KneeHub_DU Benchmark Documentation Cleveland State University

Release 1

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CONTENTS

1 Model Benchmark Summary **1**
- 1.1 Knee Model - Initial Deviations 1
- 1.2 Model Benchmarking 1

2 Initial Deviations **3**
- 2.1 Experimental Data Processing - DU 3
- 2.2 Kinematics and Kinetics Adjustment 1 - CSU/WSU convention 4
- 2.3 Kinetics Adjustment 2 - Right or Left Knee 5

3 Benchmark Simulations **7**
- 3.1 Initial Settle Step 7
- 3.2 Initial Orientation Step 9
- 3.3 Test Case Step 10

Bibliography **13**

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 DU data set. The documentation for the OpenKnee(s) 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. In the case of the DU specimen model that was delivered by the CSU/WSU team, the experimental kinematics will be updated and the model will be recalibrated. Specific changes are summarized below and detailed documentation is included in the *Initial Deviations* (page 3) section.

1.1.1 Experimental Data

The only deviation that is needed from the *Model Calibration* phase is in the processing of the given DU kinematics. The original *Model Calibration* documentation misinterpreted the reported translations as *joint translations* rather than *clinical translations*. The model calibration workflow was setup to measure the *joint translations* from the knee model, and to avoid changing the original workflow, the experimental data will be converted from *clinical translations* to *joint translations*. Any data that is reported will specify whether *clinical translations* or *joint translations* are used. See the *Initial Deviations* (page 3) section for more information.

1.2 Model Benchmarking

1.2.1 Experimental Data

The processed data delivered by the University of Denver team for benchmarking consists of anterior-posterior, varus-valgus and internal-external laxity data after anterior-cruciate ligament (ACL) resection. This data was collected at two flexion angles (roughly 15 and 55 degrees). The processed data also includes a post ACL resection passive flexion test. The recalibrated DU knee model will be used to simulate the laxity and passive flexion tests. The processed data includes what are termed "Benchmark Points", which appear to be sampled at (or near) a succession of desired laxity loads (e.g. 80 N anterior load, etc.) from the relatively high-frequency data collected during the experiment.

The Benchmarking Points data will be used as boundary conditions in the recalibrated knee model. To reflect the resection of the ACL in the experiment, the amACL and plACL will be removed from the model. The flexion angle will be kinematically controlled and experimentally measured kinetics will be applied in all 6 degrees of freedom to the tibia's fixed coordinate system. Model-predicted kinematics, ligament loads and contact mechanics will be recorded throughout the simulations and kinematics results will be compared to the measured values using root-mean-square (RMS) errors for each degree of freedom. For more information, see the *Benchmark Simulations* (page 7) section.

CHAPTER

TWO

INITIAL DEVIATIONS

The only deviation that is needed from the *Model Calibration* phase is in the processing of the given DU kinematics. The original *Model Calibration* documentation misinterpreted the reported translations as *joint translations* rather than *clinical translations* [GS83]. The model calibration workflow was setup to measure the *joint translations* from the knee model, and to avoid changing that workflow, the experimental data will be converted from *clinical translations* to *joint translations*. Any data that is reported will specify whether *clinical translations* or *joint translations* are used.

2.1 Experimental Data Processing - DU

The following process is used to convert the given *clinical translations* to *joint translations*. This uses definitions and equations from [GS83].

$$\begin{aligned} q_1 &= S_1 + S_3 cos(\beta) \\ q_2 &= S_2 \\ q_3 &= -S_3 - S_1 cos(\beta) \end{aligned}$$

Where q_1, q_2, q_3 are the reported lateral, anterior, and superior tibial translation values, and β is the angle between the tibia's *z-axis* and the femur's *x-axis*.

$$\beta = \begin{cases} \frac{\pi}{2} - varus & \text{right knee} \\ varus + \frac{\pi}{2} & \text{left knee} \end{cases}$$

Note: The definition of β varies from that reported by [GS83] in *Table 2*. The definition of β follows the convention shown in *Figure 1* [GS83].

Solving the above equation for S_1 and S_3.

$$\begin{aligned} S_1 &= q_1 - S_3 cos(\beta) \\ S_3 &= -\frac{q_3 + q_1 cos(\beta)}{1 - cos(\beta)^2} \end{aligned}$$

The calculated *joint translations* (S_1, S_2, S_3) will be used in model calibration. Following this conversion, the experimental data will be processed in the same manner as described in the *Process Experimental Data - DU* section of the *Model Calibration* documentation. The relevant section is reproduced below, and changes were made for clarity with the above calculations. Note that the load definitions were not changed in the *Model Benchmarking* phase.

2.2 Kinematics and Kinetics Adjustment 1 - CSU/WSU convention

The joint kinematics and kinetics were converted to the convention used by the CSU/WSU lab. This step was not strictly necessary, however. It was implemented to keep the data consistent with the modeling workflow used in the CSU/WSU lab, which also allowed retention of our current documentation of the description of motion. The CSU/WSU convention describes motions as:

- Medial tibial translation
- Anterior tibial translation
- Superior tibial translation
- Flexion
- Varus
- Internal tibial rotation.

To convert to the CSU/WSU convention, the sign of the kinematics for three motions were changed (Table 2.1):

1) `TF ML (mm)` (S_1 above) kinematics are multiplied by -1 to convert to medial tibial translation.
2) `TF VV (deg)` kinematics are multiplied by -1 to convert to varus rotation.
3) `TF IE (deg)` kinematics are multiplied by -1 to convert to internal tibial rotation.

To convert to the CSU/WSU convention, the sign of the kinetics for three loads were changed (Table 2.1):

1) `Force TF ML (N)` kinetics are multiplied by -1 to convert to medial tibial drawer force.
2) `Torque TF VV (Nmm)` kinetics are multiplied by -1 to convert to varus torque.
3) `Torque TF IE (Nmm)` kinetics are multiplied by -1 to convert to internal tibial rotation torque.

Table 2.1: The heading of the reported kinematic and kinetic degrees of freedom, the descriptions of the positive reported values, and the value that is multiplied by the experimental data to convert to the CSU conventions.

Reported	Reported Positive Direction	CSU/WSU convention
TF ML (mm) (S_1 above)	Lateral tibial translation	-1
TF AP (mm) (S_2 above)	Anterior tibial translation	1
TF SI (mm) (S_3 above)	Superior tibial translation	1
TF FE (deg)	Flexion	1
TF VV (deg)	Valgus	-1
TF IE (deg)	External tibial rotation	-1
Force TF ML (N)	Lateral tibial drawer force	-1
Force TF AP (N)	Anterior tibial drawer force	1
Force TF SI (N)	Distraction force	1
Torque TF FE (Nmm)	Flexion torque	1
Torque TF VV (Nmm)	Valgus torque	-1
Torque TF IE (Nmm)	External tibial rotation torque	-1

Note: There was no conversion needed for right or left knees because the kinematics were measured using the *connector* elements defined in the *Model Development* documentation. These connector elements compose the joint coordinate system ([GS83]), and their definition in developing the model takes into account whether the specimen is a right or left knee.

2.3 Kinetics Adjustment 2 - Right or Left Knee

The signs of the loads may be changed depending on whether a right or left knee specimen was simulated. This is because the loads are applied with respect to the fixed tibial coordinate system, and the positive directions of this coordinate system may not match the experimental data's loading directions.

For example, based on the CSU/WSU convention, the positive *x direction* points to the right. The reported load that corresponds to this direction is `Lateral Drawer`. For a right knee, the `Lateral Drawer` direction and the tibia's *x-axis* point in the same direction. Conversely, for a left knee the `Lateral Drawer` direction and the tibia's *x-axis* point in opposite directions. The sign of the reported data was changed because the loads were applied with respect to the tibia's fixed coordinate system.

These adjustments were applied in the part of the Abaqus `.inp` file that was used to define the *test cases* (page 10) step. An example of these adjustments can be seen in the *code block* (page 6) below.

Below is a description of how the experimental loads were adjusted for each degree of freedom.

- After the previous adjustment (Table 2.2), the data is described as `medial tibial drawer`. For a right knee, the data is multiplied by -1 (Table 2.2) to change the load to `lateral tibial drawer`.
- The data is reported as `anterior tibial drawer`, and not adjusted in the previous step (Table 2.2). The anterior direction is in the positive *y direction* relative to the fixed tibial coordinate system for left and right knees, so this value is not changed for right or left knees (Table 2.2).
- The data is reported as `distraction`, and not adjusted in the previous step (Table 2.2). A load that acts in the inferior direction relative to the fixed tibial coordinate system will cause joint distraction regardless of a right or left knee. The positive direction for the tibia's *z-axis* points in the superior direction, therefore the sign for both right and left knees is changed to make the distraction load act in the inferior direction (Table 2.2).
- The `flexion torque` from the previous step is multiplied by -1 (Table 2.2). The *medial-lateral axis* points to the right (for both a right and left knee), and a negative torque about the tibia's “flexion axis” will cause knee flexion.
- The data is reported as `varus torque`, and not adjusted in the previous step (Table 2.2). The *y-axis* of tibia's fixed coordinate system points in the anterior direction. For a right knee, a positive torque around the tibia's y-axis causes varus, so the sign is not changed for a right knee. However the sign is changed for a left knee because a positive torque about the *y-axis* of a left tibia causes valgus.
- After the previous adjustment (Table 2.2), the data is described as `internal tibial rotation torque`. A positive rotation about the positive *z-direction* of a right knee causes internal tibial rotation, so the sign is not changed for a right knee. However the sign is changed for a left knee because a positive rotation about the positive *z-direction* of a left knee causes external tibial rotation.

Table 2.2: The degree of freedom at the node that the loads are applied to, and the corresponding load description, and the relevant sign convention changes. The reported description is from the given .tdms files that contain experimental data under the `State.JCS Load` heading.

Axis	Reported	CSU/WSU convention	Right knee	Left knee
x_1	Force TF ML (N)	-1	-1	1
x_2	Force TF AP (N)	1	1	1
x_3	Force TF SI (N)	1	-1	-1
x_4	Torque TF FE (Nmm)	-1	-1	-1
x_5	Torque TF VV (Nmm)	1	1	-1
x_6	Torque TF IE (Nmm)	-1	1	-1

Below is an example code showing how loads are specified in the Abaqus input file for a simulation of a **right** knee:

```
** 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, 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 is the magnitude of the corresponding load, where the adjustments from *adjustment 1* (page 4) are reflected. The node `JointCoordSys.1` is the node that was coincident with the origin of the tibia's fixed coordinate system. The integer following `JointCoordSys.1` indicates the degree of freedom that the load was applied to, and this corresponds with x_i in Table 2.2. The final integer is multiplied by the specified amplitude. This was used to adjust for a right or left knee according to Table 2.2.

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 9) and *Test Case Step* (page 10) 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 4) 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 4) 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 was free to move in the other five degrees of freedom.

See the *loading profile* (page 11) 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 4).

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 4) 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 right knee specimen (such as DU02):

```
** 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, 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 convention (described in *Kinematics and Kinetics Adjustment 1 - CSU/WSU convention* (page 4)). 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 (*Kinetics Adjustment 2 - Right or Left Knee* (page 5)).

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). Three load points were used for each test case, and the load points were simulated sequentially. Each load point was simulated over 1.0 seconds, where the load was linearly increased to the desired value at 0.5 seconds and subsequently held constant 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.

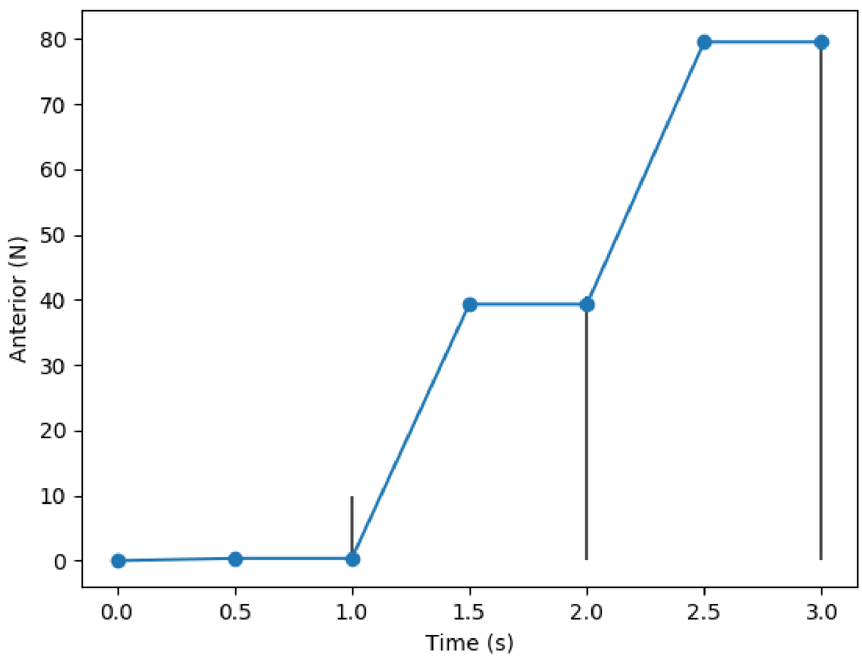

Fig. 3.1: The succession of applied anterior tibial loads throughout an anterior drawer test. The vertical lines indicate the points in the step's time where the simulation's results are extracted. Note that loads were applied in the other four degrees of freedom.

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[GS83] E. S. Grood and W. J. Suntay. A Joint Coordinate System for the Clinical Description of Three-Dimensional Motions: Application to the Knee. *Journal of Biomechanical Engineering*, 105(2):136–144, May 1983. URL: http://dx.doi.org/10.1115/1.3138397, doi:10.1115/1.3138397.