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

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INTRODUCTION

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 the knee joint, one medial and one lateral, together that cushion and stabilize the knee joint (see Figure 2). A meniscectomy is the surgical removal of all, or a part of a torn or damaged meniscus. Tears in the menisci are common in knee joint injuries and depending on the location and severity of the tear, orthopaedic surgeons who perform meniscectomies will make surgical decisions based on the age, health and activity level of the patient, as well as the meniscus's ability to heal.

AIM

To develop an intact (natural, no-defect) knee model from patient specific data, and then perform two partial meniscectomy virtual surgeries of different resection lengths (30mm & 35mm) based on a typical defect. Use the models developed to assess the change in knee mechanics & loading with variation in resection length and surgical outcome. Implement a method to rank and grade the various partial meniscectomy virtual surgeries relative to the intact natural (no-defect) model.

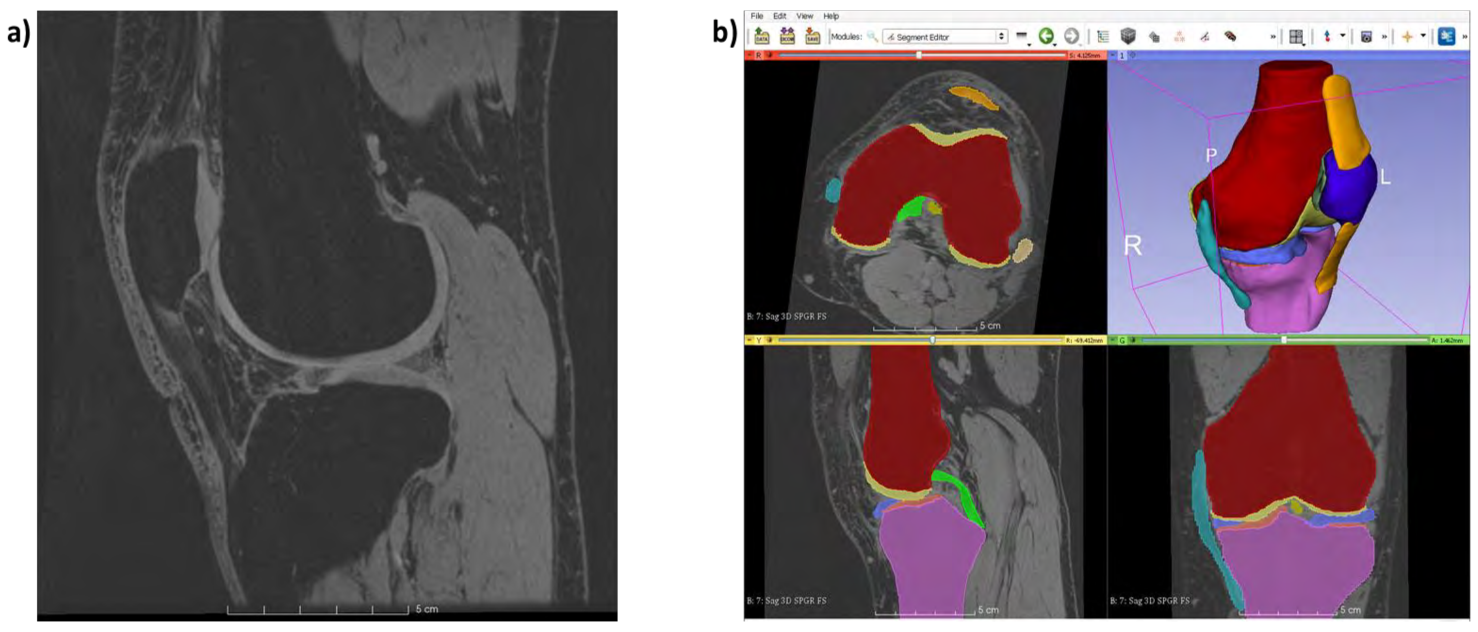

Figure 1. a) MRI image of knee section (sagittal plane) and b) screenshot of 3D Slicer and segmentation of knee region

METHOD

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 [1][2] software was used to segment the MRI data & obtain the required geometries for the model (Figure 1). A literature review of knee kinematics and modelling techniques was preformed [3-16], to assess current methods & techniques utilised in the field. From this review, three models were developed with the appropriate loads, boundary conditions & material relations. The knee domains & features implemented in the knee model are presented in Figure 2. A defect location was defined on the posterior side of the medial meniscus based on literature. Two virtual partial meniscectomy surgeries where then performed on the intact model, namely 30mm & 35mm resections on the posterior side of the medial meniscus. The three models developed including, a) natural (no-defect), b) partial meniscectomy (30mm resection), c) partial meniscectomy (35mm resection), are illustrated in Figure 3.

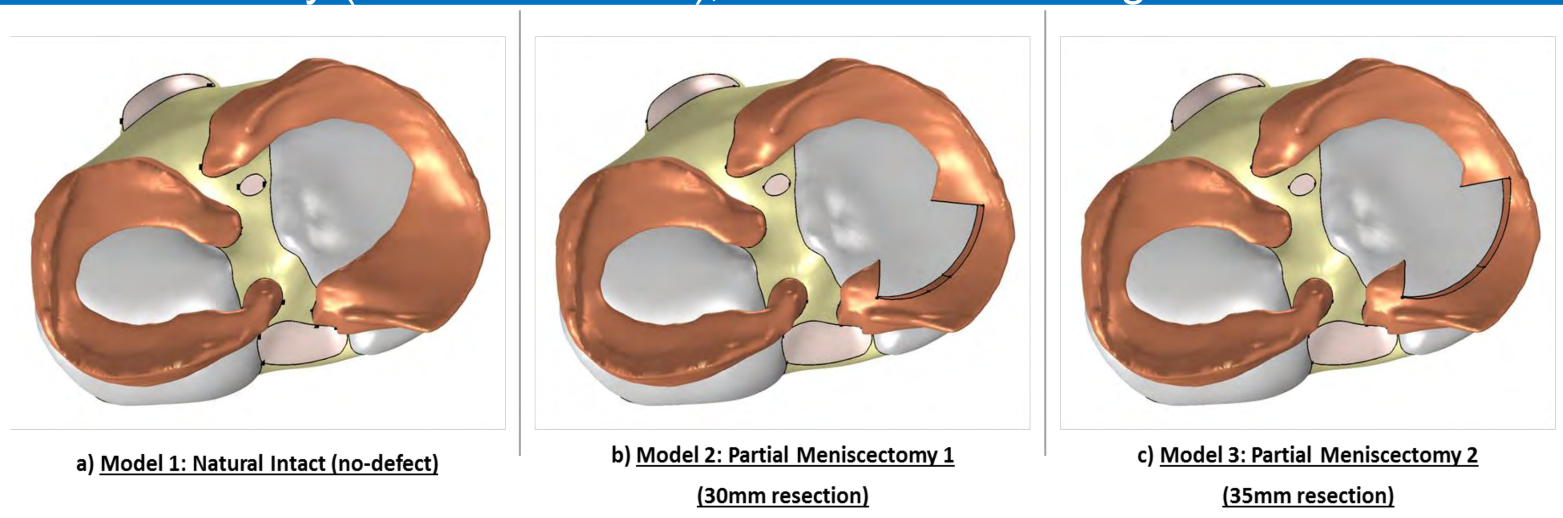

Figure 3. natural (no-defect) menisci compared to partial meniscectomy models (superior views of menisci, tibia cartilage & tibia)

The material models implemented include hyper-elastic (neo-Hookean), linear orthotropic & isotropic material models. The material models are based on the work by [6, 9-10]. A summary of the material models utilised in the model for each knee component is provided in Table 1. Frictionless contact was assumed between all articulating surfaces [5][7][11]. The load & boundary conditions applied to the knee model included two load cases, namely; 1) standing, & 2) walking gait. Only the standing load case data is presented.

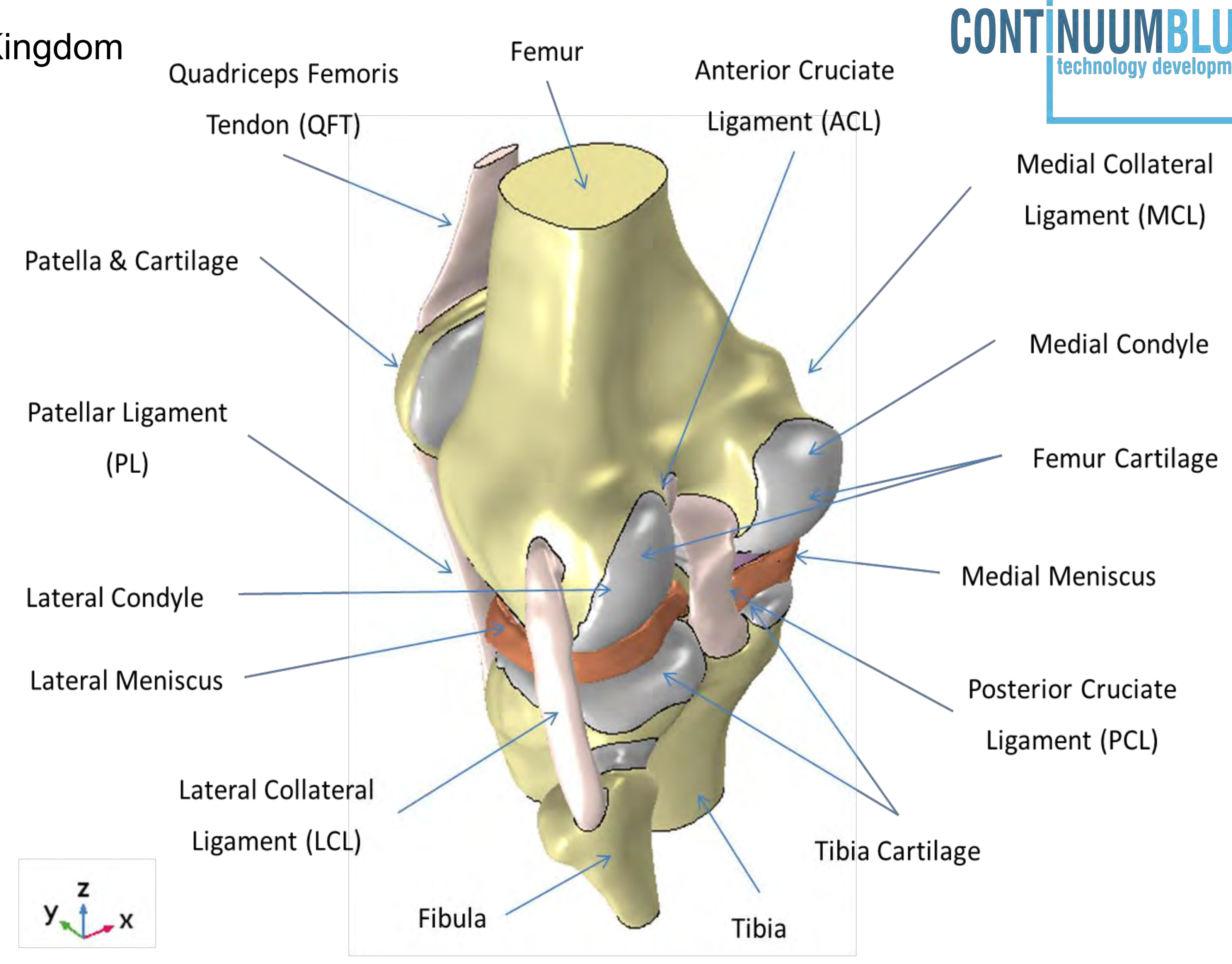

Figure 2. Knee model domains and features in COMSOL developed from MRI scan

Knee Bodies	Material Model	Values			
		Density (g/cm³)	Modulus (MPa)	Poisson's Ratio	Reference
Deformable Bony Components (Femur, Tibia, Fibula & Patella)	Linear elastic (isotropic)	2	15×10^3	0.3	[6]
Articular cartilage	Linear elastic (isotropic)	1	15	0.475	[9]
Menisci♣	Linear elastic (orthotropic)	1.5	E_1: 20	ν_{12}: 0.3	[9]
			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	[10]
			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	

Table 1. Material models utilised in FE model

RESULTS

Displacement magnitudes, contact pressures & stress magnitudes were assessed & compared to the intact (no-defect) model. Figure 4, presents the displacement magnitudes between the models on the axial plane only. From this, the displacements from the conserving 30mm resection model are a closer match to those of the intact model.

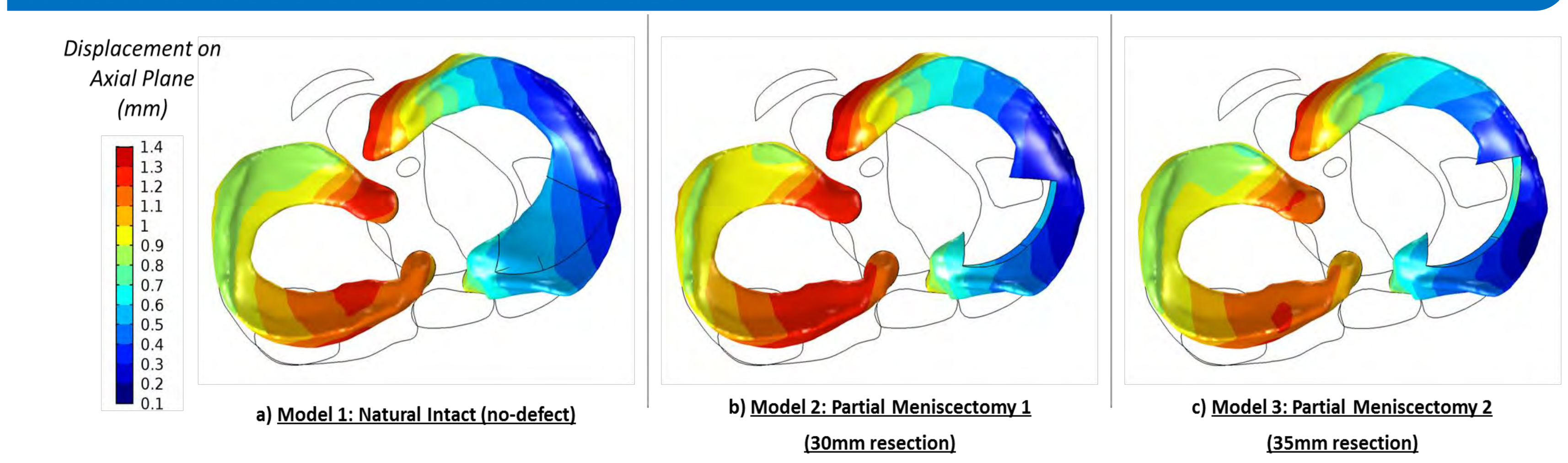

Figure 4. menisci anterior-posterior & lateral-medial direction displacement magnitudes for standing load case (superior views only)

The contact pressure & loading patterns for each model are presented in Figure 5. Again based on the observed contact footprints and contours on the lateral side of the joint are very similar for all cases. However, there is are large differences seen on the medial side of the joint, where again, it can be seen that the contact footprint in the conserving 30mm resection model, is more evenly distributed across the posteromedial side of the medial meniscus, and is a closer match to the natural (no-defect) model.

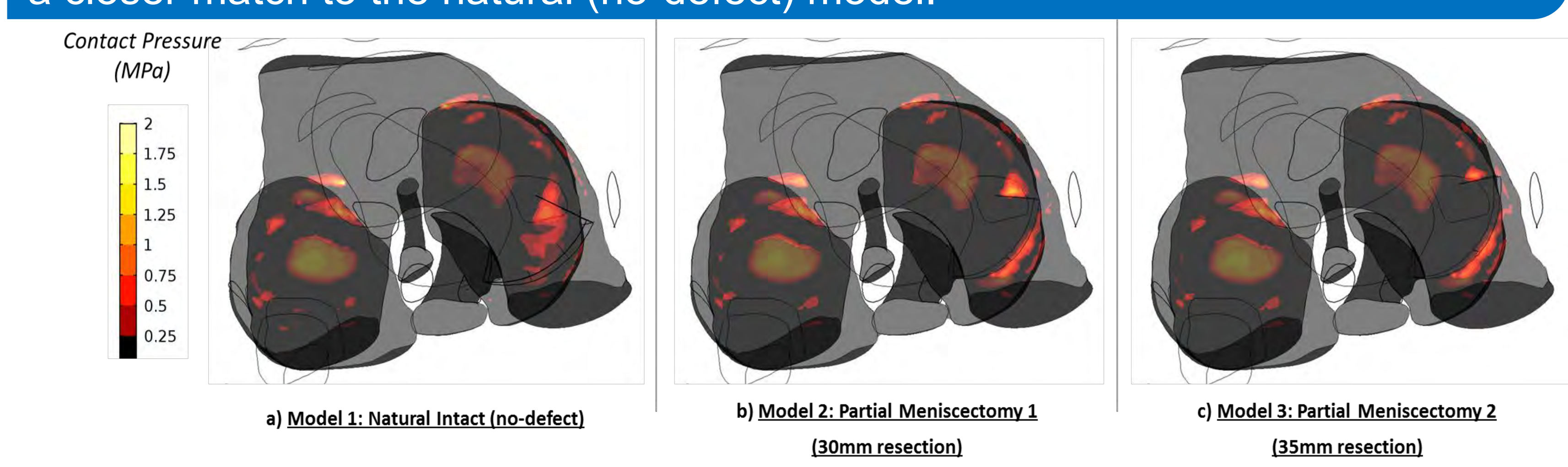

Figure 5. contact pressure & loading pattern between the various bodies and loading patterns for standing load case (superior views only)

Using the maximum & average observed displacements, stresses & contact pressures on both the lateral & medial menisci, and the articulating cartilage surfaces (femur & tibia), a method of ranking the virtual surgeries was developed based on the work by [17]. The ranking method is used to grade the virtual surgeries & assess which is better at maintaining knee function relative to the intact (no-defect) model. From the ranking results it was found that the conserving 30mm resection model was better, indicating that surgical procedures should be conserving where possible, as expected.

CONCLUSION

A knee model has been developed to help assess the change in knee mechanics & virtual partial meniscectomy surgical options.

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