KneeHub_OKS Benchmark Documentation Cleveland State University

Release 1

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CHAPTER

ONE

MODEL BENCHMARK SUMMARY

This section summarizes the steps involved in benchmarking a finite element knee model. The summary includes links to other chapters where specific details are provided.

These steps apply to the OpenKnee(s) data set. The documentation for the DU data set can be found in a separate document.

1.1 Knee Model - Initial Deviations

The knee model that was delivered for the *Model Calibration* phase will be recalibrated and used for the benchmarking phase. This step is being taken to minimize the effects of group-specific interpretation of the calibration data, where new processed experimental data was made available at the beginning of the *Model Benchmarking* phase. If modeling assumptions were found to be inconsistent with the intended use of the calibration data the teams were asked to recalibrate their models using these processed data. In our instance, there will be changes to the model's fixed femoral coordinate system, and corresponding changes to the experimental kinematics that are used. These changes are summarized below and documented in more detail in the *Initial Deviations* (page 3) section.

1.1.1 Coordinate Systems

There are two primary ways the knee model's fixed coordinate systems will be updated. The first will change the way that the coordinate systems were defined. Rather than using the transforms reported in the experimental *state.cfg* file, digitized landmarks will be used to define the fixed femoral and tibial coordinate systems. The second change is in the selection of the fixed femoral coordinate system. The *state.cfg* file reports two femoral coordinate systems, one which is used to determine kinematics using Optotrak sensor positions, and the other is used to determine kinematics using the robot's end effector position. Due to these differences, two sets of kinematics are reported in each *.tdms* file. The teams were asked to use kinematics defined using the Optotrak sensor positions, which differs from the kinematics used by the CSU/WSU team in the *Model Calibration* phase. Due to this, the knee model's fixed femoral coordinate system was changed from that used in the *Model Calibration* phase. See the *Coordinate Systems* (page 3) section for more information.

1.1.2 Experimental Data

There are two primary ways that the experimental data used for model calibration will change. First, rather than parsing data from the given *.tdms* files, the experimental data has already been parsed and given in a .csv file. Second, the kinematics that will be used to calibrate the knee model will use a different set of experimental kinematics than was used in the *Model Calibration* phase. See the *Experimental Data* (page 5) section for more information.

1.2 Model Benchmarking

1.2.1 Benchmarking Simulations

The processed data delivered by the Cleveland Clinic team for "combined loading" will be run using the model that was recalibrated following the application of the *initial deviations* (page 3). This data consists of measured kinematics at 0, 30, 60 and 90 degrees flexion for simultaneously applied moments of 10 Nm valgus and 5 Nm internal (i.e. "combined" loads). These loads are defined in the joint coordinate system (JCS) and were parsed from the .tdms file and provided by the Cleveland Clinic team in a .csv file (see the download package on the KneeHub SimTK site).

The recalibrated model will kinematically control the flexion angle and apply the experimentally measured forces to the tibia's fixed coordinate system in all six degrees of freedom. See the *Benchmark Simulations* (page 6) section for more information. The model's predicted kinematics, contact mechanics, and ligament loads will be recorded and kinematics results will be compared to the measured values using root-mean-square (RMS) errors for each degree of freedom.

CHAPTER

TWO

INITIAL DEVIATIONS

2.1 Coordinate Systems

The way that the femoral and tibial coordinate systems were calculated was changed, however workflow to define registration between the experimental and MR image coordinate systems was not changed. It was verified that the previous workflow (documented under the *Tibiofemoral Model* > *Registration* section in the *Model Calibration* phase) for defining the digitized points around the registration fiducials yielded the same results as the given data. Therefore, the previous workflow was used instead of importing point coordinates from the following files:

- data-MB-oks003/RECALIBRATION-Probed_Points_Files/Fem_RM_lateral.xyz
- data-MB-oks003/RECALIBRATION-Probed_Points_Files/Fem_RM_medial.xyz
- data-MB-oks003/RECALIBRATION-Probed_Points_Files/Fem_RM_posterior.xyz
- data-MB-oks003/RECALIBRATION-Probed_Points_Files/Tib_RM_lateral.xyz
- data-MB-oks003/RECALIBRATION-Probed_Points_Files/Tib_RM_medial.xyz
- data-MB-oks003/RECALIBRATION-Probed_Points_Files/Tib_RM_posterior.xyz

2.1.1 Fixed Femoral Coordinate System

The femur's fixed coordinate system was calculated using the digitized landmark coordinates reported in the file `data-MB-oks003/RECALIBRATION-Probed_Points_Files/Fem_AL.xyz`. The methods described on pg. 5 of `data-MB-oks003/DESCRIPTION-DataRepresentation_OpenKnees.docx` were used to define the femur's fixed coordinate system in the optotrak sensor's global coordinate system ($T_{Sensor1\_Fem}$).

$$T_{Sensor1\_FEM} = \begin{bmatrix} F_x^0 & F_y^0 & F_z^0 & O_F^0 \\ F_x^1 & F_y^1 & F_z^1 & O_F^1 \\ F_x^2 & F_y^2 & F_z^2 & O_F^2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where F_x^i, F_y^i, F_z^i, and O_F^i are defined on pg. 5 in `data-MB-oks003/DESCRIPTION-DataRepresentation_OpenKnees.docx`. The superscripts in the above equation indicate the vector's index.

Next the transform from the MR image's global coordinate system to the femur's fixed coordinate system in the MR image ($T_{Im\_Sensor1}$) was defined. $T_{Im\_Sensor1}$ (which is determined using methods described in the *Tibiofemoral Model* > *Registration* section in the *Model Calibration* phase) is multiplied by $T_{Sensor1\_Fem}$

$$T_{Im\_Fem} = T_{Im\_Sensor1} T_{Sensor1\_Fem}$$

T_{Im_Fem} can be used to define the femur's fixed coordinate system in the knee model using the SimVitro convention, where the positive direction on the *anterior-posterior* axis points posteriorly. To match the convention used by the

CSU lab, the fixed femoral coordinate system defined by T_{Im_Fem} was rotated 180 degrees about the fixed femur's z-axis. This defined the positive direction along the *anterior-posterior* axis as pointing anteriorly.

$$S_{Im\_Fem} = T_{Im\_Fem} * \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The last row in S_{Im_Fem} is neglected, and the columns are used to define the axes of the fixed femoral coordinate system and its origin.

$$\begin{aligned} x_{axis} &= [S_{Im\_Fem}(0,0), S_{Im\_Fem}(1,0), S_{Im\_Fem}(2,0)] \\ y_{axis} &= [S_{Im\_Fem}(0,1), S_{Im\_Fem}(1,1), S_{Im\_Fem}(2,1)] \\ z_{axis} &= [S_{Im\_Fem}(0,2), S_{Im\_Fem}(1,2), S_{Im\_Fem}(2,2)] \\ origin &= [S_{Im\_Fem}(0,3), S_{Im\_Fem}(1,3), S_{Im\_Fem}(2,3)] \end{aligned}$$

2.1.2 Fixed Tibial Coordinate System

The tibia's fixed coordinate system was calculated using the digitized landmark coordinates reported in the file `data-MB-oks003/RECALIBRATION-Probed_Points_Files/Fem_AL.xyz`. The methods described on pg. 4-5 of `data-MB-oks003/DESCRIPTION-DataRepresentation_OpenKnees.docx` were used to define the tibia's fixed coordinate system in the optotrak sensor's global coordinate system ($T_{Sensor2\_Tib}$).

$$T_{Sensor2\_Tib} = \begin{bmatrix} T_x^0 & T_y^0 & T_z^0 & O_T^0 \\ T_x^1 & T_y^1 & T_z^1 & O_T^1 \\ T_x^2 & T_y^2 & T_z^2 & O_T^2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where T_x^i, T_y^i, T_z^i, and O_T^i are defined on pg. 4-5 in `data-MB-oks003/DESCRIPTION-DataRepresentation_OpenKnees.docx`. The superscripts in the above equation indicate the vector's index.

Next the transform from the MR image's global coordinate system to the tibia's fixed coordinate system in the MR image ($T_{Im\_Sensor2}$) was defined. $T_{Im\_Sensor2}$ (which is determined using methods described in the *Tibiofemoral Model* > *Registration* section in the *Model Calibration* phase) is multiplied by $T_{Sensor2\_Tib}$

$$T_{Im\_Tib} = T_{Im\_Sensor2} T_{Sensor2\_Tib}$$

T_{Im_Tib} can be used to define the tibia's fixed coordinate system in the knee model using the SimVitro convention, where the positive direction on the *anterior-posterior* axis points posteriorly. To match the convention used by the CSU lab, the fixed tibial coordinate system defined by T_{Im_Tib} is rotated 180 degrees about the fixed tibia's z-axis. This defines the positive direction along the *anterior-posterior* axis as pointing anteriorly.

$$S_{Im\_Tib} = T_{Im\_RB2} * \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The last row in S_{Im_Tib} is neglected, and the columns are used to define the axes of the fixed tibial coordinate system and its origin.

$$\begin{aligned} x_{axis} &= [S_{Im\_Tib}(0,0), S_{Im\_Tib}(1,0), S_{Im\_Tib}(2,0)] \\ y_{axis} &= [S_{Im\_Tib}(0,1), S_{Im\_Tib}(1,1), S_{Im\_Tib}(2,1)] \\ z_{axis} &= [S_{Im\_Tib}(0,2), S_{Im\_Tib}(1,2), S_{Im\_Tib}(2,2)] \\ origin &= [S_{Im\_Tib}(0,3), S_{Im\_Tib}(1,3), S_{Im\_Tib}(2,3)] \end{aligned}$$

2.2 Experimental Data

The primary difference between *Model Calibration* and *Model Benchmarking* phase is the source of the kinematic data. The *Extract Experimental Data* section *Model Calibration* phase describes how kinematics from the `State.JCS` part of the data was used to define kinematics. Due to changes in the *femoral coordinate system* (page 3), kinematics classified under `State.Knee JCS` are used instead. Additionally, the experimental data will be taken from the given *.csv* files located in `data-MB-oks003/RECALIBRATION-Processed_Data` rather than being extracted from *.tdms* files.

The experimental data will be processed in the same way as described in the *Process Experimental Data - OpenKnee(s)* section of the *Model Calibration* documentation. Any data that was originally referenced as coming from the `State.cfg` file or *.tdms* file will be defined using the files in `data-MB-oks003/RECALIBRATION-Processed_Data` instead.

CHAPTER

THREE

BENCHMARK SIMULATIONS

This section describes the specific steps and boundary conditions that were used during Abaqus/Explicit FE simulations of the benchmark load cases. The differences between the different load case simulations simulations was the magnitude of the specified kinematics and loads in the *Initial Orientation Step* (page 8) and *Test Case Step* (page 9) steps. The magnitude of these loads and boundary conditions were defined as `*Amplitudes` in the Abaqus .inp files, and the corresponding *processed experimental data* (page 5) were used to define the amplitudes each simulation. This section does not delineate between values that were used for each simulation.

3.1 Initial Settle Step

Before this simulation, the ligament meshes have been defined from the results of the *reference simulation* defined during the *Model Calibration* phase, so there was no overclosure between the ligaments and other bodies.

The total time for this step is 0.01 seconds.

3.1.1 Interactions

All of the desired interactions are active in this step.

Table 3.1: Active interactions between different bodies and structures during the *Initial Settle* step.

Name	Femur	Tibia	Femoral Cartilage	Medial Tibial Cartilage	Lateral Tibial Cartilage
amACL	x	x	x		
plACL	x	x	x		
alPCL	x	x	x		
pmPCL	x	x	x		
sMCLProx	x	x	x	x	
sMCLDist	x	x	x	x	
dMCL	x	x	x	x	
LCL	x	x			
ALL	x	x	x		x
PFL	x	x	x		x
OPL	x	x	x		x
Femur		x		x	x
Tibia	x		x		
Femoral Cartilage		x		x	x
Medial Tibial Cartilage	x		x		
Lateral Tibial Cartilage	x		x		
Medial Meniscus	x	x	x	x	
Lateral Meniscus	x	x	x		x

3.1.2 Kinematic Boundary Conditions

The rigid bodies were fixed in all degrees of freedom.

Femur

The femur was fixed in all degrees of freedom throughout this step.

Tibia

The tibia was fixed in all degrees of freedom throughout this step.

3.1.3 Kinetic Boundary Conditions

There were no external loads.

Femur

No external loads were applied to the femur in this step.

Tibia

No external loads were applied to the tibia in this step.

3.2 Initial Orientation Step

This step moves the femur from it's initial position to the flexion angle for the specific benchmark test case. The femur's flexion angle was controlled, but the femur was free to move in other degrees of freedom. The initial flexion angle was defined by the joint's position in the MR images, and the final flexion angle was defined by the flexion angle that is experimentally measured during the simulated test case. There was a nominal 20 N compressive load applied to the femur throughout this step.

The total time for this step is 0.5 seconds.

3.2.1 Interactions

The orientation of the knee at the end of this step is orientation at the beginning of the simulated test case. As such, all of the interactions that are desired for the simulated test are active during this step (Table 3.1).

3.2.2 Kinematic Boundary Conditions

Femur

For the simulated test, the femur was unconstrained in all directions except for rotation about the flexion axis. The angle about the femur's flexion axis was assigned throughout this step.

The initial orientation of the knee is known after the femur and tibia coordinate systems are defined with respect to the MR image's coordinate system. The initial flexion angle was used to define the kinematic boundary condition for the femur during this step. Rotation was applied to the connector element that corresponds to the flexion axis (see the *Model Development* documentation for details on the joint coordinate system connectors).

The final flexion angle of the knee was specified as experimentally measured flexion angle. Note that this is the absolute flexion angle, which is defined from the *processed experimental data* (page 5) and linearly ramped from the imaged position. The knee is free to move in all other degrees of freedom.

Tibia

The tibia was fixed in all degrees of freedom. This ensured that the tibia's origin was in the desired orientation at the beginning of the test case step.

3.2.3 Kinetic Boundary Conditions

Femur

To reduce the instability in the simulation, a nominal 20 N compressive force was applied to the femur during this step. This force was applied to the connector that defines internal-external tibial rotation axis (see the *Model Development* documentation for details on the joint coordinate system connectors). No other external forces are applied to the femur.

Tibia

No external loads were applied to the tibia in this step.

3.3 Test Case Step

This step applied the experimentally measured loads to the node that is coincident with the fixed tibial coordinate system's origin. The femur was fixed throughout this step, the flexion angle was specified, and the tibia is free to move in the other five degrees of freedom.

See the *loading profile* (page 10) section for more information on how the benchmarking test case loads were applied to the knee model in this step.

3.3.1 Interactions

All interactions that are assigned for the simulated test are active during this step (Table 3.1).

3.3.2 Kinematic Boundary Conditions

Femur

The femur is fixed in all degrees of freedom throughout this step.

Tibia

The flexion angle of the joint was specified throughout this step, however, the tibia was free to move in the other five degrees of freedom. The flexion angle was defined as the experimentally measured flexion angles. Note that this is the absolute flexion angle, defined using *processed experimental data* (page 5).

3.3.3 Kinetic Boundary Conditions

Femur

No external loads were applied to the femur in this step.

Tibia

The experimentally measured tibial loads were applied to the node that was coincident with the fixed tibial coordinate system. As described in the *Tibial Origin Orientation* section of the *Model Calibration* documentation, a transform was used to define the orientation of this node as coincident with the fixed tibial coordinate system. The *processed experimental* (page 5) tibial forces used to define the profile of the tibial loads in 6 degrees of freedom. Each loading value was applied as linear ramps between each load point. Note that the tibia is fixed in flexion about the JCS coordinate system, however the JCS flexion axis is not necessarily coincident with any of the axes of the tibia's fixed coordinate system, therefore, loads in all 6 degrees of freedom were applied.

Below is an example of the loads used for a left knee specimen (such as oks003):

```
** Medial tibial drawer force, -1. for right knee and 1. for left knee
*CLOAD, amplitude=medialTibialDrawerForce, follower, op=new
JointCoordSys.1, 1, 1.
** Anterior tibial drawer force, 1. for right and left knee
*CLOAD, amplitude=anteriorTibialDrawerForce, follower, op=new
JointCoordSys.1, 2, 1.
** Distraction force, -1. for right and left knee
*CLOAD, amplitude=distractionForce, follower, op=new
JointCoordSys.1, 3, -1.
** Flexion torque, -1 for a right and left knee
*CLOAD, amplitude=flexionTorque_Posteriordrawer_oks003, follower, op=new
JointCoordSys.1, 4, -1.
** Varus torque, 1. for right knee and -1. for left knee
*CLOAD, amplitude=varusTorque, follower, op=new
JointCoordSys.1, 5, -1.
** Internal tibial rotation torque, 1. for right knee and -1. for left knee
*CLOAD, amplitude=internalTibialRotationTorque, follower, op=new
JointCoordSys.1, 6, -1.
```

Where each amplitude was the magnitude of the corresponding load and the descriptions of the loads match the CSU/WSU convention (described in *Experimental Data* (page 5)). These values can be found in the corresponding test's *.inp* file. The `follower` option ensures the applied loads follow the orientation of the node `JointCoordSys.1` as the tibia moves throughout the simulation.

The node `JointCoordSys.1` is the node that is coincident with the origin of the tibia's fixed coordinate system. The integer following `JointCoordSys.1` indicates the degree of freedom that the load is applied to. The final integer is multiplied by the specified amplitude. This is used to adjust for a right or left knee (see the *Kinetics Adjustment 2 - Right or Left Knee* section in the *Model Calibration* documentation for more information).

Note: The loads were applied relative to this node's (`JointCoordSys.1`) coordinate system. This coordinate system is likely not coincident with the global coordinate system.

Tibia Loading Profile

A ramp-and-hold scheme was used to apply the desired loads from the benchmarking test case (Fig. 3.1). The given test point was simulated over 4.0 seconds, where the load was linearly increased to the desired value at 3.5 seconds and subsequently held for 0.5 seconds (Fig. 3.1). These loading profiles apply the experimentally measured loads in all 6 degrees of freedom. Note that Fig. 3.1 highlights the dominate loading axes, however every degree of freedom likely has a non-zero load throughout the simulation.

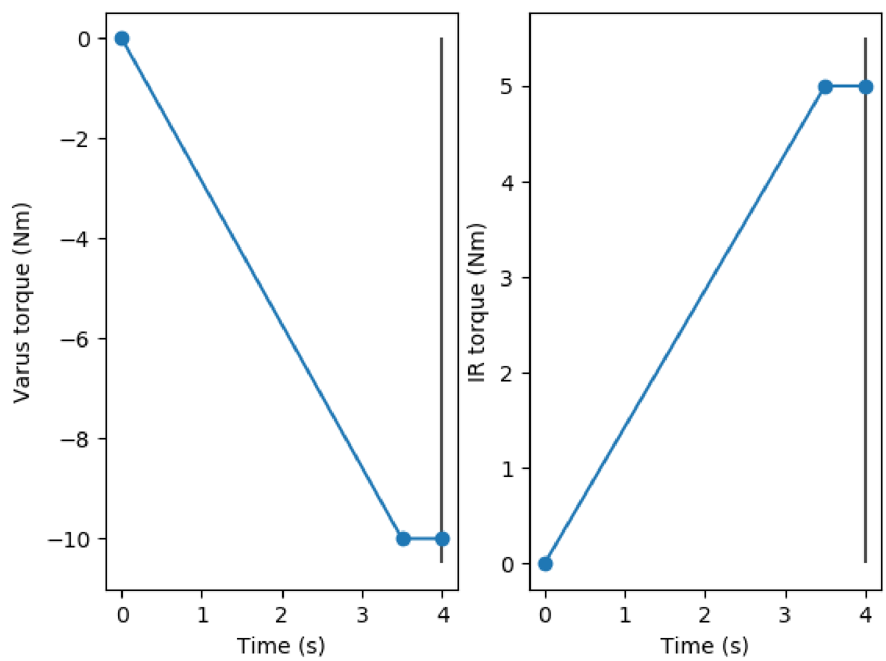

Fig. 3.1: The succession of applied varus and internal rotation loads throughout a combined loading test. The vertical lines indicate the points in the step's time where the simulation's results are extracted. Note that loads were applied in the other four degrees of freedom.