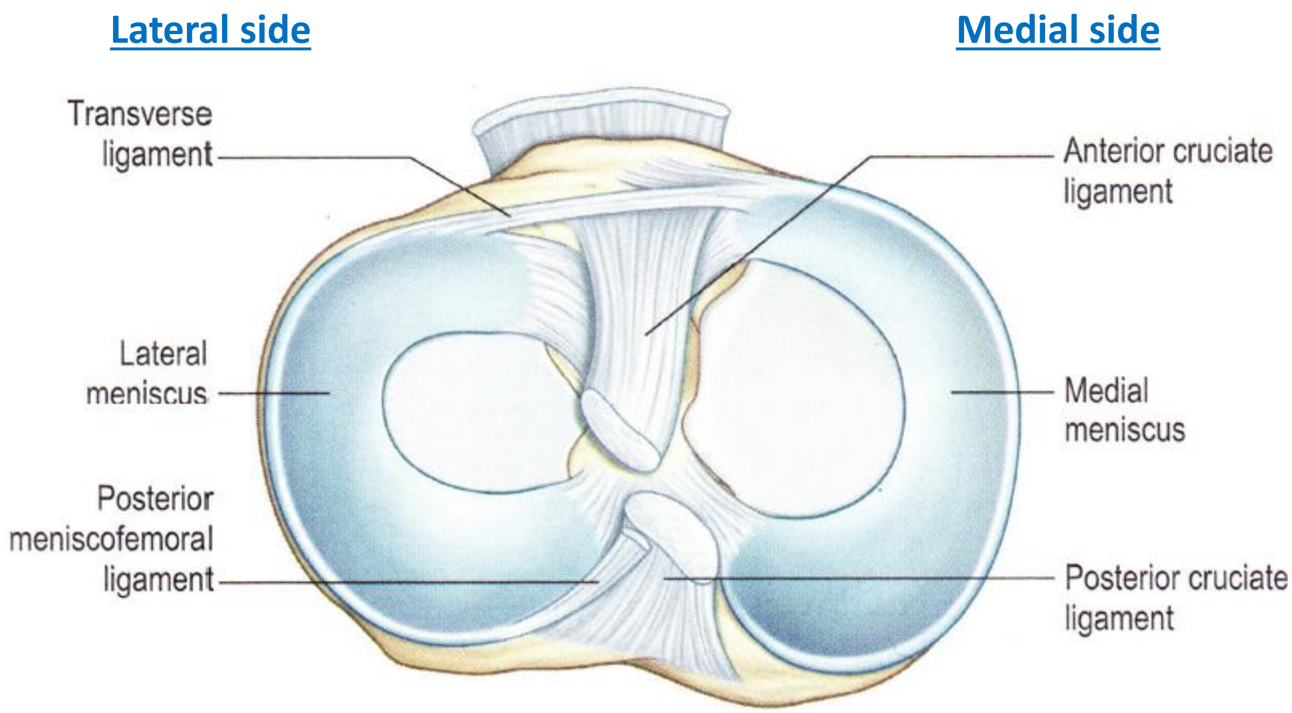
E-mail: info@continuum-blue.com
Website: www.continuum-blue.com
Telephone: +44 (0) 2920 444 033

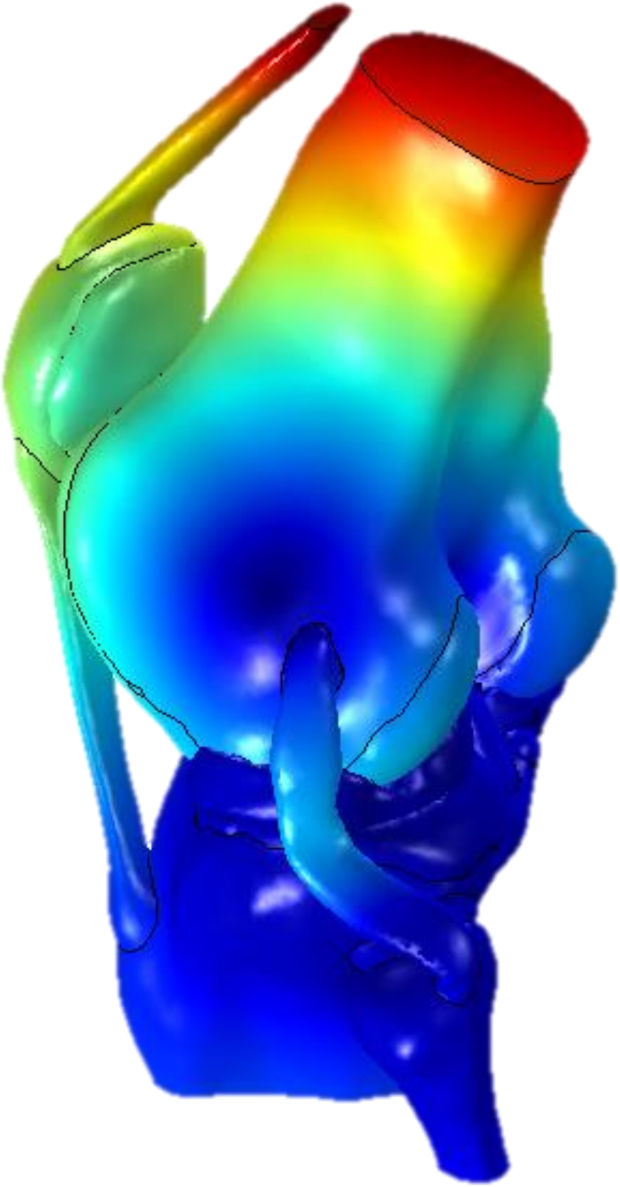
COMSOL Certified Consultant

MENISCI

LATERAL & MEDIAL

The meniscus is a crescent-shaped fibrocartilaginous structure that lies between the cartilage of the femur and tibia of the knee joint. Two menisci are present in each knee joint, one medial and one lateral, together they cushion & stabilize the knee[1].





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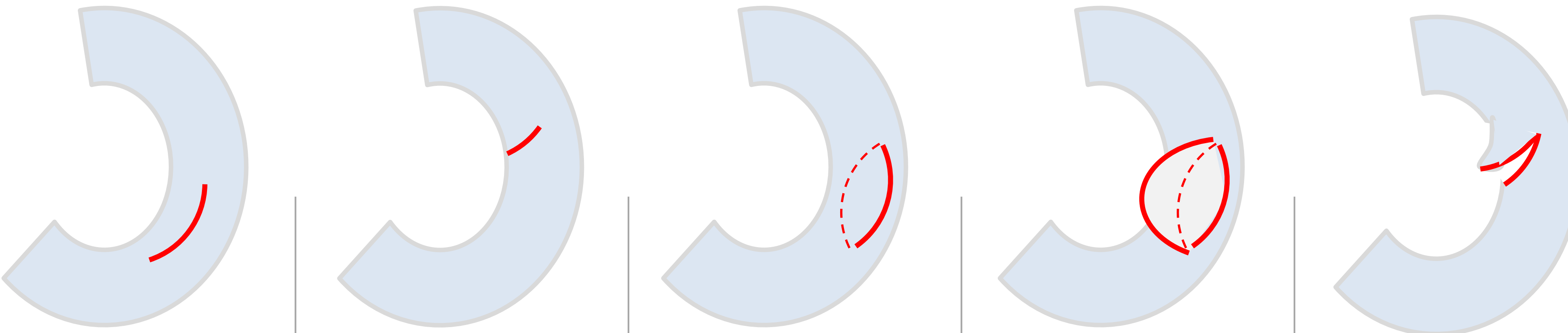
Menisci Tears & Repair

Healing vs. Non-Healing

Peripheral (outer rim) tears are highly vascularized and thus have the potential to heal. Inner rim tears which lack a good blood supply do not tend to heal.

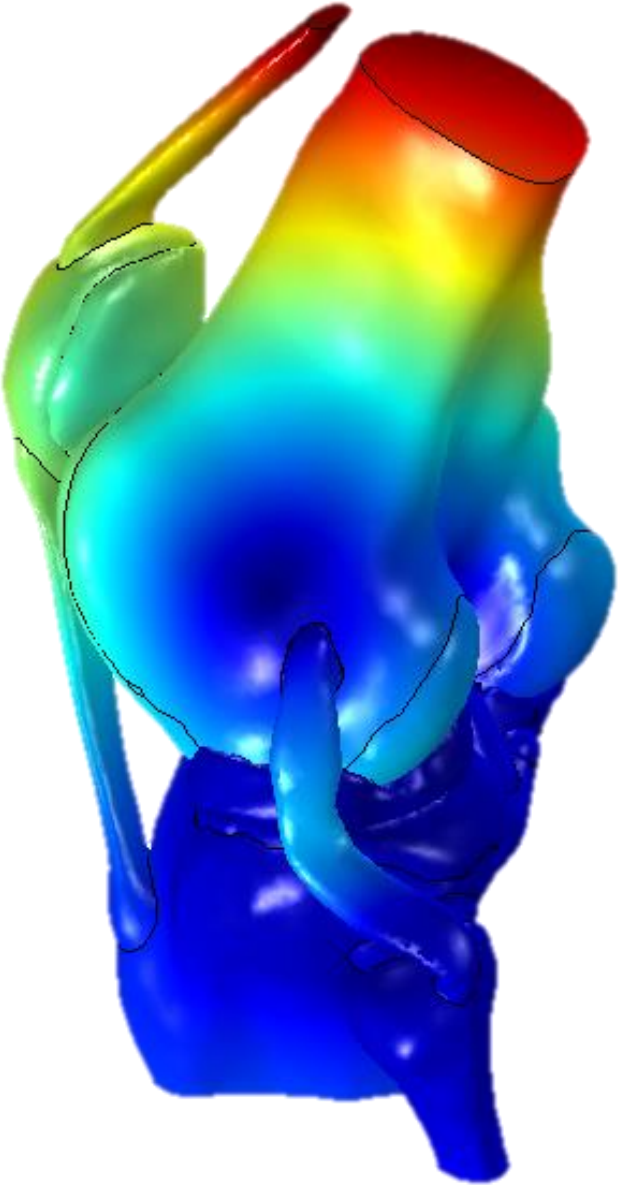
Medial meniscus



Longitudinal | Radial | Horizontal | Flap tear | Displaced radial tear

Longitudinal, Radial: Repairable, depending on their location,

Horizontal, Flap tear, Displaced radial tear: Generally not repairable.



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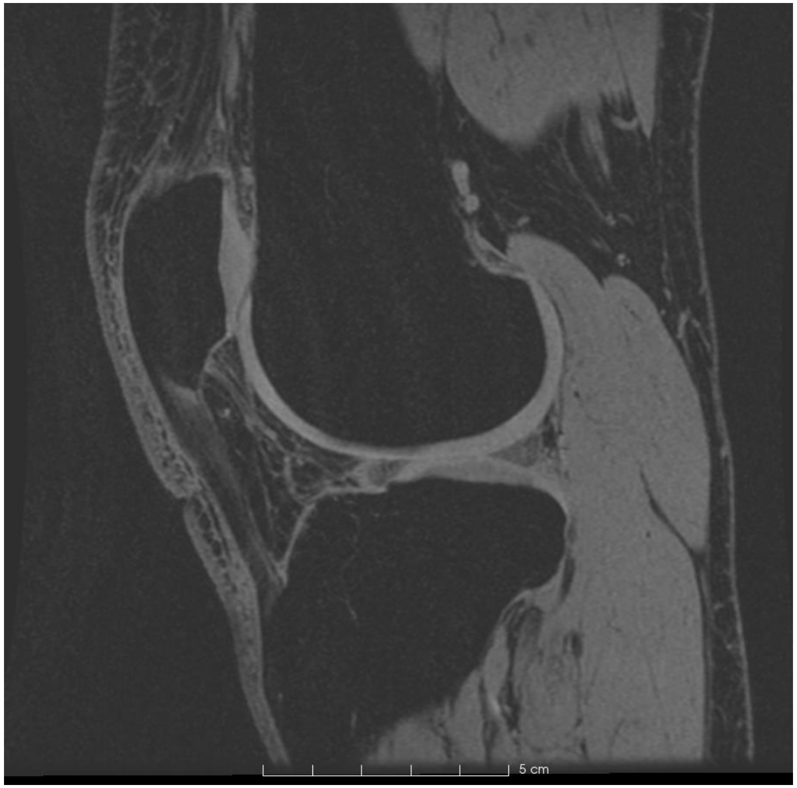
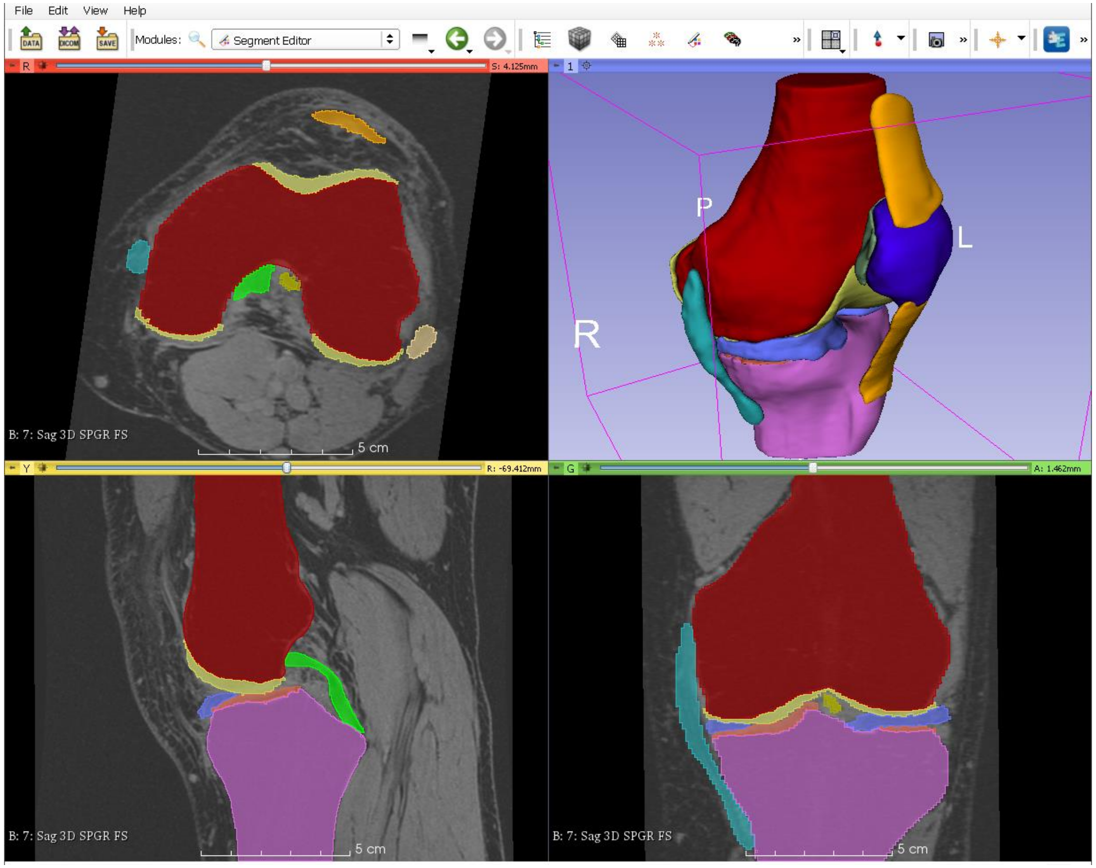
MRI DATA

44 YEAR OLD CAUCASIAN MALE

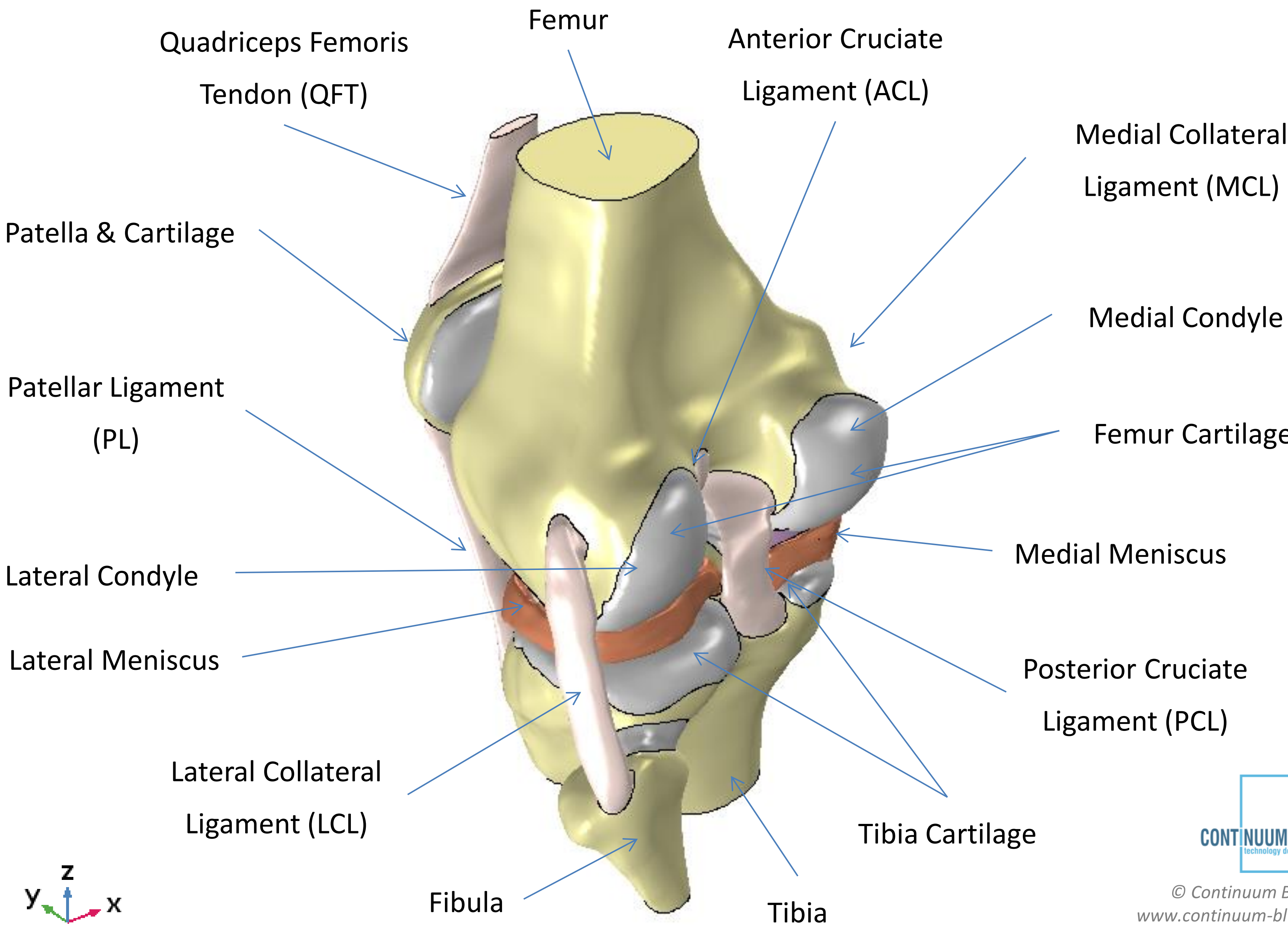
- MRI imaging data was obtained from a 48 year old Caucasian male (weight 78kgs), with no previous history of hip, knee or ankle problems.
- 3D Slicer v4.6 [2-3] software was used to segment the MRI data





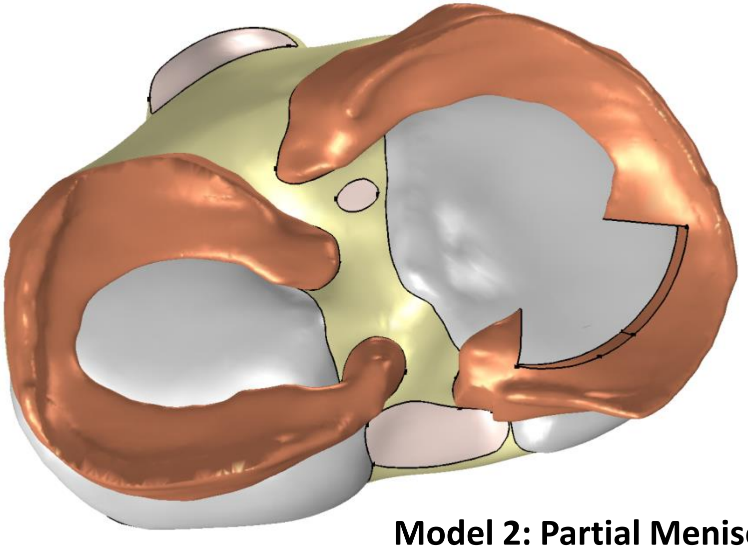
Geometries Included in Model

Knee Domains



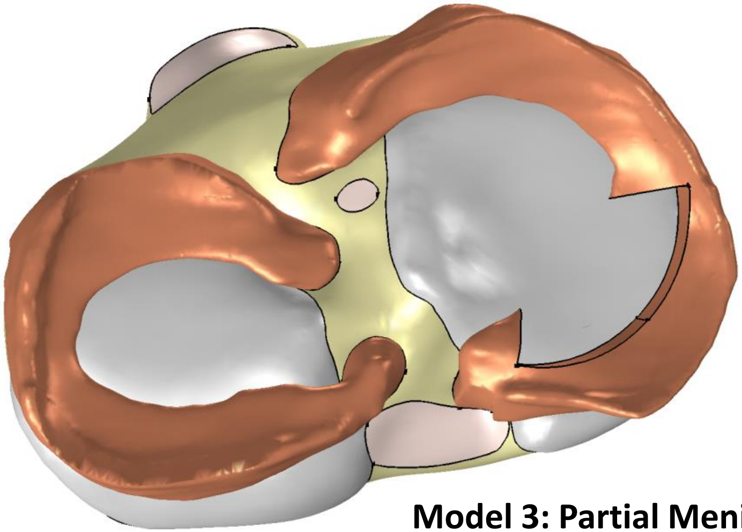
Virtual Surgeries vs. Intact

Resection Lengths & Position



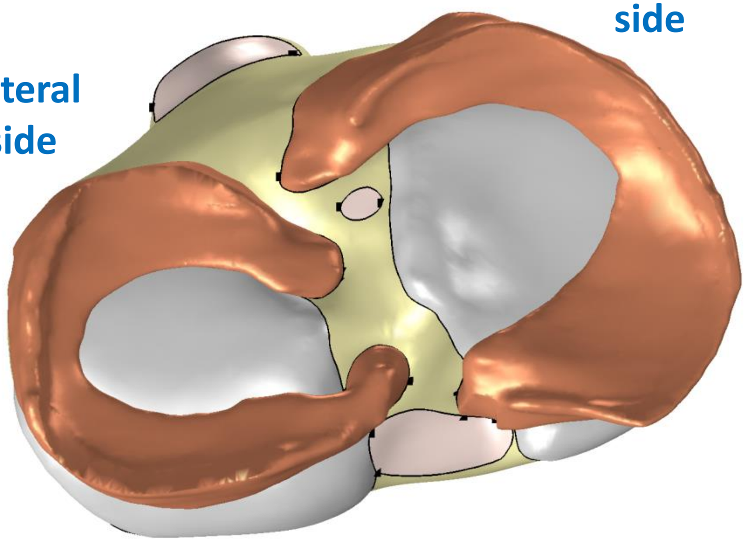
Model 2: Partial Meniscectomy 1

(30mm resection)



Model 3: Partial Meniscectomy 2

(35mm resection)



Model 1: Natural Intact (no-defect)

LOAD & BOUNDARY CONDITIONS

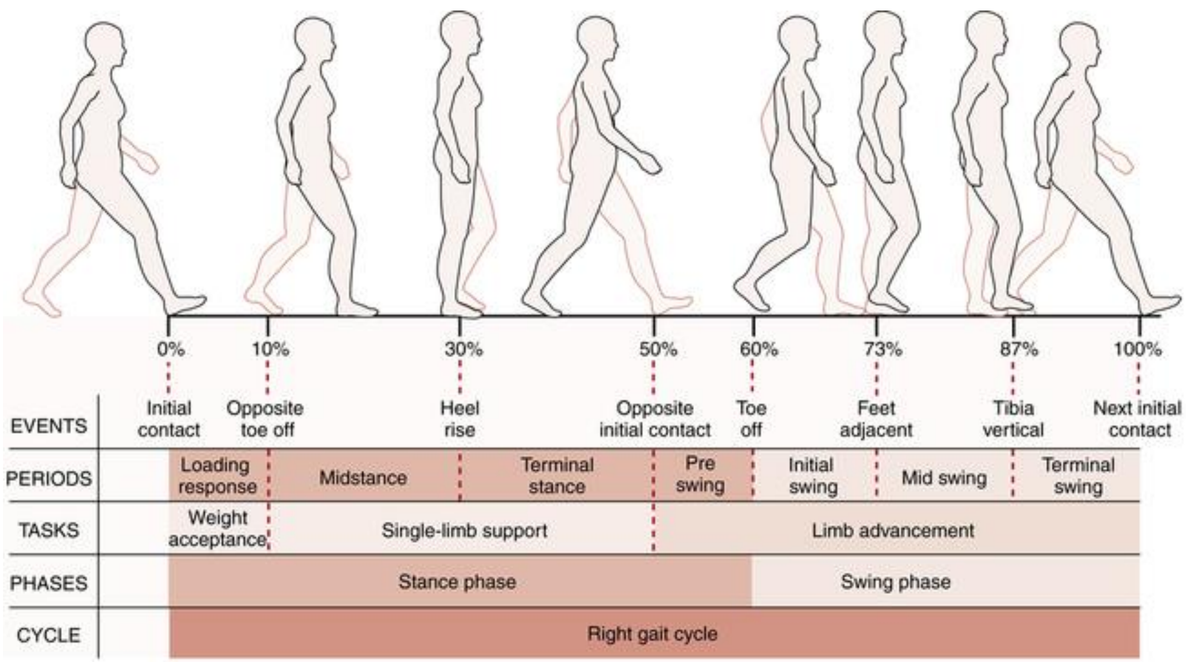
STANDING & GAIT CYCLE

load and boundary conditions applied to the knee model included two load cases, namely:

1. Standing
2. Walking gait

The standing load case assumed zero rotations or moments applied to the femur bony components, and only an axial load is applied from the inferior surfaces of the tibia and fibula. Axial load is equal to half the axial force of the weight of the patient.

The walking gait load case assesses the knee model during a gait cycle (stance and swing).

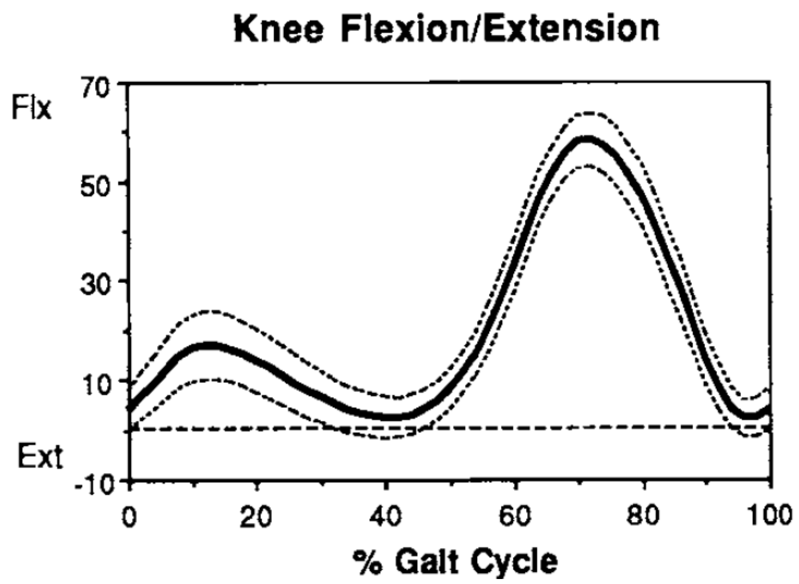


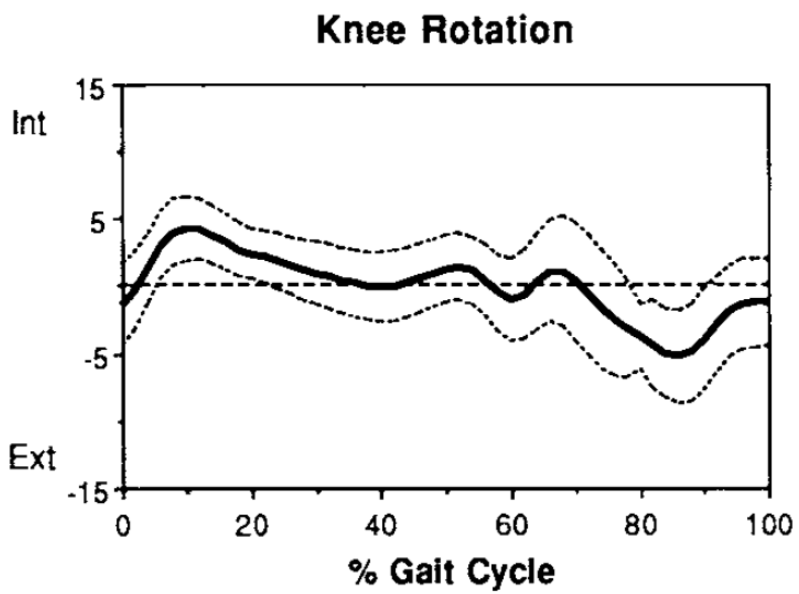
Gait Cycle Boundary Contitions

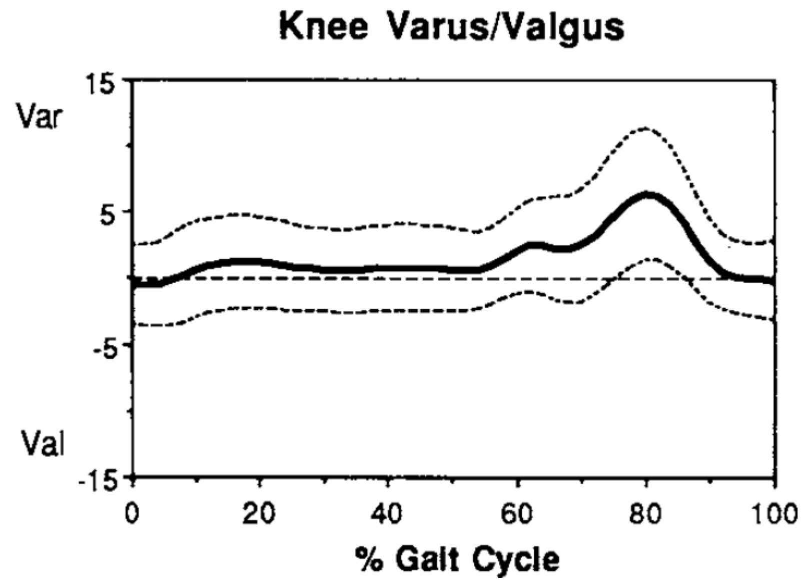
Gait Cycle Rotations

Rotations, including flexion-extension, internal-external and abduction-adduction were applied to the femur, while the tibia is axially loaded in compression and allowed to freely traverse laterally and in the posterior-anterior direction without rotation.

The applied rotations were based on the mean rotations in the three planes (sagittal, coronal and axial) obtained from [16].







Knee Compressive Load during Gait

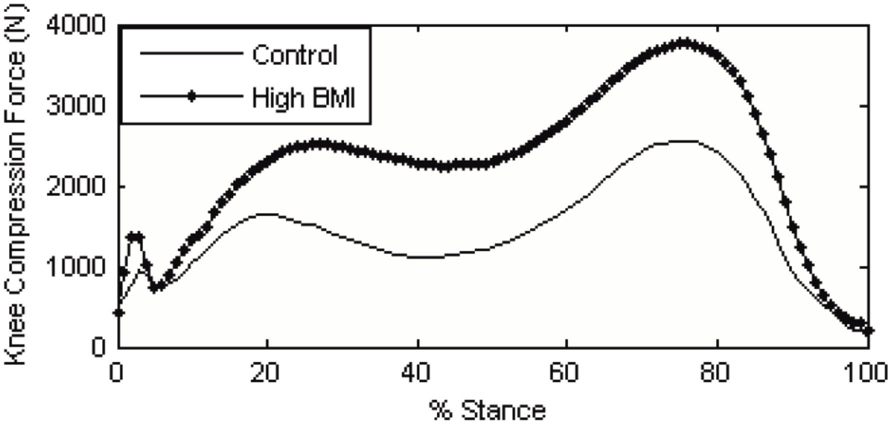
Referenced from Tibia

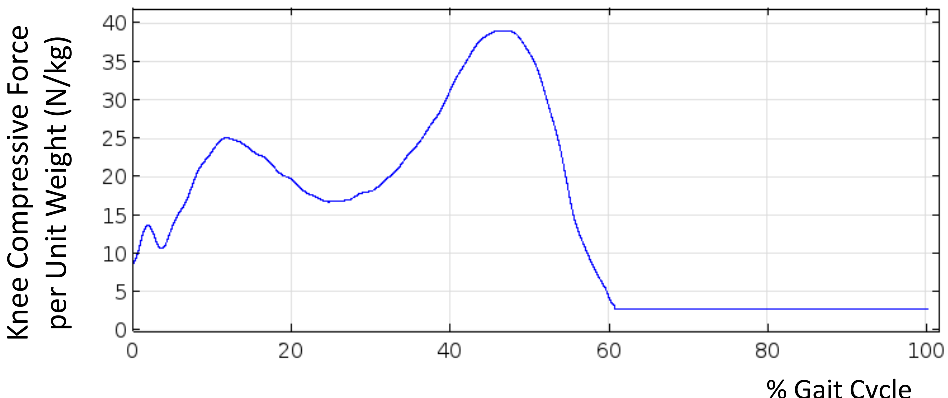
Distal compressive loads were applied on the tibia and fibula inferior surfaces.

Compressive loads are based on the stance phase of the control group from Sanford *et al.* (2014)[14], which are reported in the reference frame of the segment distal (or tibia) to the knee joint.

The average weight of the control group was 65.5 kg[14]. This was used to normalise the compressive force curves & adjust them to the weight of our specific patient weight (78kg).

The stride compressive force curves from [14]





Normalised gait cycle compressive force per unit mass curve utilised in the model

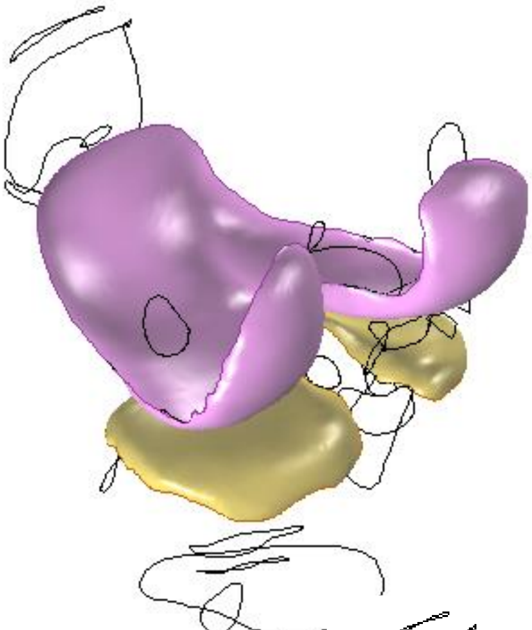
Material Relations

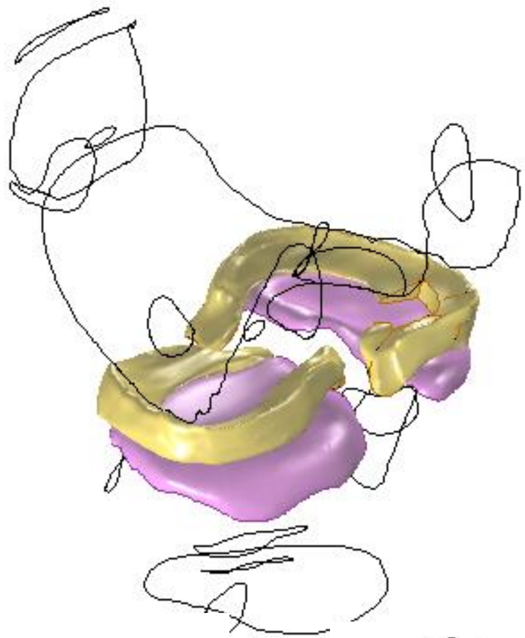
Knee bodies	Material Model	Density (g/cm^3)	Modulus (MPa)	Poisson's Ratio	Reference
Deformable Bony Components (Femur, Tibia, Fibula & Patella)	Linear elastic (isotropic)	2	15×10^3	0.3	[7]
Articular cartilage	Linear elastic (isotropic)	1	15	0.475	[10]
Menisci♣	Linear elastic (orthotropic)	1.5	E_1: 20	ν_{12}: 0.3	[10]
			E_2: 120	ν_{13}: 0.45	
			E_3: 20	ν_{23}: 0.3	
Ligaments♠	Hyper-elastic (neo-Hookean)	1	LCL: 6.06	0.45	[11]
			MCL: 6.43	0.45	
			ACL: 5.83	0.45	
			PCL: 6.06	0.45	
			PL: 5.83	0.45	
			QFT: 5.83	0.45	

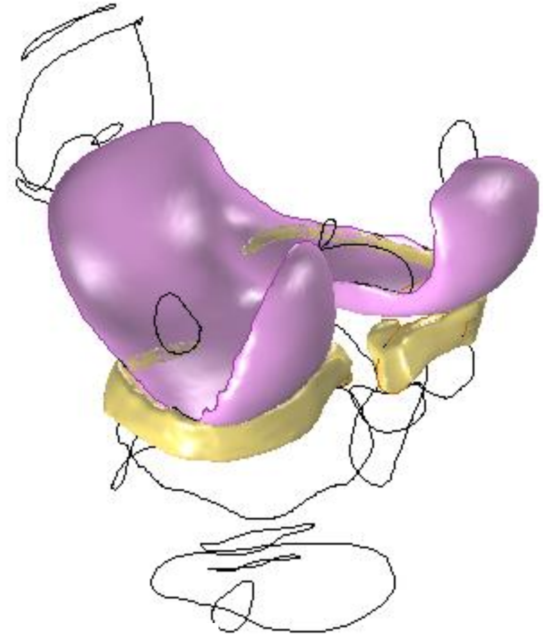
♣ Direction 1 is radial, 2 is circumferential, and 3 is axial
♠ Refer to Figure 2 for acronyms for specific ligaments

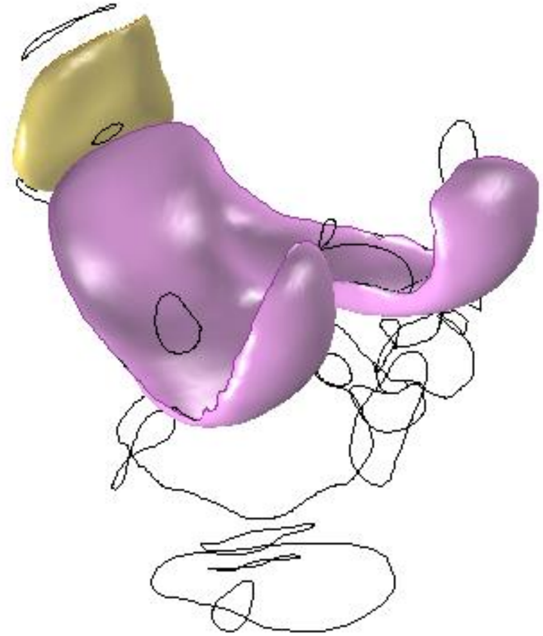
CONTACT SETS

FRICTIONLESS





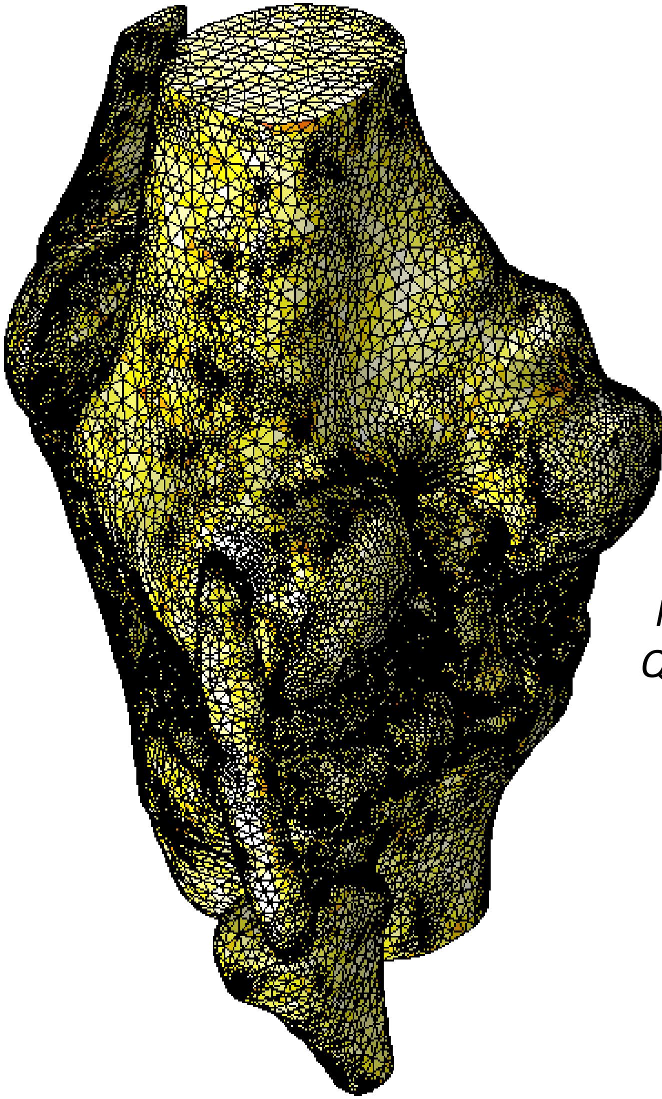


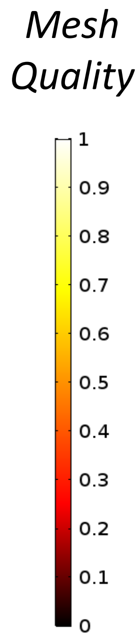


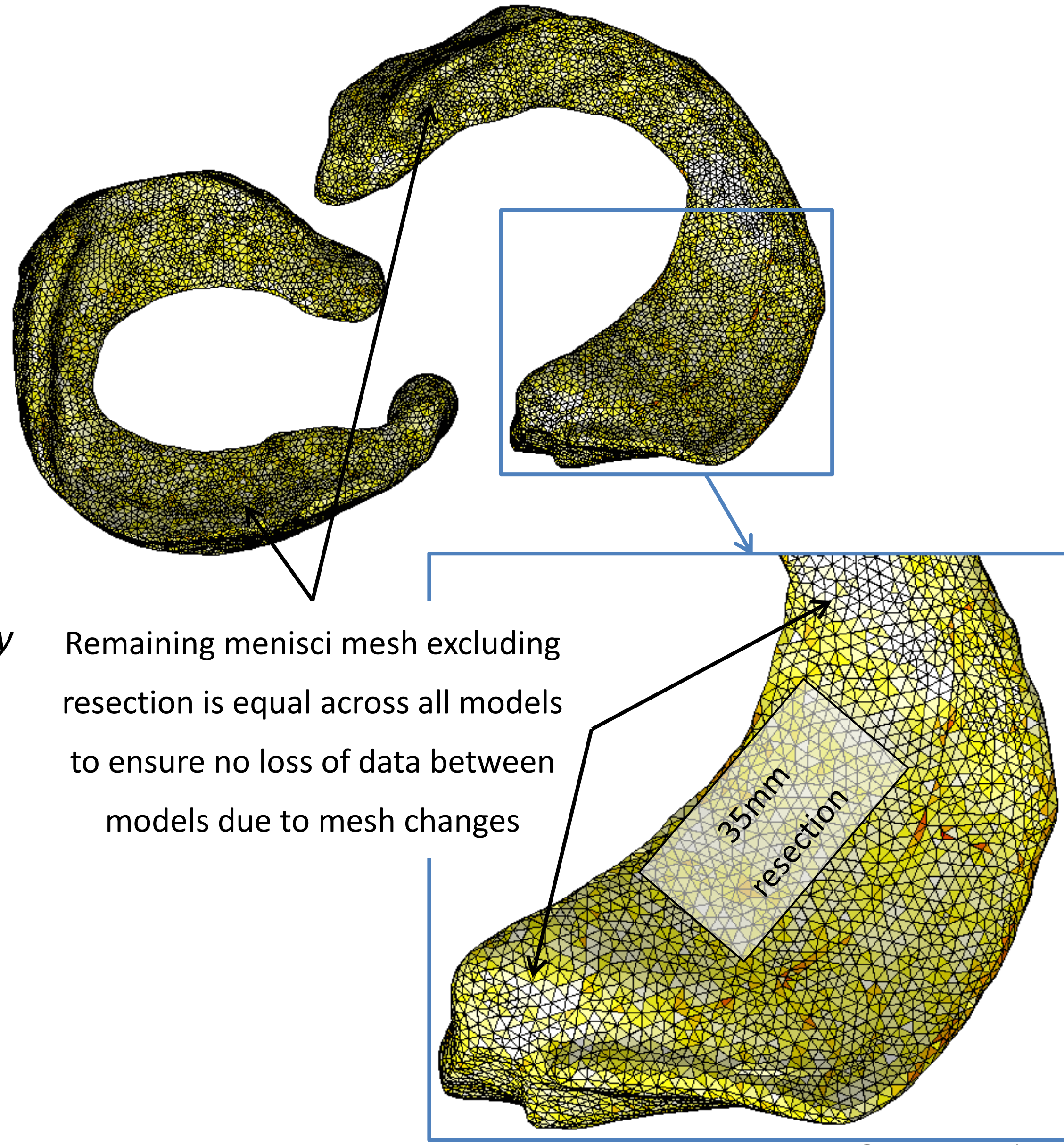
Contact set between all articulating surfaces, including between ligaments & cartilage

Mesh

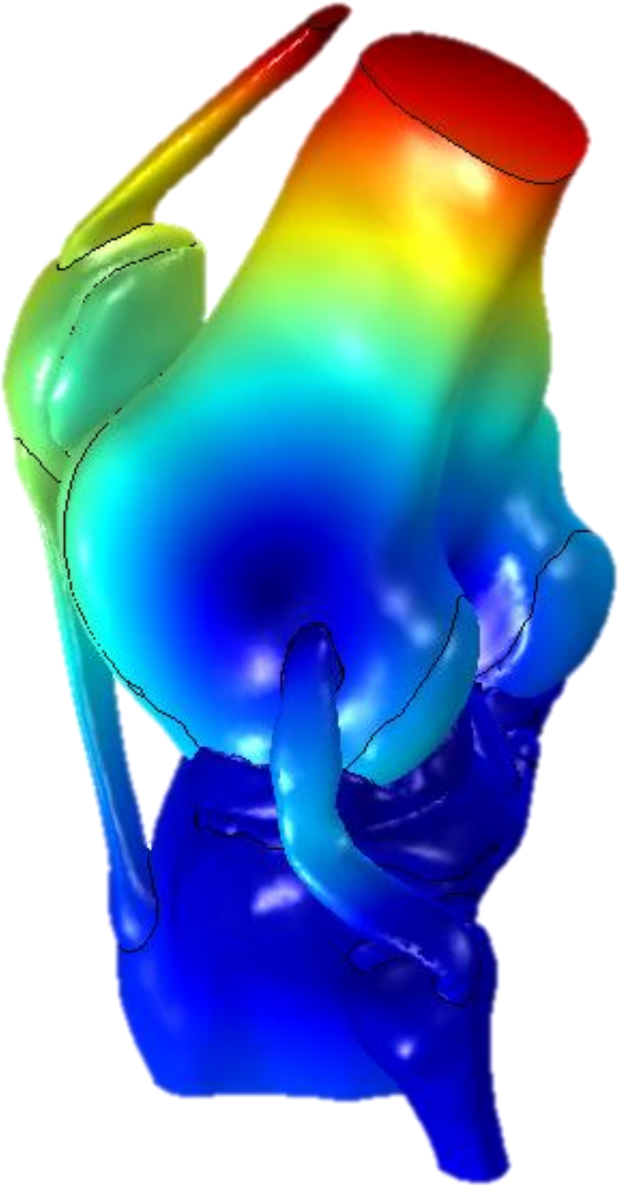
High Quality & Highly Refined Around Cartilage







Remaining menisci mesh excluding resection is equal across all models to ensure no loss of data between models due to mesh changes



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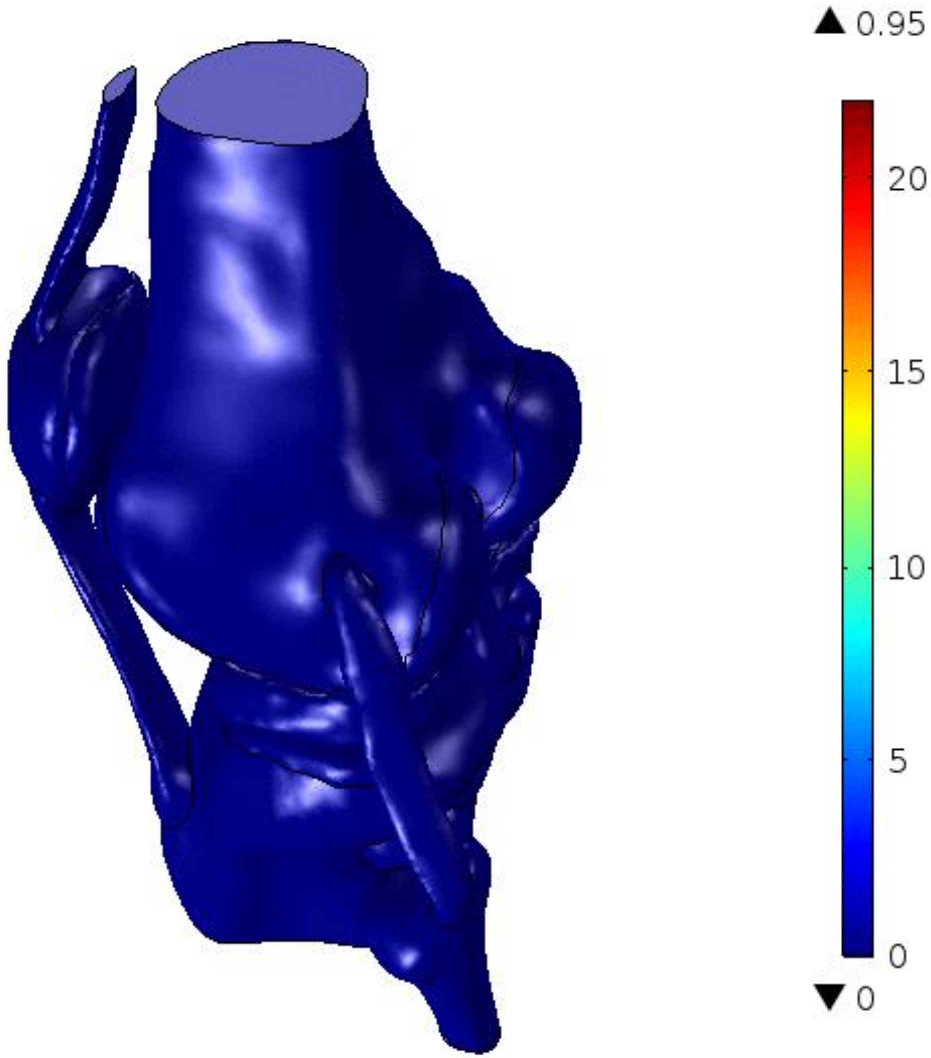
Gait Cycle Displacement

Animation



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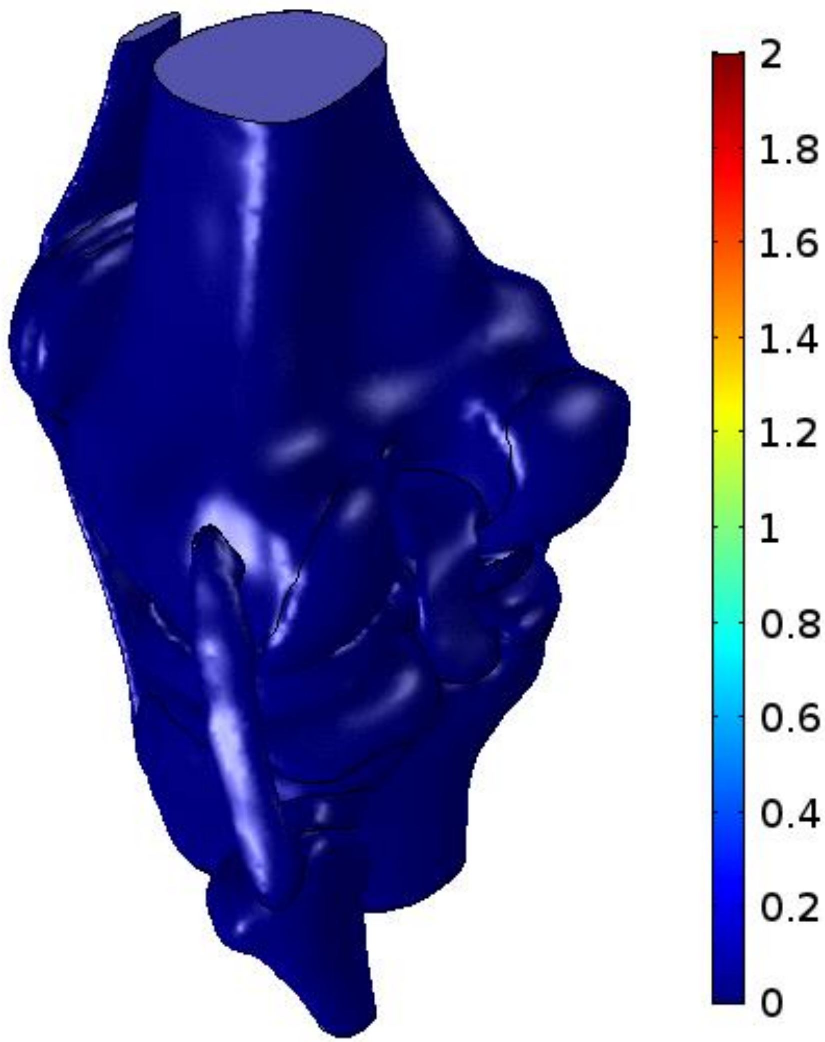
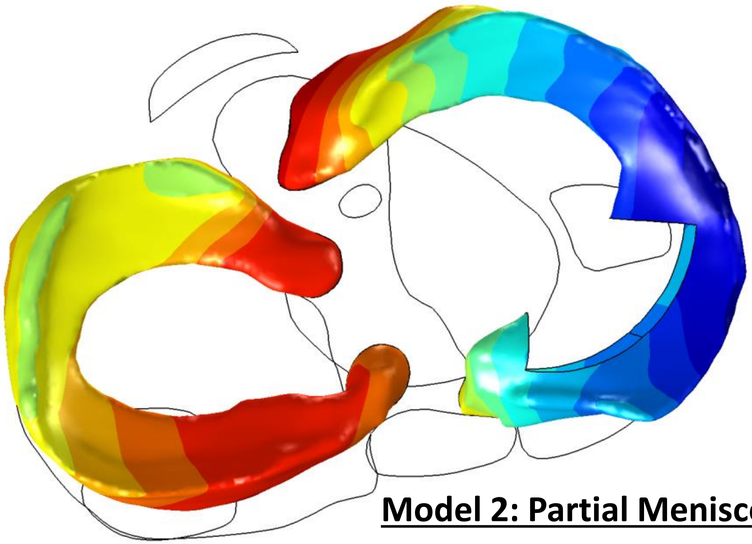
Standing Case Displacement

Animation

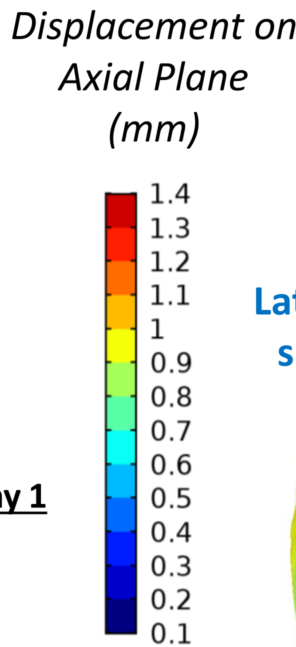


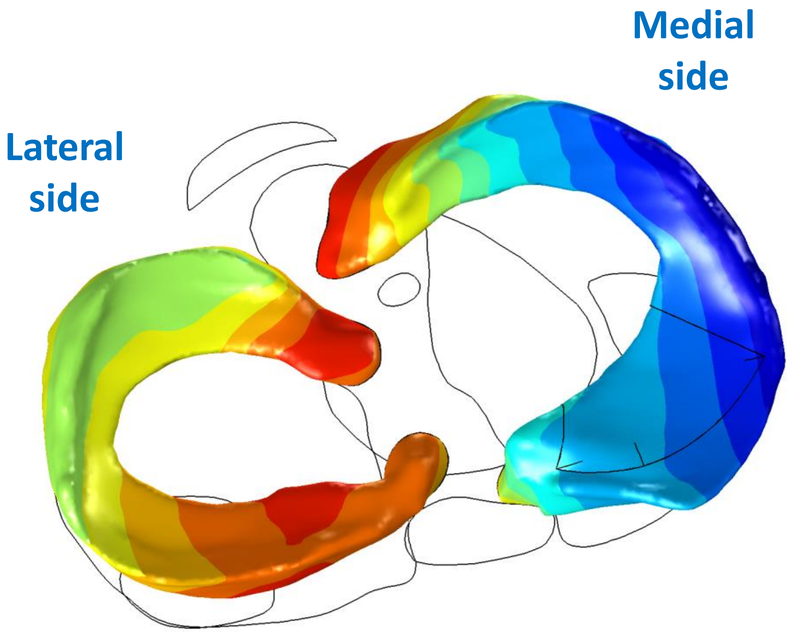
Axial Plane Movement

AP & ML Displacement

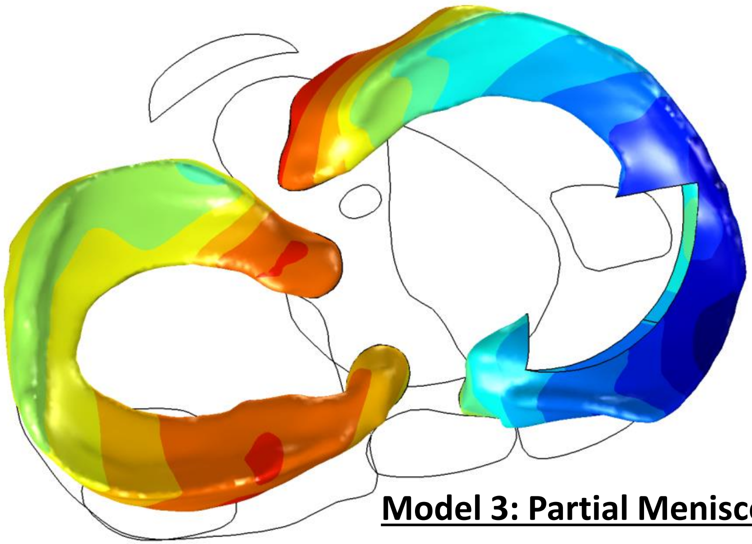


Model 2: Partial Meniscectomy 1 (30mm resection)



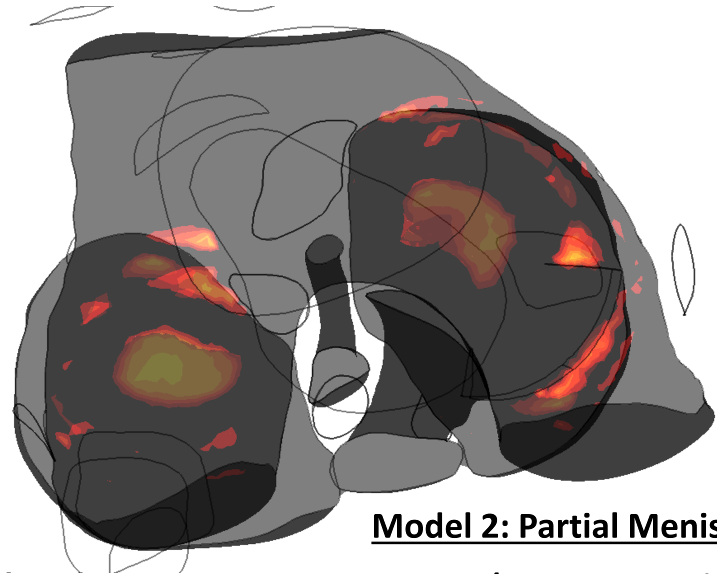


Model 1: Natural Intact (no-defect)



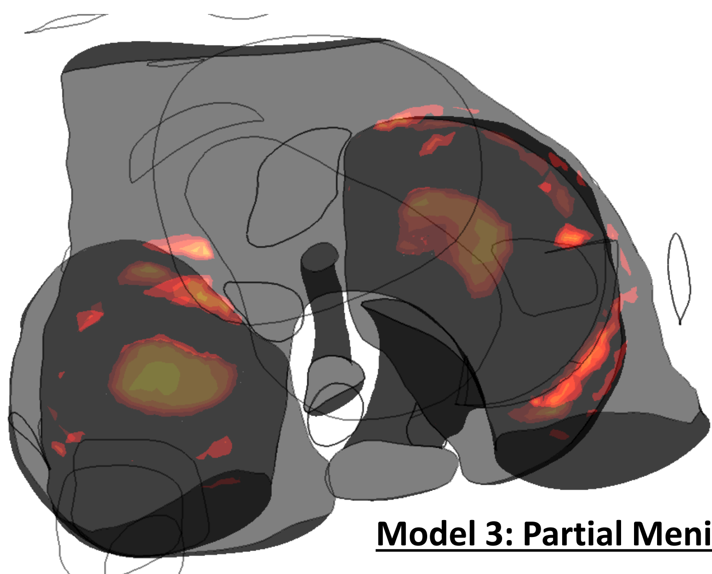
Model 3: Partial Meniscectomy 2 (35mm resection)

Contact Pressure on Articulating Surfaces



Model 2: Partial Meniscectomy 1

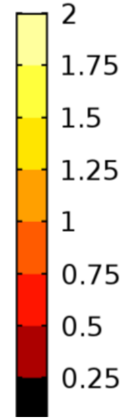
(30mm resection)

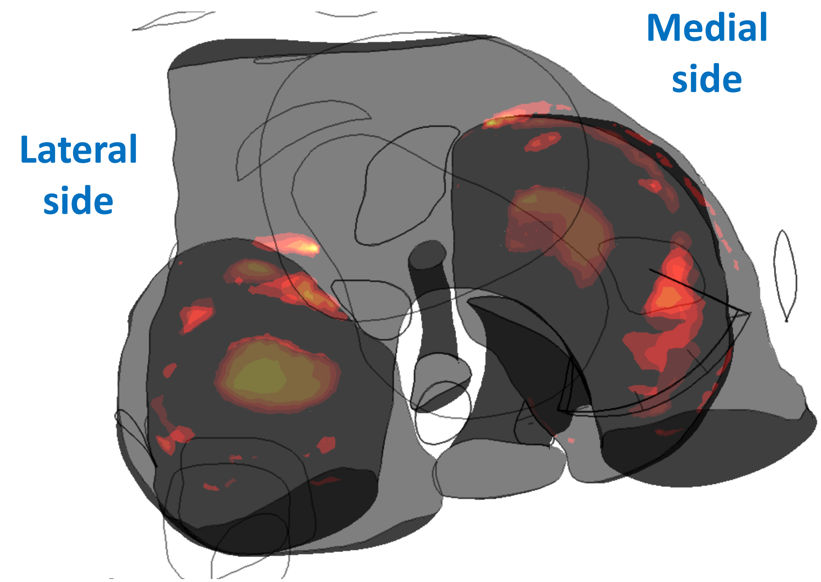


Model 3: Partial Meniscectomy 2

(35mm resection)

Contact Pressure (MPa)

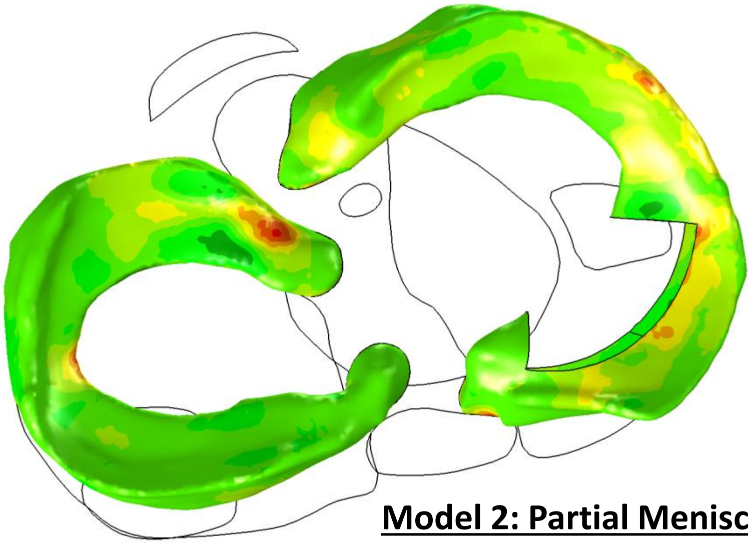




Model 1: Natural Intact (no-defect)

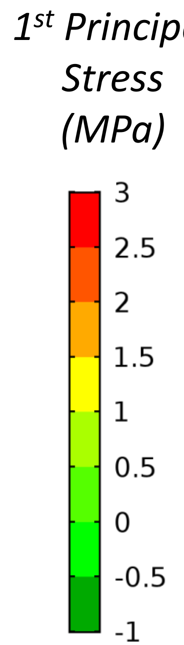
1ST PRINCIPAL STRESS

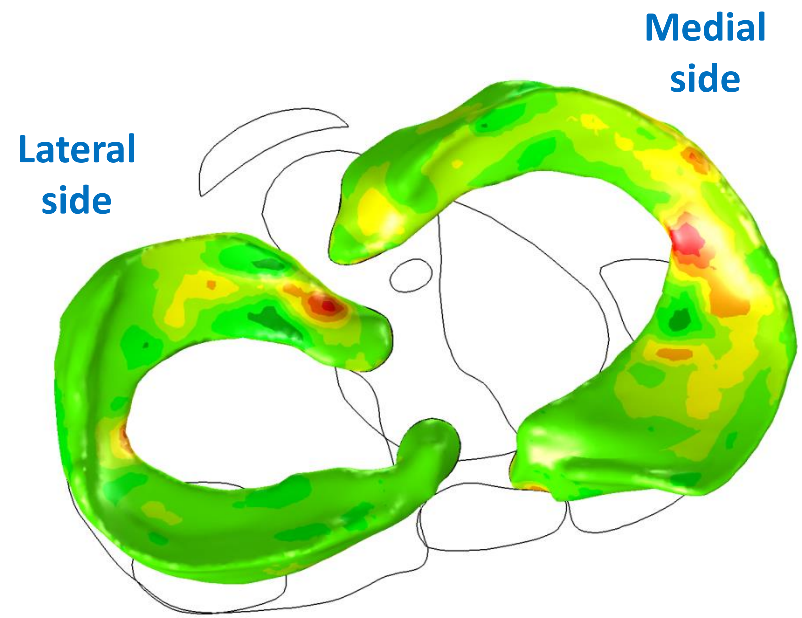
MAXIMUM TENSILE



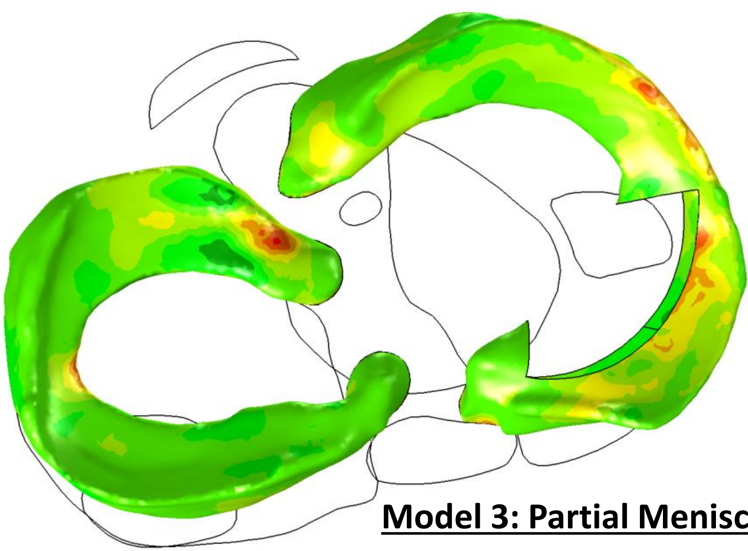
Model 2: Partial Meniscectomy 1

(30mm resection)





Model 1: Natural Intact (no-defect)



Model 3: Partial Meniscectomy 2

(35mm resection)

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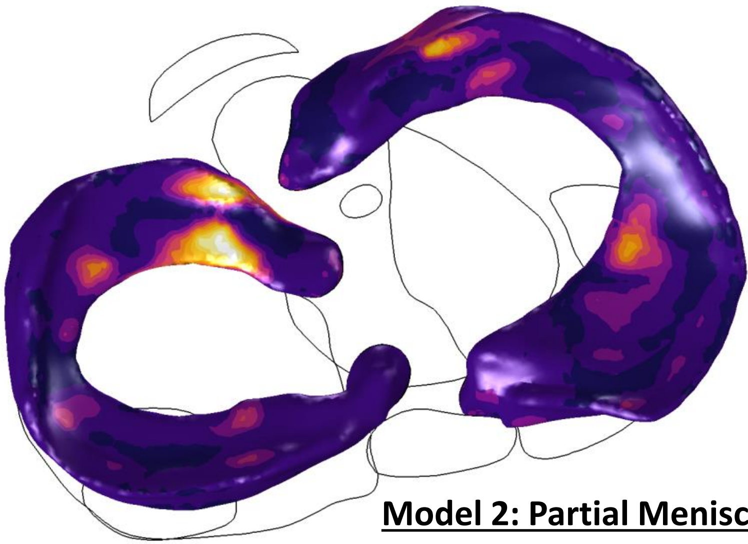
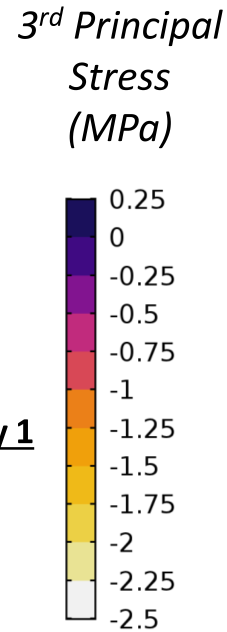
3RD PRINCIPAL STRESS

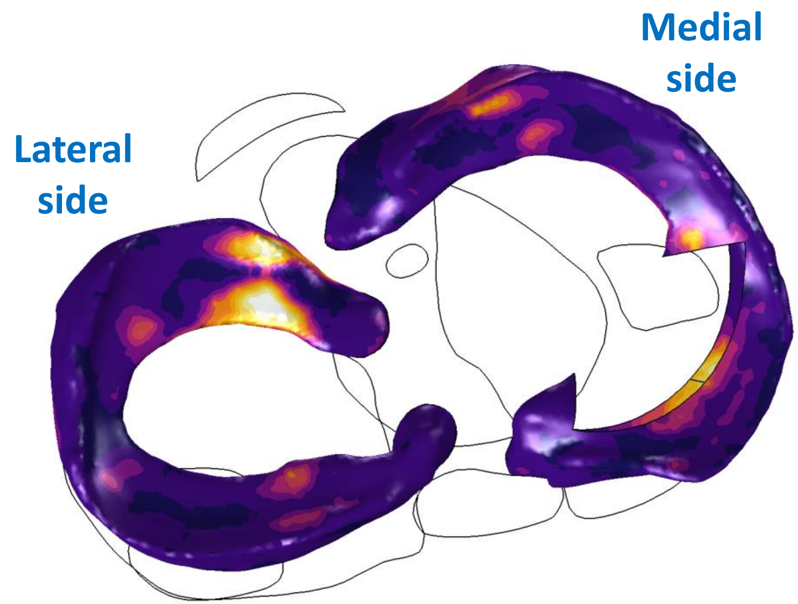
MAXIMUM COMPRESSIVE



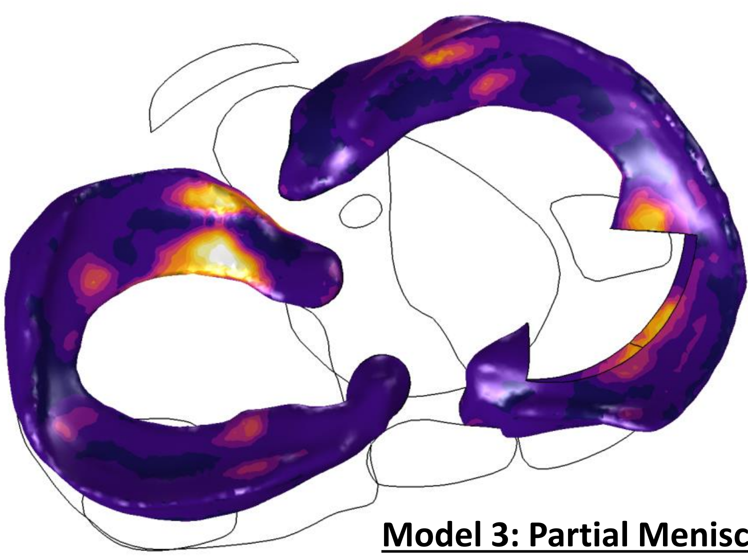
Model 2: Partial Meniscectomy 1

(30mm resection)





Model 1: Natural Intact (no-defect)



Model 3: Partial Meniscectomy 2

(35mm resection)

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TABULATED DATA

CONTACT PRESSURE, STRESSES, DISPLACEMENTS

Section	Model	Contact Pressure Between Various Bodies						Anterior-Posterior & Lateral-Medial Displacement Magnitudes				1st Principal stresses			
		Medial Menisci & Tibia Cartilage		Femur & Tibia Cartilage		Lateral Menisci & Tibia Cartilage		Medial Meniscus		Lateral Meniscus		Medial Meniscus		Lateral Meniscus	
		Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max
Standing Load Results	Natural	0.05 MPa	0.82 MPa	0.05 MPa	1.90 MPa	0.02 MPa	1.22 MPa	0.66 mm	1.30 mm	1.05 mm	1.30 mm	0.36 MPa	8.20 MPa	0.21 MPa	5.78 MPa
	Partial Meniscectomy (30mm Resection)	0.04 MPa	1.07 MPa	0.05 MPa	1.46 MPa	0.02 MPa	1.11 MPa	0.65 mm	1.37 mm	1.11 mm	1.35 mm	0.37 MPa	9.14 MPa	0.20 MPa	6.08 MPa
	Partial Meniscectomy (35mm Resection)	0.04 MPa	1.08 MPa	0.05 MPa	1.34 MPa	0.02 MPa	1.11 MPa	0.64 mm	1.27 mm	1.04 mm	1.24 mm	0.38 MPa	10.48 MPa	0.19 MPa	6.57 MPa

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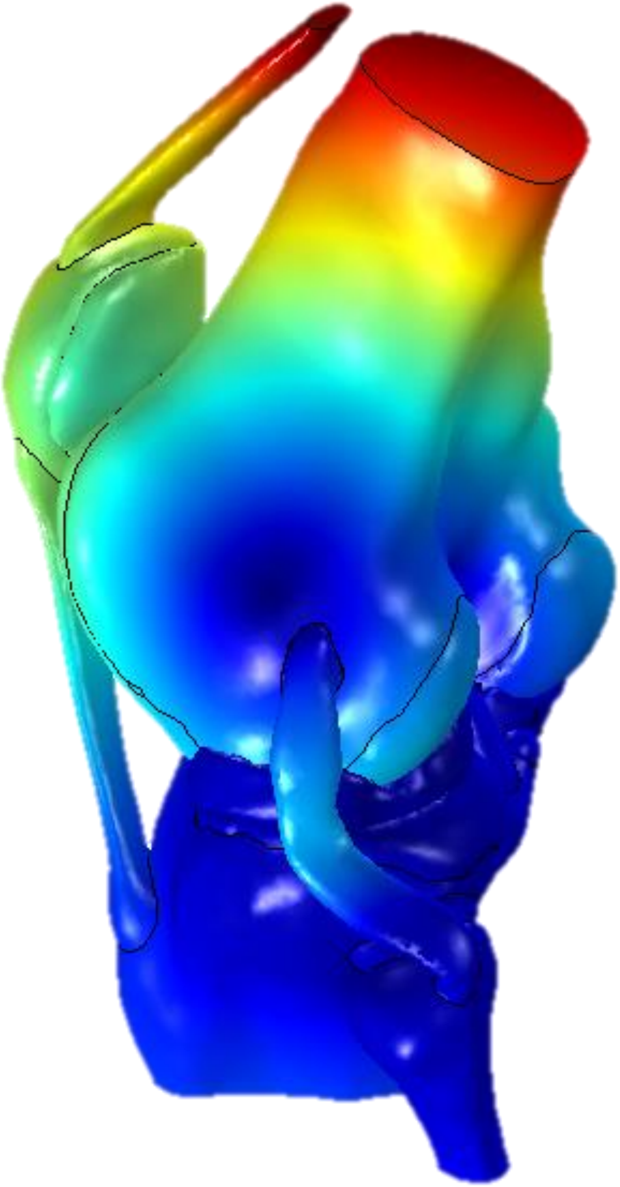


RANKED EVALUATION

WEIGHTED FORMULA

Using the maximum and average data, a method of ranking the virtual surgeries was developed based on the work by [18].

Ranking method is used to grade the virtual surgeries and assess which is better at maintaining knee function relative to the intact case.

Ranking method sums the weighted normalized parameter differences between virtual surgery data & intact reference data, as follows:

$$\emptyset = \frac{\sum_i w_{\alpha_i}\left(1 - \left|\frac{\alpha_i^{VS} - \alpha_i^{ND}}{\alpha_i^{ND}}\right|\right)}{\sum_i w_{\alpha_i}} \qquad (1)$$

Where:

ϕ is the overall ranked value for the virtual surgery being assessed

α is the model parameter being evaluated (stress, displacement or contact pressure)

Parameters with superscript VS represent the virtual surgery model data

Parameters with superscript ND represent the intact (no-defect) model data

From Equation (1), as $\phi \rightarrow 1$, the closer the virtual surgery solution is to the intact reference model.

Ranked Values

Using weighting values of unity (one) for the mean parameters, and two for the maximum parameters, and substituting these into Equation (1), the overall ranked values come out as:

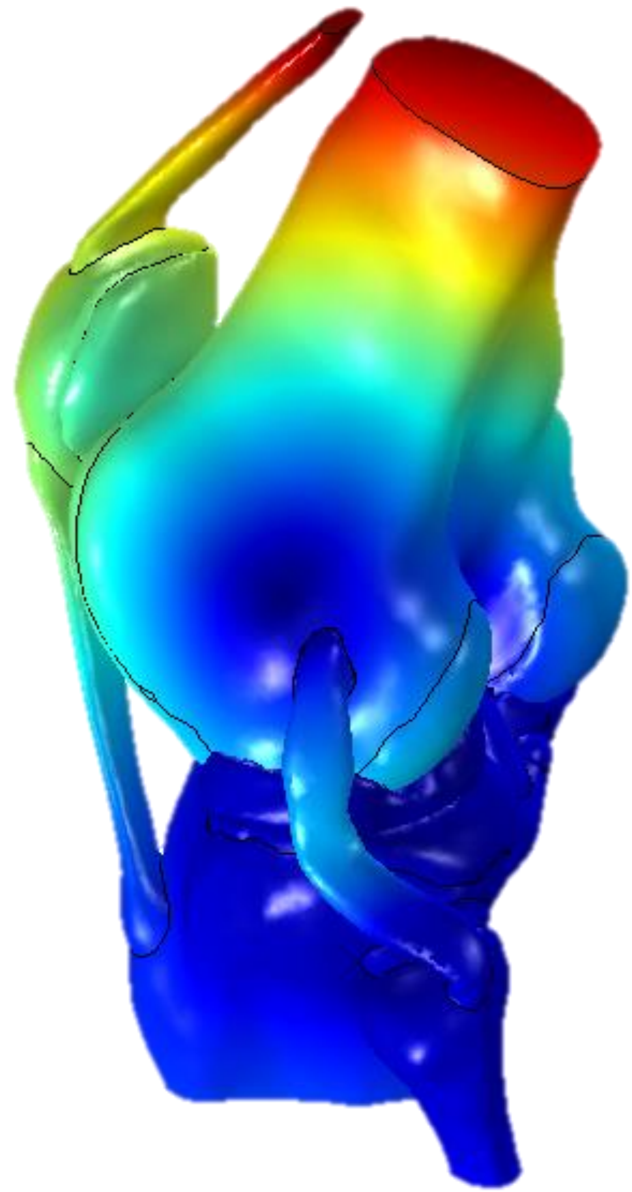
- 0.90 for the 30mm resection model.
- 0.86 for 35mm resection model.

Thus these ranked values show that the conserving 30mm resection model is indeed better, indicating that surgical procedures should be conserving where possible, as expected.

Tabulated Data

Percentage Variation & Partial Ranked Values

Section	Model	Contact Pressure Between Various Bodies						Anterior-Posterior & Lateral-Medial Displacement Magnitudes				1st Principal stresses			
		Medial Menisci & Tibia Cartilage		Femur & Tibia Cartilage		Lateral Menisci & Tibia Cartilage		Medial Meniscus		Lateral Meniscus		Medial Meniscus		Lateral Meniscus	
		Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max
Standing Load Results	Natural	0.05 MPa	0.82 MPa	0.05 MPa	1.90 MPa	0.02 MPa	1.22 MPa	0.66 mm	1.30 mm	1.05 mm	1.30 mm	0.36 MPa	8.20 MPa	0.21 MPa	5.78 MPa
	Partial Meniscectomy (30mm Resection)	0.04 MPa	1.07 MPa	0.05 MPa	1.46 MPa	0.02 MPa	1.11 MPa	0.65 mm	1.37 mm	1.11 mm	1.35 mm	0.37 MPa	9.14 MPa	0.20 MPa	6.08 MPa
	Partial Meniscectomy (35mm Resection)	0.04 MPa	1.08 MPa	0.05 MPa	1.34 MPa	0.02 MPa	1.11 MPa	0.64 mm	1.27 mm	1.04 mm	1.24 mm	0.38 MPa	10.48 MPa	0.19 MPa	6.57 MPa
Percentage variation from Natural Case	Partial Meniscectomy (30mm Resection)	-19.26 %	30.88 %	-0.63 %	-23.07 %	-9.81 %	-8.88 %	-0.41 %	5.43 %	5.44 %	3.83 %	5.16 %	11.45 %	-3.89 %	5.18 %
	Partial Meniscectomy (35mm Resection)	-26.04 %	32.12 %	-0.56 %	-29.37 %	-14.38 %	-9.08 %	-2.73 %	-2.26 %	-1.57 %	-4.31 %	6.26 %	27.79 %	-6.06 %	13.71 %
Partial Ranked Values	Partial Meniscectomy (30mm Resection)	0.81	0.69	0.99	0.77	0.90	0.91	1.00	0.95	0.95	0.96	0.95	0.89	0.96	0.95
	Partial Meniscectomy (35mm Resection)	0.74	0.68	0.99	0.71	0.86	0.91	0.97	0.98	0.98	0.96	0.94	0.72	0.94	0.86



CONCLUSION

A knee model has been developed to help assess the change in knee mechanics and virtual partial meniscectomy surgical options, and a quantitative virtual surgery ranking method described by Equation (1), is given.

It was found that for the standing load case, the 30mm resection model presents a closer mechanical response to the ideal intact (no–defect) model.

The overall ranking values obtained were 0.90 and 0.86 for the 30mm and 35mm resection models, respectively.

This quantitatively shows that the conserving 30mm resection surgery is better than the 35mm resection surgery, as the closer the ranking value (ϕ) tends to unity, the closer the solution is to the ideal intact case. Thus, this virtual surgery option will better restore the function of the knee with a medial menisci defect to that of an intact knee, under the standing load conditions presented.

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DISCUSSION

Although the results demonstrate that 30mm conserving resection is beneficial, only a single defect sight was assessed, where the benefits observed in conserving the menisci in this region may not necessarily be applicable at other defect sites or resections sizes. Thus, the assessment of other defect sizes and locations (e.g. medial vs. lateral and anterior vs. posterior) would be of further interest and benefit, especially if they can be correlated to clinical data.

In addition, only a small number of stress, displacement and contact pressure parameters (α) were utilized in the ranking evaluation. Future work could use additional data and parameters, such as knee joint centre of rotation, relative angular changes of the femur and tibia, and ligament stresses. These additional parameters, combined with a sensitivity analyses on the effect of the weightings could be done and correlated against clinical data and outcomes, to further develop the models and the ranking method.

This is a first effort at providing a quantitative method of comparing two surgical options, future work still needs to be done in order to validate the models and ranked method against clinical data and patient outcomes. However, the modelling technique and ranking show potential as a feasible solution for surgeons to use in a clinical setting to aid to resection options prior to surgery.

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Thank You

Mark Yeoman

Continuum Blue Ltd.

E: mark@continuum-blue.com

W: www.continuum-blue.com

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Questions & Answers

Research & Development

Multiphysics Modeling (FEA/CFD)

Motion & Load Analysis

Material Selection & Optimization

Testing & Assessment

Mechanical Testing

Material Assessment

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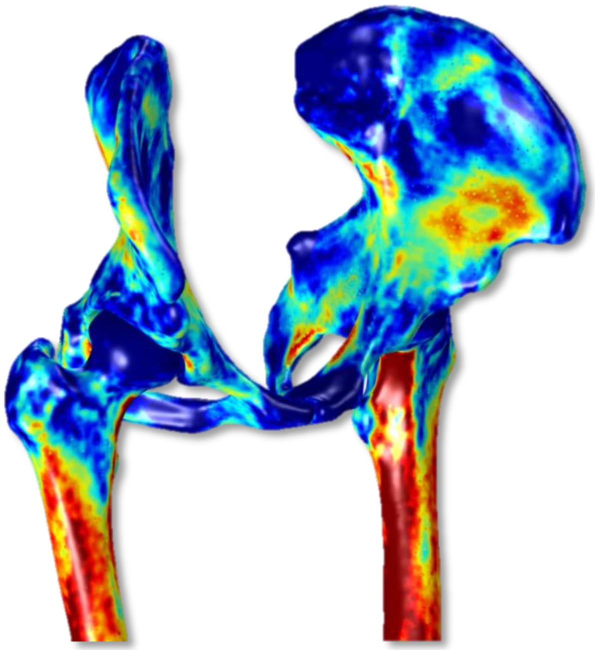
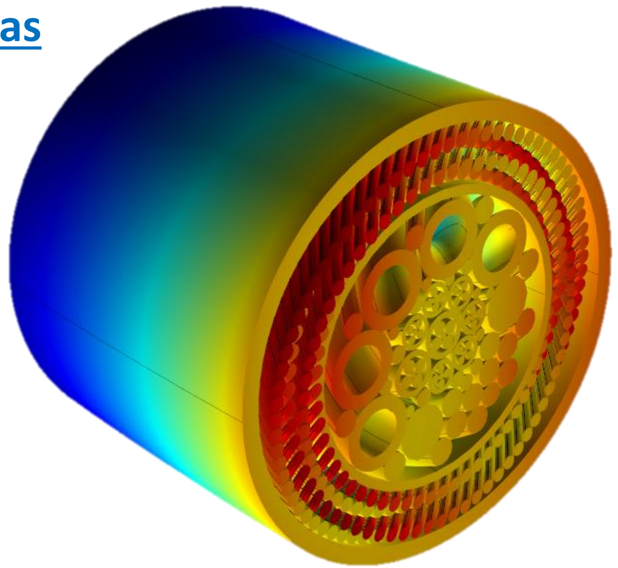
Structural Projects

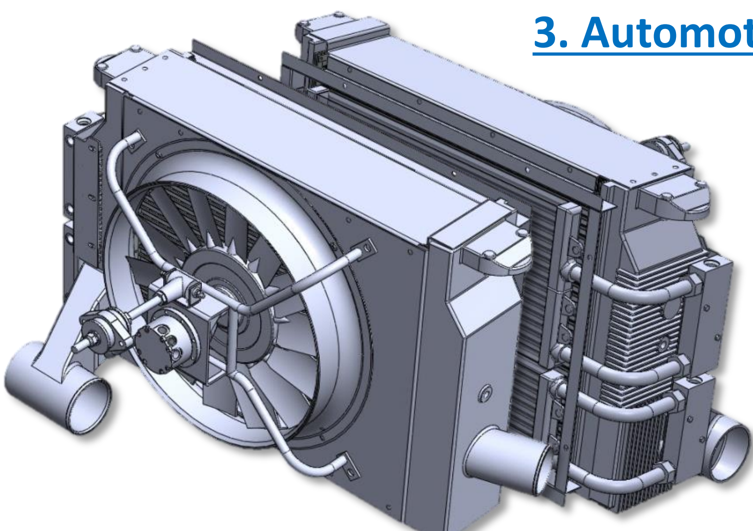


1. Medical Implants

2. Oil & Gas



3. Automotive



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1. Drug Delivery

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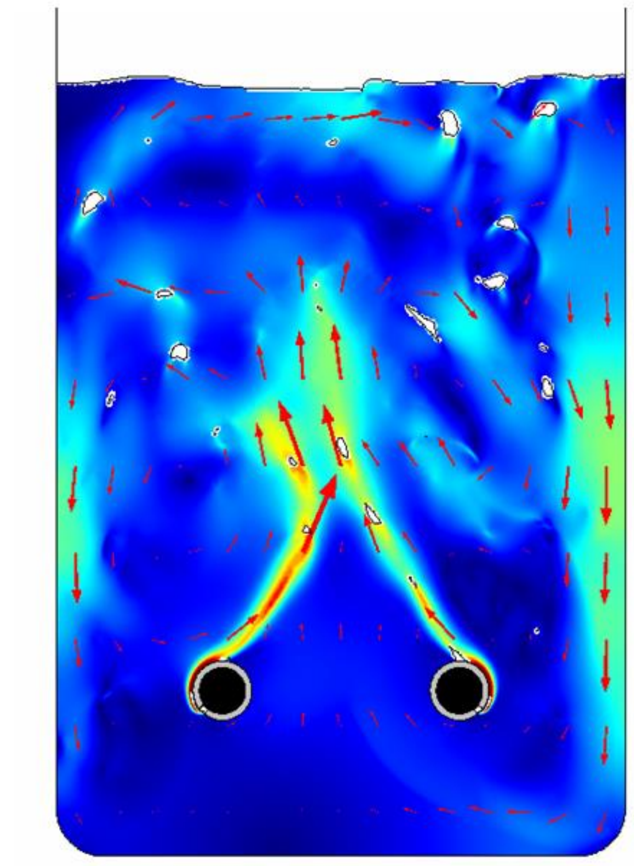

2. Bioreactors

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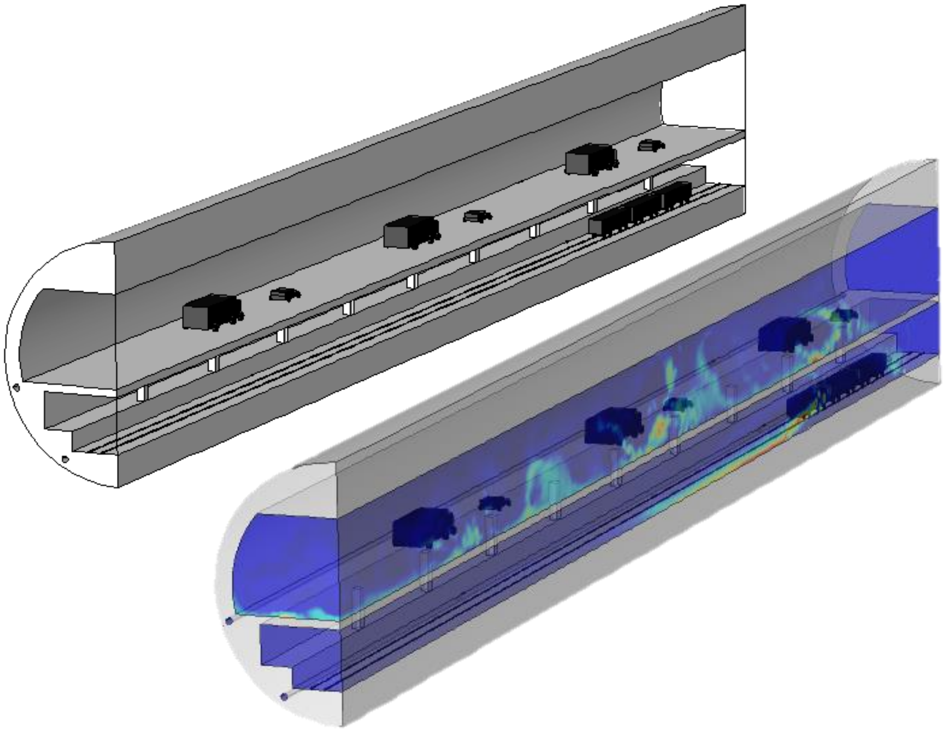
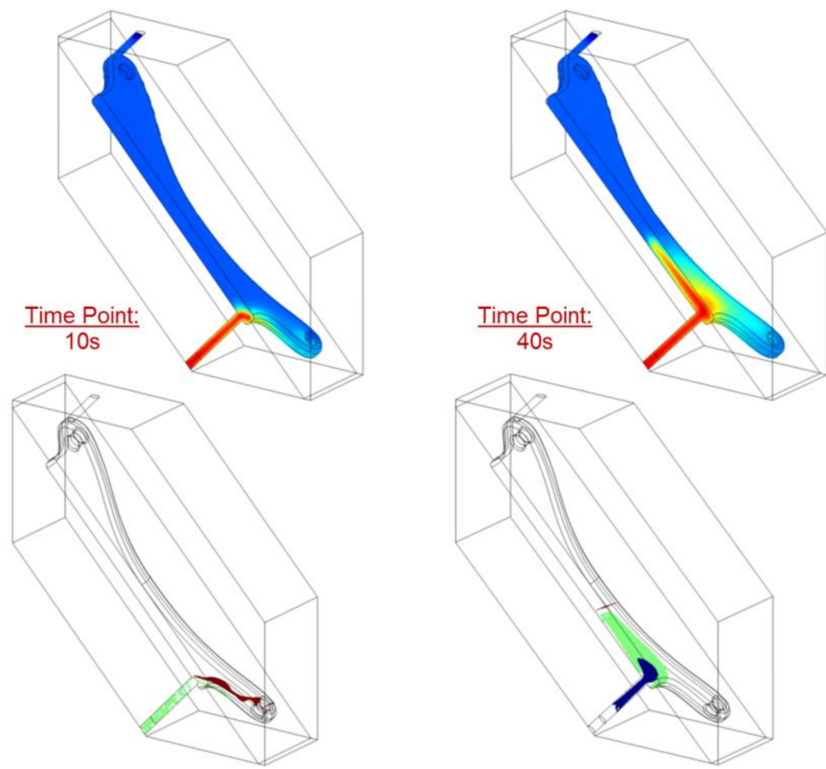


3. Transport

- Vehicle emissions in tunnel
- Air quality analysis

4. Mould Flow Analysis

- Multiphase flow
- Mixing of Polymers
- Thermal
- Polymer curing



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