Development of a Statistical Shape-function Model of the Implanted Knee to Predict Joint Mechanics

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I. Introduction

Outcomes of Total Knee Arthroplasty (TKA) are dependent on surgical technique, patient variability, and implant design.

- Poor designs result in undesirable contact mechanics, including instability and reduced range of motion.
- Patient satisfaction rates have been reported to range from 75% to 92%, with only 22% of patients rating the surgical results as 'excellent' (Yount-Joon 2016, Knee Surg Relat Res 1-15).

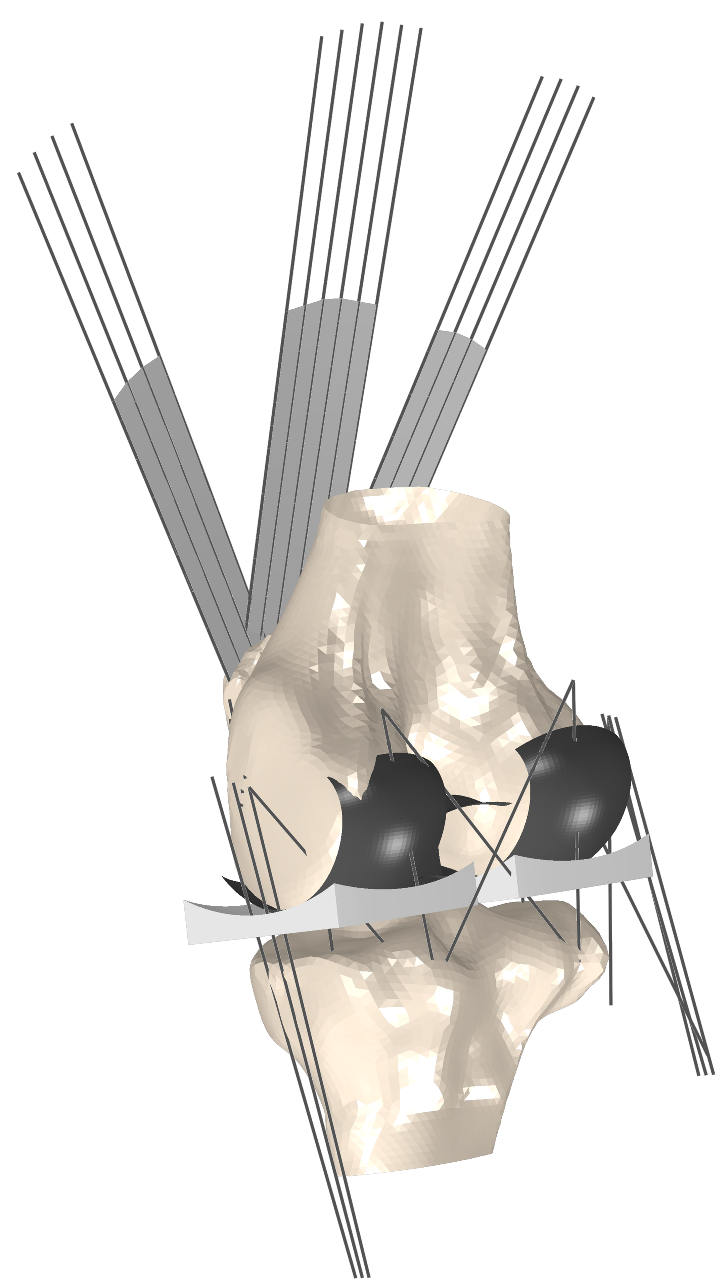


Fig. 1: Back view of TKA model.

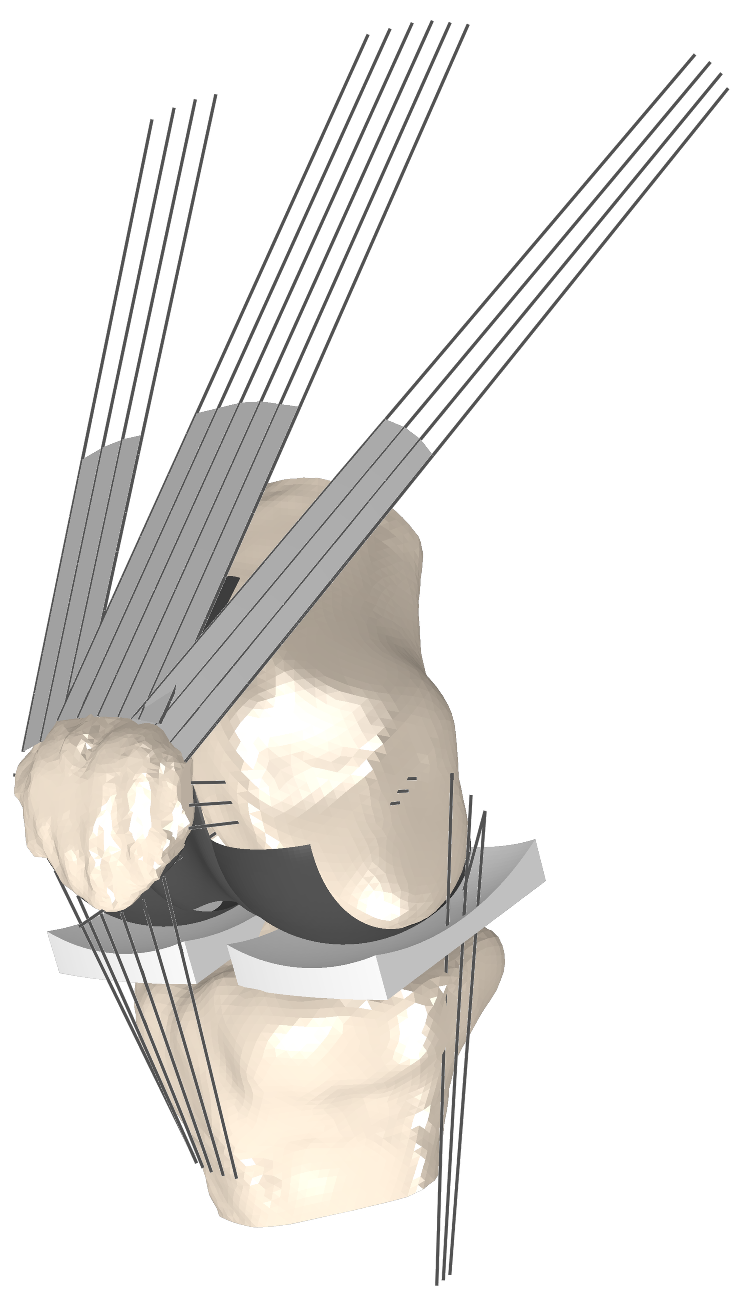


Fig. 2: Front view of TKA model in partial squat.

Past efforts have given valuable insight into predicting surgical outcomes following TKA, they all required significant investment of time, software, and expertise.

- Cadaveric experiments require regulatory approval and the contracting of a surgeon.
- Computational modeling requires use of expensive software licenses and the efforts of highly trained engineers in order to produce and validate each knee model.
- Design is iterative, so these costly processes must be done many times before a device comes to market.

II. Objective

Our objective was the development of a statistical shape-function model of a posterior stabilized implant knee to predict output mechanics in a timely and resource efficient matter. Which could be useful to design teams in a number of ways.

- Optimize design outputs before the prototyping stage
- Allow technicians to produce and screen outputs before engineers
- Generate design parameters from supplied outputs

III. Methods

Using a previously validated tibial-femoral (TF) implant joint model performing a squat cycle (Fitzpatrick 2012, J Orthop 2015-2024), design of experiments (DOE) techniques were used to model joint behavior.

- Implant geometry parameterized using 9 predictor variables.
- Ranges of design parameters were determined from measurements of current TKA components.

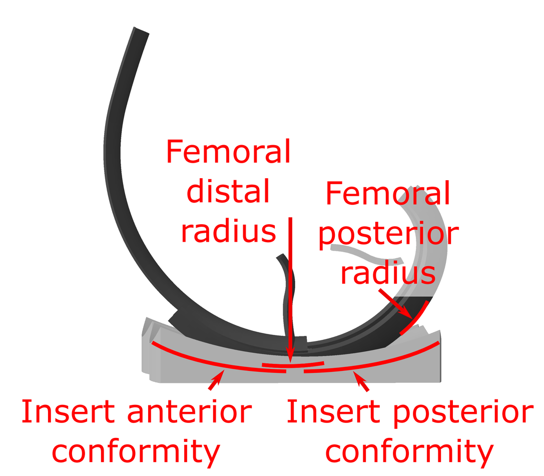


Fig. 3: Front view of implant geometry.

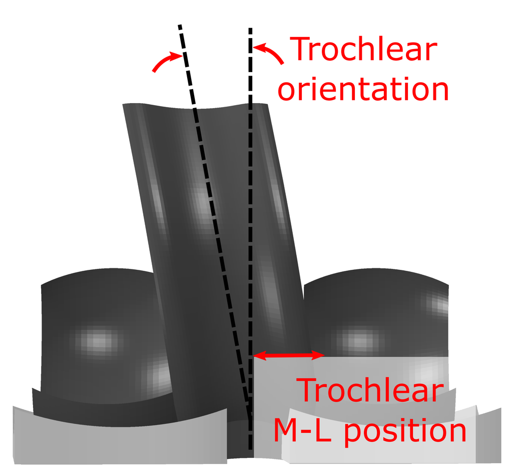


Fig. 4: Front view of implant geometry.

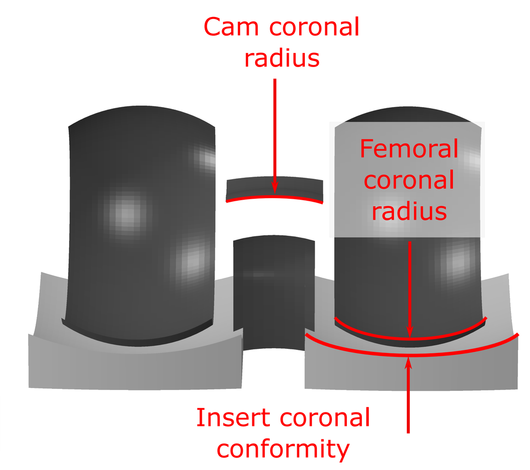


Fig. 5: Back view of implant geometry.

DOE sampling can cause odd combinations of parameters, which can lead to FEA simulations failing to finish. To combat this a subspace was sampled initially, with further iterations introducing wider sample spaces.

1. Initial samples formed an inscribed central composite design (100% successful)
2. An expanded full factorial cube was performed (99% successful)
3. A full-factorial sampling of the entire space was added (52% successful)

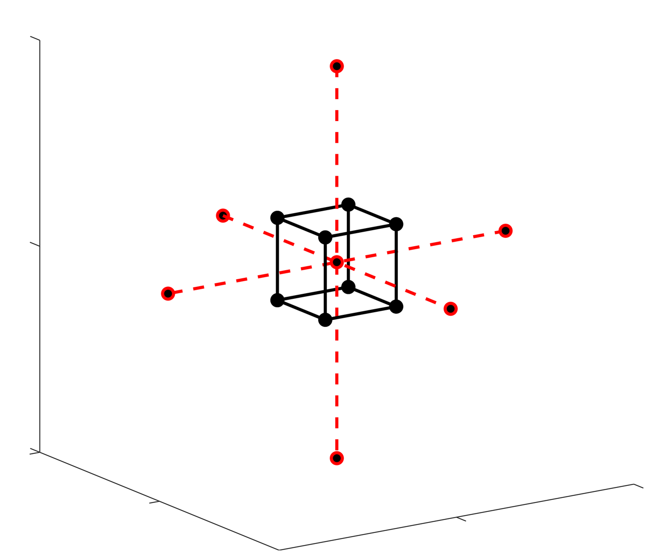


Fig. 6: Three factor representation of an inscribed central composite design.

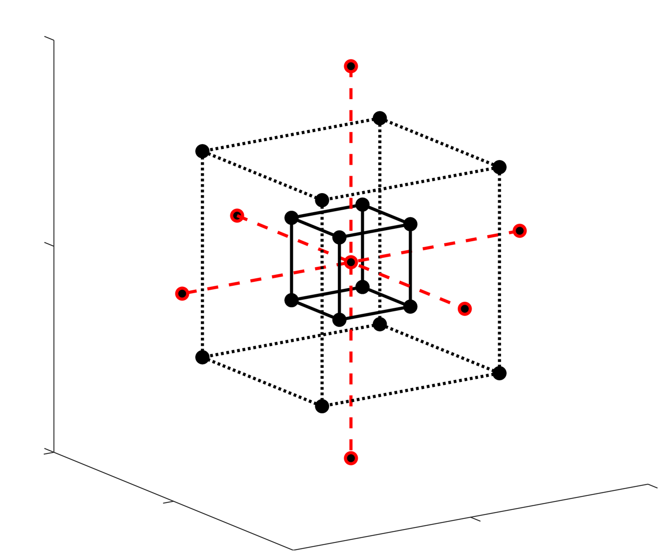


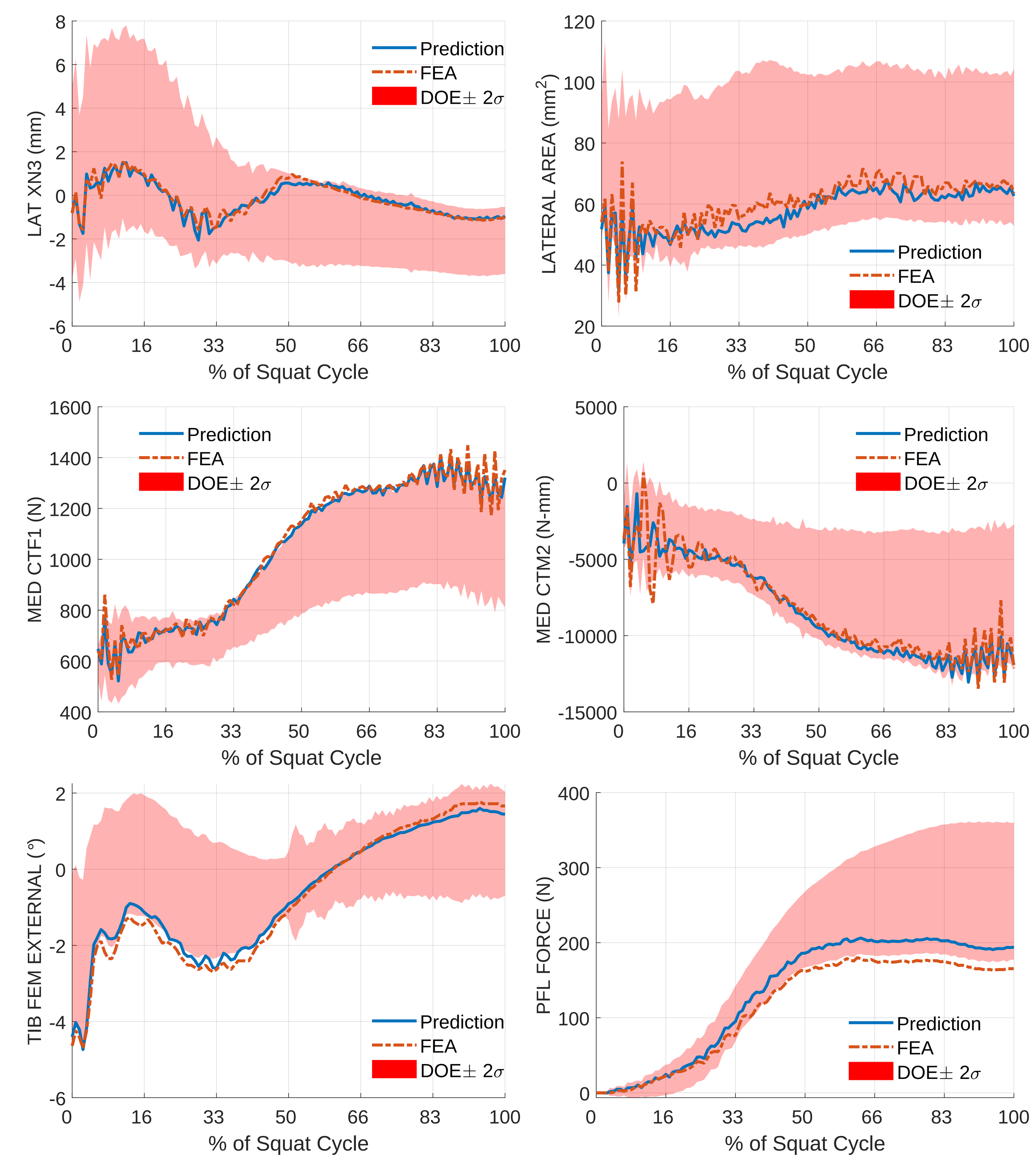
Fig. 7: Schematic showing first iteration of expanding the sample space.

Tab. 1: Factor levels chosen for sampling the design space.

Femur Radii(mm)			Tibial Conformity			Trochlea(°, mm)		Cam(mm)
Distal	Posterior	Coronal	Anterior	Posterior	Coronal	Angle	Offset	Radius
20.0	20.0	15.0	0.20	0.20	0.20	7.00	−3.00	20.0
27.1	22.9	19.7	0.37	0.37	0.37	9.38	−1.58	27.1
31.9	24.7	22.9	0.48	0.48	0.48	11.0	−0.63	31.9
35.0	26.0	25.0	0.55	0.55	0.55	12.0	0.00	35.0
38.2	27.3	27.1	0.62	0.62	0.62	13.1	0.63	38.2
42.9	29.2	30.3	0.73	0.73	0.73	14.6	1.58	42.9
50.0	32.0	35.0	0.90	0.90	0.90	17.0	3.00	50.0

- Linear regression models with quadratic predictors
- Interaction terms included for all iterations

IV. Results



High quality prediction throughout the sample space for:

- Kinematic translations
- Kinematic Rotations
- Mid flexion joint contact forces
- Ligament displacements

More tuning of the model is required for the prediction of:

- Early and late flexion contact forces
- Joint contact moments
- Contact area and pressure
- Ligament forces

V. Next Steps

1. Run a similar DOE with surgical parameters.
   - Anterior insert slope
   - Tibial V-V alignment
   - Femoral I-E alignment
   - Femoral V-V alignment
2. Combine the most sensitive parameters from each study for a final DOE.
3. Insert shape-function models into design optimization pipeline.