Chapter 7
Development and calibration of eight finite element knee joint models

7.1 Introduction

Developing and calibrating computational knee joint models is a difficult, costly and labour intensive process. This results in the number of models included in simulation studies often being small, which is frequently indicated as a study limitation. Generating a semi-automatic model development and calibration workflow could decrease modelling time and thereby increase the number of models included in simulation studies. Next to this, having a semi-automatic modelling workflow could decrease the hurdle to clinical application of computational knee joint models.

A model development and calibration workflow were developed (Chapter 3 and Chapter 6) in the two corresponding phases of the KneeHub project (*https://simtk.org/projects/kneehub*). Before looking into automating these workflows, it should be investigated if the workflows can be reused on additional imaging and cadaveric laxity datasets.

The aim of this study is to develop and calibrate eight finite element knee joint models using the previously established workflows. Obtaining a cohort of eight computational knee joint models will give us the ability to perform simulations on a larger number of subjects, to be able to draw more informed conclusions. Next to this, by applying the model development and calibration workflows to an additional six subjects, the reusability of our model generation and calibration workflows to other datasets can be investigated.

7.2 Methods

7.2.1 Subject data

Eight cadaveric knee joints were included in this study (Table 7.1). Seven datasets were obtained from the Open Knee(s) project (Bennetts et al., 2015; Bonner et al., 2015; Colbrunn et al., 2015; Erdemir et al., 2015; *https://simtk.org/projects/openknee*), and one was obtained from the Natural Knee Data project (Harris et al., 2016; Ali et al., 2016; *https://digitalcommons.du.edu/natural_knee_data/*).

Table 7.1: Subject data characteristics.

Subject number	Sex	Age (yrs)	Height (m)	Mass (kg)
du02	Male	44	1.83	70.31
oks001	Male	71	1.83	77.10
oks002	Female	67	1.55	45.30
oks003	Female	25	1.73	68
oks004	Female	46	1.575	54.43
oks006	Female	71	1.524	49.4
oks007	Male	71	1.70	65.77
oks008	Male	40	1.778	63.5

7.2.2 Model development

The previously developed workflows in Chapter 3 were used to develop eight finite element models. Two models (du02 and oks003) were previously established, but due to small changes to the model development workflows, these two models were partly developed and calibrated again to ensure consistency over all eight models. The meshes of model du02 and oks003 were not changed compared to Chapter 3.

7.2.2.1 Segmentations

For the additional six models, the segmentation data from the OpenKnee(s) database (*https://simtk.org/projects/openknee*) was used. Irregularities in the segmentations of the cartilages and the ligaments were manually removed before mesh generation (MeshLab version 2016.12 *https://www.meshlab.net*). The bone segmentations were cut-off to have open ends at the non-articulating sites, and the tibia and fibula segmentations were merged (CloudCompare version 2.10-alpha, *https://www.danielgm.net/cc/*) since the statistical shape model used to produce the full bone meshes is based on the tibia and fibula together (Zhang, Fernandez et al., 2016; Zhang, Hislop-Jambrich et al., 2016). The segmentations were resampled to 25000 points for the tibia-fibula and to 20000 points for the femur segmentation using MeshLab.

7.2.2.2 Mesh generation

The meshes were generated as described in Chapter 3 (Model version 3). The number of elements per structure was based on the previously developed model oks003 (Table 7.2). The cartilage, ligament and meniscus meshes were generated using FEBioStudio (version 1.0.0, Maas et al., 2012) instead of FEBio Preview which was used in Chapter 3.

Table 7.2: Mesh generation element types and number of elements.

Structure		**Element type**	**Number of elements**
Bone	**Femur**	Triangular	~15000
	Tibia	Triangular	~10000
	Fibula	Triangular	~ 5000
Cartilage	**Femur**	Tetrahedral	~29500
	Tibia - Medial	Tetrahedral	~7500
	Tibia - Lateral	Tetrahedral	~7500
Ligaments	**Anterior cruciate ligament**	Tetrahedral	~7500
	Posterior cruciate ligament	Tetrahedral	~9000
	Medial collateral ligament	Tetrahedral	~14500
	Lateral collateral ligament	Tetrahedral	~6500
Meniscus	**Medial**	Tetrahedral	~16000
	Lateral	Tetrahedral	~15000

7.2.2.3 Model assembly

A few changes were made compared to the model assembly described in Chapter 3. These changes were also applied to the two already developed models. FEBioStudio was used for model assembly instead of Preview. The meniscus contact formulation was changed by turning off “two-pass”. This change increased convergence and decreased computational time. Next to that, the nodes involved in the anatomical coordinate system (ACS) calculations were changed. The registered probed point anatomical landmarks were not always located exactly on the mesh, with generally a few mm distance between the probed point and the mesh, which induced an error in the ACS calculations. To overcome this, floating nodes were added to the models at the probed point locations. These were used to calculate the ACS instead of the closest point to the probed point locations in the mesh.

7.2.2.4 Sensitivity analyses before calibration

Multiple sensitivity analyses were performed to investigate the convergence of the models before calibration and to find the prestretch factor calibration bounds. Sensitivity studies 1 and 2 were performed for all models except for model du02 and model oks003. Sensitivity study number 3 was performed for all models. The full methods of the sensitivity analyses can be found on https://simtk.org/projects/abi_knee_models, but are summarised in Table 7.3.

Table 7.3: Summary of the methods of the sensitivity analyses performed before model calibration. Abbreviations: anterior-posterior (AP), internal-external (IE), Anterior & Posterior cruciate ligaments (ACL & PCL) & Medial & Lateral collateral ligaments (MCL & LCL)

		Sensitivity analysis 1		Sensitivity analysis 2		Sensitivity analysis 3	
Description		Investigate the sensitivity to changing ligament prestretch values, changing one at the time (others set to 1), using a prestretch and axial load application simulation.		Investigate the sensitivity to changing ligament prestretch values, changing one at the time (others set to 1), in a simulation rotating the knee joint to the flexion angle in which the robot data was obtained.		A sensitivity study to find the ligament prestretch bounds to use in the calibrations. AP simulations to investigate ACL & PCL, IE simulations to investigate all ligaments and VV simulations to investigate MCL & LCL prestretch values. Ligament prestretch values changed one at a time where the others were set to 1.	
Simulation timesteps & description		0 - 0.1	Settling	0 - 0.1	Apply prestretch	0 - 0.1	Apply prestretch
		0.1 - 0.2	Prestretch application	0.1 - 0.6	Rotate to the flexion angle in which the robot data was obtained.	0.1 - 0.5	Apply -20N axial load (only oks models)
		0.2 - 0.5	Apply axial load (-20N)	0.6 - 1.0	Apply -20N axial load	0.5 - 1.5	Apply load of interest
Prestretch values explored	**ACL**	0.9 - 1.05 (step size = 0.01)		0.9 - 1.05 (step size = 0.01)		0.75 - 1.0 (step size = 0.01)	
	PCL	0.9 - 1.10 (step size = 0.01)		0.9 - 1.10 (step size = 0.01)		0.95 - 1.2 (step size = 0.01)	
	MCL	0.9 - 1.10 (step size = 0.01)		0.9 - 1.10 (step size = 0.01)		0.95 - 1.2 (step size = 0.01)	
	LCL	0.9 - 1.10 (step size = 0.01)		0.9 - 1.10 (step size = 0.01)		0.85 - 1.1 (step size = 0.01)	
Loads explored	**AP**	N.A.		N.A.		-50N, 50N, -100N, 100N	
	IE	N.A.		N.A.		-2000Nmm, 2000Nmm, -4000Nmm, 4000Nmm	
	VV	N.A.		N.A.		-4000Nmm, 4000Nmm, -8000Nmm, 8000Nmm	
Outcome parameters		convergence & convergence time		convergence & convergence time		convergence, convergence time & kinematics	

7.2.3 Model calibration to robot laxity data

The previously developed calibration workflows in Chapter 6 were used to calibrate eight finite element models. Some adjustments were made. The largest adjustment was the calibration of the models only in full extension, compared to the previous calibration workflow where the calibration simulations were performed in two flexion angles. Two models (du02 and oks003) were previously calibrated, but due to changes in the workflows, these two models were calibrated again to ensure consistency over all eight models.

7.2.3.1 Processing the robot laxity data

The robot laxity data of each knee joint was processed as described in Chapter 6. Only the robot laxity data at ~0 degrees of knee flexion was used. In the laxity data of subject du02, the minimal FE angle was 2.9 degrees. Therefore we evaluated the robot data at 3 degrees instead of at 0 degrees to avoid extrapolation of the robot data.

7.2.3.2 Model alignment to the robot data

The models were aligned to the robot data as described in Chapter 6. The tibia coordinate system (CS) was aligned to the FEBio CS.

7.2.3.3 Model calibration

Multiple model calibrations were performed consecutively (Table 7.4), changing the calibration methods on each iteration based on the previous calibration results. The objective function described in Chapter 6 was used for calibration 1, with the following adjustments:

- The knee models were only calibrated at ~0 degrees of knee flexion.
- The cartilage contact penalty factor was not calibrated but set to 1.
- The load curves of the prestretch factor values were changed since a mistake was found. If no ligament prestretch has to be simulated a prestretch factor of 1 has to be assigned. Previously a prestretch factor of 0 was assigned.
- The assignment of the error values to the simulation results was updated.
- An extra error calculation on the convergence of the first simulation (Prestretch application, flexion to the robot flexion angle and application of axial load) was added.
- The calibration bounds of the prestretch factor values were increased since they were found to be too small in previous calibrations in Chapter 6.

Two optimisation algorithms, L-BFGS-B and TNC, were used for all calibrations. For each algorithm, the model calibrations were started from 5 different sets of starting values, resulting in 10 starts per model. For Calibration 1 to 4 (Table 7.4), all prestretch factor start values were used as described in Chapter 6. From calibration 5, the start prestretch factor values described in Table 7.5 were used. For the calibrations in which Young's moduli were calibrated as well (calibration 3-9), the calibrations were started with the middle value of the bounds as the starting value. Full methods and the Python scripts used in the calibrations are available on *https://simtk.org/projects/abi_knee_models*.

Table 7.4: Calibrations performed. Abbreviations: calibration (calibr.), Young's modulus (YM), anterior-posterior (AP), internal-external (IE), varus-valgus (VV), Anterior & Posterior cruciate ligaments (ACL & PCL), Medial & Lateral collateral ligaments (MCL & LCL) and root mean square error (RMSE).

		Calibration 1		Calibration 2	Calibration 3	Calibration 4	Calibration 5	Calibration 6	Calibration 7	Calibration 8	Calibration 9
Description		Initial calibration with large prestretch value bounds.		Updated error calculation, Lower normalisation values, and smaller prestretch value bounds compared to calibration 1.	Added the ligament Young's modulus values as parameters to be calibrated.	Used updated models and ACS calculations. Calibration is the same as calibr. 3.	Addition of an MCL-bone contact to prevent penetration & Increased prestretch value bounds compared to calibr. 4.	Large increase in prestretch factor value bounds compared to calibr. 5.	Increased prestretch value bounds compared to calibr. 5.	Compared to calibration 7: Decreased PCL bounds, increased the weight of AP and Increased YM bounds.	Compared to calibration 8: Increased the weight of AP more.
Simulation timesteps & description		0 - 0.1	Prestretch application	As calibr. 1.	As calibr. 2.	As calibr. 3	As calibr. 4	As calibr. 5	As calibr. 5	As calibr. 7	As calibr. 8
		0.1 - 1.0	Rotate to robot data flexion angle (du02 model)								
		0.1 - 0.5	Rotate to robot data flexion angle (oks models)								
		0.5 - 1.0	Apply -20N axial load (oks models)								
		1.0 - 1.4	3 separate VV, AP & IE simulations to max. load value.								
		1.4 - 2.2	3 separate VV, AP & IE simulations to min. load value.								
Simulation loads	**AP**	-100N, 100N		-80N, 60N	As calibr. 2.	As calibr. 3	As calibr. 4	As calibr. 5	As calibr. 5	As calibr. 7	As calibr. 8
	IE	-4000Nmm, 4000Nmm		As calibr. 1.	As calibr. 2.	As calibr. 3	As calibr. 4	As calibr. 5	As calibr. 5	As calibr. 7	As calibr. 8
	VV	-5000Nmm, 5000Nmm		As calibr. 1.	As calibr. 2.	As calibr. 3	As calibr. 4	As calibr. 5	As calibr. 5	As calibr. 7	As calibr. 8
Error calculation		2 = Axial load application failed		As calibr.1, but all error values +2.	As calibr. 2.	As calibr. 3	As calibr. 4	As calibr. 5	As calibr. 5	As calibr. 7	As calibr. 8
		1.4 - 1.9 = AP, IE, & VV: not run at all									
		1.2 = AP, IE & VV: Converged 0-25%									
		1.175 = AP, IE & VV: Converged 25-50%									
		1.15 = AP, IE & VV: Converged 50-75%									
		1.125 = AP, IE & VV: Converged 75-100%									
		Normalized RMSE robot and simulated position for AP, IE & VV simulations that converged fully.									
Normalization values		Maximal absolute position values in entire robot data		Maximal absolute position values in the robot data at the minimal and maximal applied load.	As calibr. 2.	As calibr. 3	As calibr. 4	As calibr. 5	As calibr. 5	As calibr. 7	As calibr. 8
AP, IE, VV weights for total error to minimize		AP = 1, IE = 1, VV = 1		As calibr. 1.	As calibr. 2.	As calibr. 3	As calibr. 4	As calibr. 5	As calibr. 5	AP = 2, IE = 1, VV = 1	AP = 5, IE = 1, VV = 1
Prestretch value bounds	**ACL**	0.75 – 1.25		0.85 - 1.05	As calibr. 2.	As calibr. 3	0.8 to 1.15	0.6 - 1.4	0.7 - 1.2	As calibr. 7	As calibr. 8
	PCL	0.75 – 1.25		0.85 - 1.05	As calibr.2.	As calibr. 3	0.8 to 1.15	0.6 - 1.4	0.7 - 1.2	0.7 - 1.0	As calibr. 8
	MCL	0.75 – 1.25		0.85 - 1.05	As calibr. 2.	As calibr. 3	0.8 to 1.15	0.6 - 1.4	0.7 - 1.2	As calibr. 7	As calibr. 8
	LCL	0.75 – 1.25		0.85 - 1.05	As calibr. 2.	As calibr. 3	0.8 to 1.15	0.6 - 1.4	0.7 - 1.2	As calibr. 7	As calibr. 8
Young's modulus value bounds (step size = 10)	**ACL**	N.A.		N.A.	73 - 173	As calibr. 3	As calibr. 4	As calibr. 5	As calibr. 5	13 - 223	As calibr. 8
	PCL	N.A.		N.A.	118 - 218	As calibr. 3	As calibr. 4	As calibr. 5	As calibr. 5	8 - 218	As calibr. 8
	MCL	N.A.		N.A.	174 - 274	As calibr. 3	As calibr. 4	As calibr. 5	As calibr. 5	114 - 324	As calibr. 8
	LCL	N.A.		N.A.	230 - 330	As calibr. 3	As calibr. 4	As calibr. 5	As calibr. 5	170 - 380	As calibr. 8

Table 7.5: Prestretch factor start values used in Calibrations 5 to 9.

	ACL	PCL	MCL	LCL
Start prestretch factors 1	0.9	1	1	1
Start prestretch factors 2	1	0.9	1	1
Start prestretch factors 3	1	1	1.1	1
Start prestretch factors 4	1	1	1	0.9
Start prestretch factors 5	1	1	1	1

7.3 Results

7.3.1 Model development

All eight models were developed successfully.

7.3.1.1 Sensitivity analysis 1: Prestretch and axial load application

Most of the models had trouble converging for part of the prestretch values explored, with most convergence difficulties found in models oks004, oks006 and oks007. The full results of this sensitivity analysis are available on *https://simtk.org/projects/abi_knee_models*.

7.3.1.2 Sensitivity analysis 2: Rotate the knee joint to the flexion angle in which the robot data is obtained.

Most models showed some convergence difficulties, especially at the edges of the ranges of the prestretch factor values explored. Especially models oks004 and oks007 showed convergence issues. For these models, potential problems with the meshes and the contact formulations were found. Since changing the contacts in the models did not solve the issues entirely, it was decided to make new models for subject oks004 and oks007, going through all the steps of the model development workflow again. This resulted in models with similar convergence compared to the other models. The full results of this sensitivity analysis are available on *https://simtk.org/projects/abi_knee_models*.

7.3.1.3 Sensitivity analysis 3: Obtain the bounds of prestretch values to use in the calibration

Convergence issues in the oks002, oks006 and oks007 models were found. However, it was chosen to run the calibrations with the models as they were to see if calibrating the models would solve these issues. The calibration bounds of the ligament prestretch values were chosen to be 0.75 - 1.25 since no clear bounds were obtained in this sensitivity analysis. The full results of this sensitivity analysis are available on *https://simtk.org/projects/abi_knee_models*.

7.3.2 Model calibration

The full calibration results are available on https://simtk.org/projects/abi_knee_models.

In Calibration 1, in which larger prestretch factor value bounds compared to the calibration in Chapter 3 were used, many calibrations did not perform well. Many calibrations resulted in a total error of 2 (the maximal error) early during the calibration, and this error did not decrease. In some models, a large condylar lift-off was found. This was due to the calibrated ligament prestretch factor values of 1.25, which resulted in an increase in ligament size of 25%. Next to this, the calibrated prestretch factor values caused the joint to be too stiff in the anterior-posterior (AP) direction for some of the models.

After updating the error calculations, using lower normalisation values and smaller prestretch factor value bounds in Calibration 2, almost all VV normalised root mean square error (RMSE) were 1.4. This meant the error was higher than the normalisation value. This indicated that the values of the errors assigned in the objective function had to be changed. In general, the calibration errors were high and the calibrated prestretch factor values were on or close to the calibration bounds.

The calibration of the ligament Young's moduli was added to the calibration of the ligament prestretch factor values in Calibration 3. A couple of errors in the models were found, which were corrected for Calibration 4. Models du02, oks004 and oks007 had "max_ups" in the control settings set to 10, where the other models' "max_ups" was set to 0. When max_ups is set to 0, FEBio will use the Full-Newton method, which reforms the stiffness matrix in each iteration (Maas et al., 2012). In model oks006, a meniscus spring was found to be in the wrong location.

In the models using the prestretch factor values obtained from Calibration 4, condylar lift-off was present, and the medial collateral ligament (MCL) penetrated the bones for multiple models. In Calibration 5, an MCL-bone contact was added, and the prestretch factor value bounds were increased compared to Calibration 4. The results from Calibration 5 were better compared to previous calibrations. However, the calibrated prestretch factor values went to the calibration boundaries for multiple models.

The prestretch factor value bounds were increased in Calibration 6. This caused the joint to distract and no medial and lateral cartilage contact was present for some of the models. This indicated that the bounds of the prestretch values were too large. In Calibration 7 the bounds of the prestretch factor values were increased compared to Calibration 5 but not as much as in Calibration 6. This resulted in adequate calibration results for four out of eight models in Calibration 7. The calibration results were better for the internal-external (IE) and varus-valgus (VV) simulations compared to the AP simulations for most models, where the joint seemed to be too stiff in the AP direction.

In all calibrations so far, the weight of the normalised AP, IE and VV error in the total error to be minimised was the same for each degree of freedom. In Calibration 8, the AP weight was doubled compared to the weight of IE and VV. Next to this, the posterior cruciate ligament (PCL) prestretch factor value bounds and the Young's moduli bounds were increased. This resulted in better calibration results for some of the models. Since this was not the case for all models, the AP weight was further increased in Calibration 9, where the AP weight was five times the weight of that of IE and VV. Comparing the results of Calibration 9 to Calibration 7, some models showed better calibration results but the calibration results of other models were worse.

7.3.2.1 Best calibration results per model

In Table 7.6, Figure 7.1 & Figure 7.2, the best calibration results per model from calibrations 7, 8 and 9 were summarised. For four out of eight models, the calibration results were poor (models oks002, oks004, oks007 and oks008).

Table 7.6: Best three calibration results per model.

Model		**From: (calibration nr: algorithm-start values set)**	**RMSE**			**Prestretch factor value**				**Young's modulus (MPa)**			
			AP (mm)	**IE (deg.)**	**VV (deg.)**	**ACL**	**PCL**	**MCL**	**LCL**	**ACL**	**PCL**	**MCL**	**LCL**
du02	**1**	7: TNC-3	3.592	0.802	0.703	1.133	1.154	0.93	1.2	73	178	224	240
	2	8: L-BFGS-B-2	1.819	2.178	0.520	0.7	1	0.7	1.009	13	8	194	330
	3	9: TNC-4	2.708	0.845	0.606	0.931	1	0.877	1.135	53	158	324	300
oks001	**1**	7: L-BFGS-B-2	1.912	1.767	0.700	1.152	1.2	0.943	1.175	73	158	214	240
	2	7: TNC-5	1.984	2.328	0.882	1.159	1.2	0.893	1.158	73	168	214	260
	3	7: TNC-3	2.213	1.837	0.574	1.117	1.2	0.95	1.2	133	118	244	300
oks002	**1**	7: L-BFGS-B-1	5.841	1.294	0.930	1.2	1.2	0.7	0.877	93	218	174	240
	2	7: TNC-3	5.947	1.595	0.620	1.2	1.2	0.719	0.857	93	218	274	300
	3	7: TNC-2	5.740	1.194	1.633	1.073	1.2	0.807	0.869	173	198	234	310
oks003	**1**	8: L-BFGS-B-4	1.309	4.086	1.331	0.7	0.965	1.026	0.814	133	38	114	210
	2	7: L-BFGS-B-4	1.600	3.650	1.161	0.7	1.2	1.2	0.878	123	118	174	290
	3	8: TNC-2	1.428	2.709	2.207	0.7	0.7	1.007	1.007	53	138	114	290
oks004	**1**	8: L-BFGS-B-1	2.426	8.163	0.955	1.052	0.842	1.015	1.158	63	8	254	250
	2	9: L-BFGS-B-1	3.349	6.920	1.360	1.036	1	1.085	1.2	143	18	324	280
	3	7: TNC-2	5.505	4.889	1.177	0.999	1.2	1.065	1.2	73	118	244	330
oks006	**1**	7: TNC-2	2.078	1.705	0.802	0.791	1.2	0.848	0.797	113	118	174	330
	2	7: L-BFGS-B-5	2.020	1.939	1.087	0.7	1.2	0.896	0.7	73	168	174	250
	3	7: TNC-1	2.197	2.441	0.884	0.78	1.2	0.793	0.7	173	138	174	230
oks007	**1**	7: L-BFGS-B-1	3.919	5.102	3.496	0.829	1.2	0.7	1.2	103	128	274	230
	2	9: TNC-4	1.636	3.172	4.471	0.7	1	0.7	1.2	193	8	244	170
	3	9: L-BFGS-B-4	2.056	2.892	4.654	0.7	1	0.7	1.2	143	8	224	220
oks008	**1**	7: TNC-1	1.782	12.147	4.917	1.2	1.116	1.2	0.7	103	138	254	240
	2	7: TNC-5	1.297	11.180	5.485	1.2	1.2	1.2	0.819	163	118	204	320
	3	9: L-BFGS-B-2	2.007	10.751	5.900	0.7	1	1.2	0.7	13	118	264	250

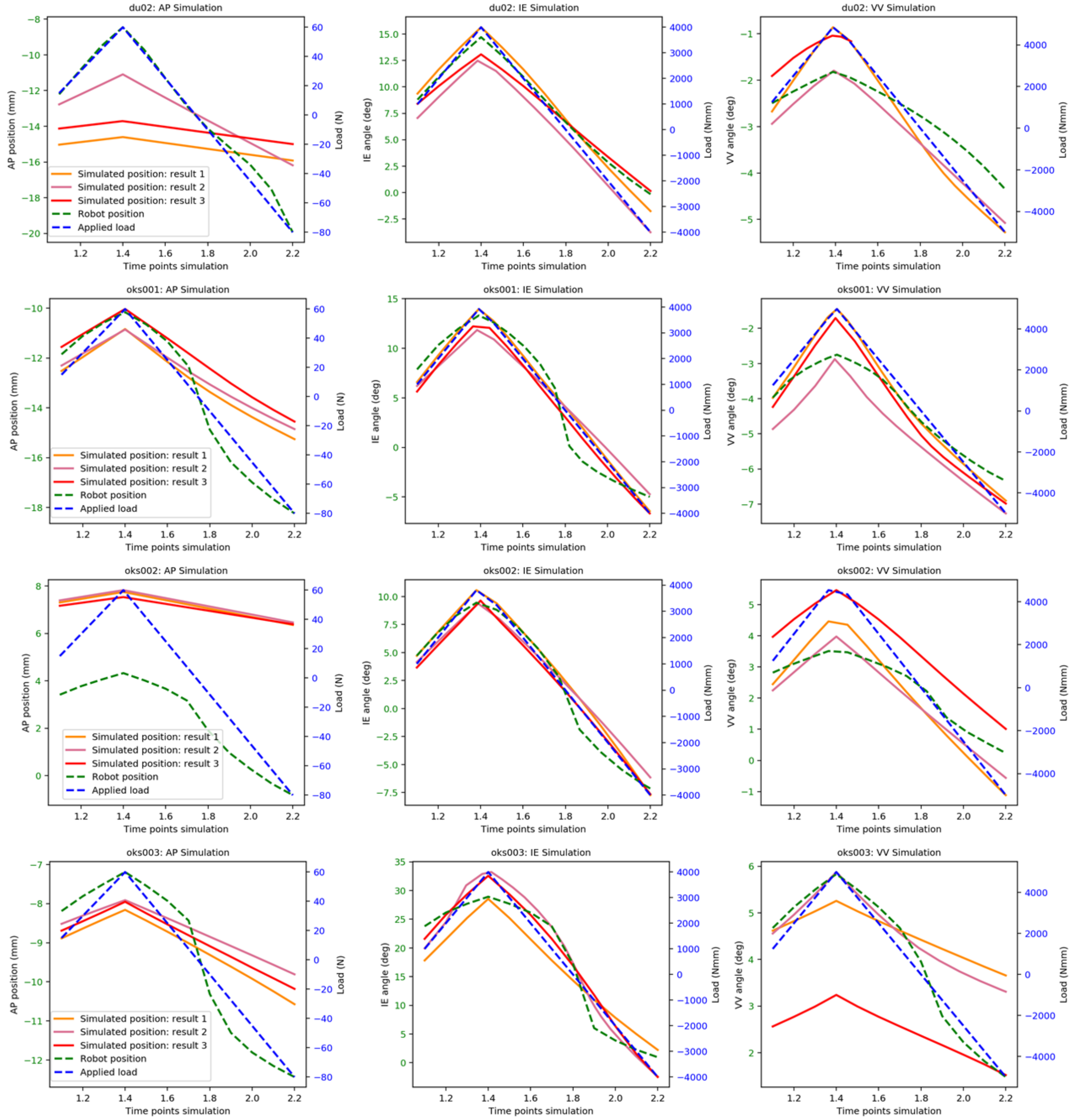

Figure 7.1: The three best calibration AP, IE and VV simulation results (Table 7.6) of model du02, oks001, oks002 and oks003.

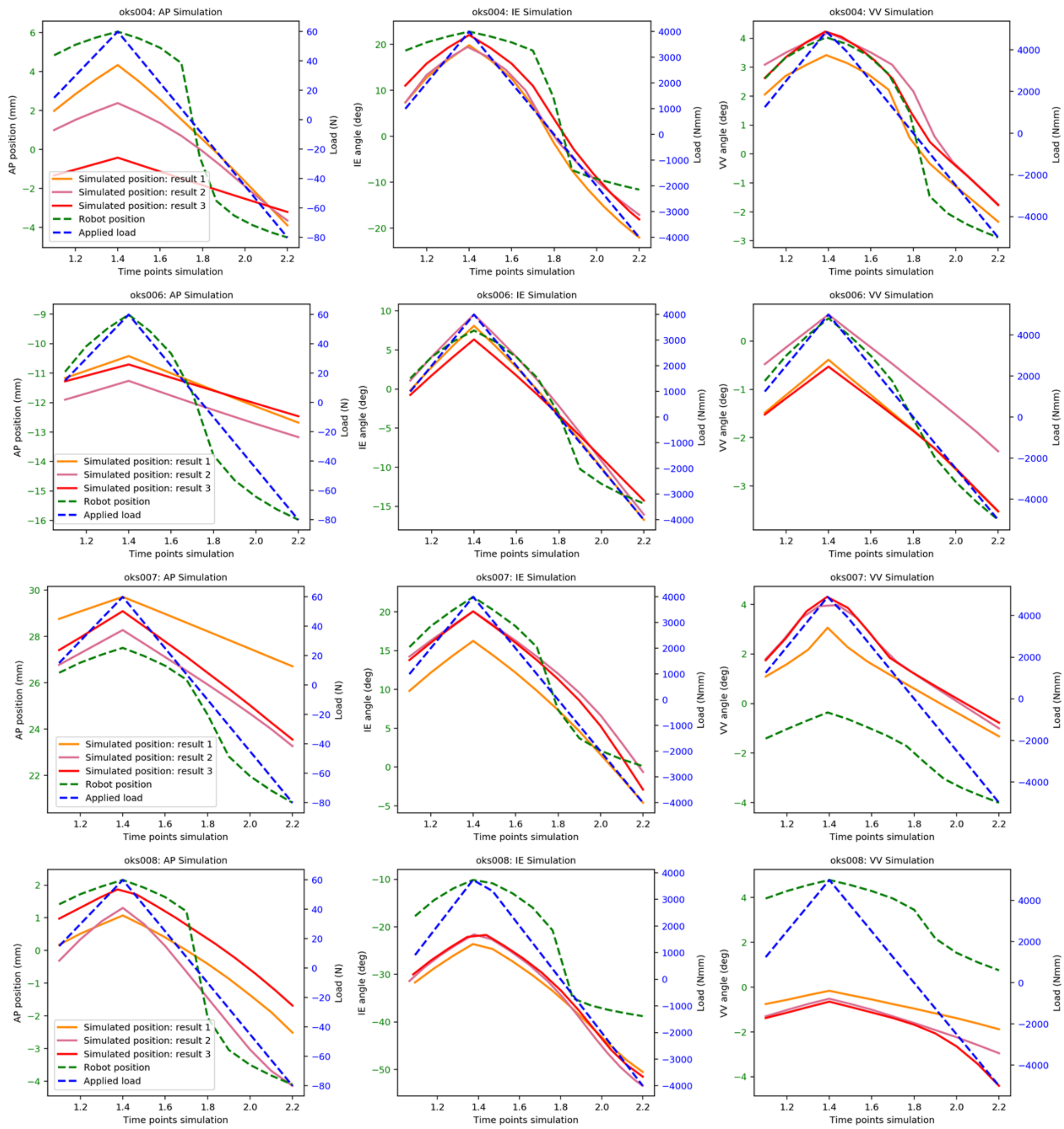

Figure 7.2: The three best calibration AP, IE and VV simulation results (Table 7.6) of model oks004, oks006, oks007 and oks008.

7.4 Discussion

7.4.1 Model development

Eight models were developed successfully using the workflow described in Chapter 3 with modifications. The most significant difference between the modelling workflow described in Chapter 3 and the workflow used here was the difference in ACS. This improvement of the model improves calibration quality since the ACS was better aligned to the robot laxity data coordinate system.

7.4.2 Model calibration

The model calibration objective function was adjusted iteratively depending on the results obtained from previous calibrations, improving the calibration results and improving the calibration workflow. In the end, four out of eight models had an acceptable calibration quality, whereas the other four showed considerable differences in laxity to the robot data.

Obtaining a calibration workflow is an iterative process. Decisions have to be made on what to change in the calibration workflow to obtain better results. These decisions made are dependent on the modeller, most probably resulting in variation in model calibration workflows. A lot of changes to the calibration workflow can be made, for example, which model parameters to calibrate, which simulations to perform in the objective function and how to calculate the error to minimise in the objective function. Ideally, all model parameters would be calibrated, but this would be computationally very expensive. A large scale sensitivity analysis might give more insight into which parameters influence model outcomes most to help decide which parameters to calibrate.

The multiple starts of the model calibrations of one model resulted in different calibration results. It is difficult to determine which calibration result to choose as the best result since the AP, IE and VV simulations each get their own RMSE value. For example, a certain VV angle RMSE might have a different effect on the final outcomes compared to the same RMSE in IE angle. Considerable differences in calibrated prestretch factor values and Young's modulus values were found for the same model. This shows that there might be multiple different combinations of calibrated parameters resulting in similar calibration results.

Some of the model simulations showed condylar lift-off in the AP, IE and VV simulations during calibration. This is unlikely to happen in the natural knee. However, this could be happening in the cadaveric knee in the robot since there are no muscle forces present keeping the joint together. Since the skin was still in place around the knee joint while obtaining the robot laxity data, it is not known if condylar lift-off was present during the robot laxity tests.

The VV simulation using the best calibration results of model du02 number 3 crashed when rerunning the simulation (Figure 7.1), where during calibration, this simulation did converge. This indicates that the best calibration result might not result in the most stable model.

7.4.3 Future work

In future work, there should be looked into improving the calibration workflow further. Ideally, the models would be calibrated at multiple degrees of flexion, depending on the flexion angle of interest.

However, it is computationally expensive to calibrate at multiple flexion angles. To improve the calibration workflow, there could be looked into calibrating more parameters to be able to get the model laxity as close as possible to the robot laxity data. For example, the ligament attachment sites could be taken into account. The models are now only calibrated to robot laxity data. To be able to draw valid contact mechanics conclusions, it would be best to calibrate to contact pressure data as well.

7.4.4 Conclusions

The model development workflow resulted in converging models for all eight datasets. Four adequately calibrated models were obtained that can be used in future studies with the knee joint in full extension. The calibration workflow developed needs to be improved before we can look into changing the workflow into a semi-automatic workflow.

References

Ali, A. A., Shalhoub, S. S., Cyr, A. J., Fitzpatrick, C. K., Maletsky, L. P., Rullkoetter, P. J., & Shelburne, K. B. (2016). Validation of predicted patellofemoral mechanics in a finite element model of the healthy and cruciate-deficient knee. *Journal of Biomechanics., 49*(2), 302-309.

Bennetts, C. J., Chokhandre, S., Donnola, S. B., Flask, C. A., Bonner, T. F., Colbrunn, R. W., & Erdemir, A. (2015). Open Knee(s): magnetic resonance imaging for specimen-specific next generation knee models. *SB3C2015, Summer Biomechanics, Bioengineering and Biotransport Conference, Utah, USA, June 17-20, 2015.*

Bonner, T. F., Colbrunn, R. W., Chokhandre, S., Bennetts, C., & Erdemir, A. (2015). Open Knee(s): comprehensive tibiofemoral joint testing for specimen-specific next generation knee models. *SB3C2015, Summer Biomechanics, Bioengineering and Biotransport Conference, Utah, USA, June 17-20, 2015*.

Colbrunn, R. W., Bonner, T. F., Chokhandre, S. K., Bennetts, C. J., Halloran J., & Erdemir, A. (2015). Open Knee(s): comprehensive patellofemoral joint testing for specimen-specific next generation knee models. *ASB 2015, 39th Annual Meeting of the American Society of Biomechanics, Columbus, Ohio, USA, August 5-8, 2015*.

Erdemir, A., Bennetts, C., Bonner, T., Chokhandre, S. K., & Colbrunn, R. W. (2015). Open Knee(s): founding data for next generation knee models. *BMES/FDA, Frontiers in Medical Devices Conference: Innovations in Modeling and Simulation, Washington, DC, USA, May 18-20, 2015*.

Harris, M. D., Cyr, A. J., Ali, A. A., Fitzpatrick, C. K., Rullkoetter, P. J., Maletsky, L. P., & Shelburne, K. B. (2016) A Combined Experimental and Computational Approach to Subject-Specific Analysis of Knee Joint Laxity. *Journal of biomechanical engineering, 138*(8), 0810041–0810048.

Maas, S.A., Ellis, B.J., Ateshian, G.A., Weiss, J.A. (2012). FEBio: Finite Elements for Biomechanics. *Journal of Biomechanical Engineering, 134*(1), 011005.

Zhang, J., Fernandez, J., Hislop-Jambrich, J., & Besier, T. F. (2016). Lower limb estimation from sparse landmarks using an articulated shape model. *Journal of biomechanics, 49*(16), 3875-3881.

Zhang, J., Hislop-Jambrich, J., & Besier, T. F. (2016). Predictive statistical models of baseline variations in 3-D femoral cortex morphology. *Medical engineering & physics, 38*(5), 450-457.