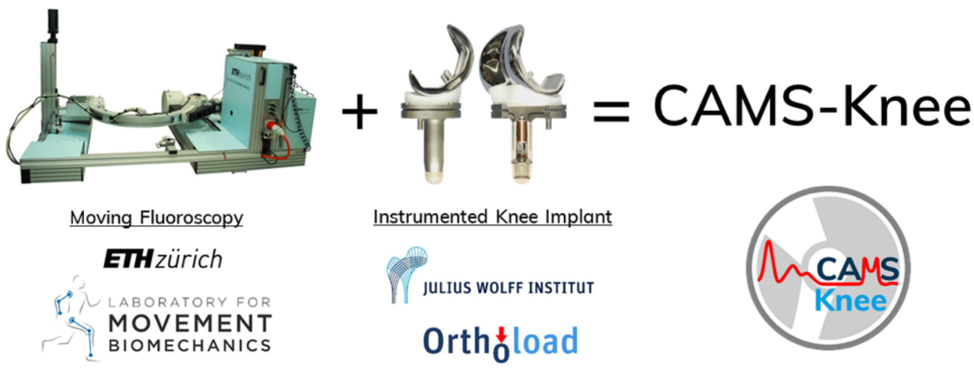
Description of the complete CAMS-Knee datasets

Version 1.1; update Feb 2023



General notes

The CAMS-Knee database contains processed data of multiple trials captured from different activities performed by subjects measured within the CAMS-Knee project. The studied activities include level walking, stair descent, downhill walking (ramp down), sit-stand-sit, squatting, as well as standing (please check Taylor et al., 2017 for more details). This CAMS-Knee description document will be updated from time to time and can be found at https://cams-knee.orthoload.com/data/request/

Release notes

In February 2023, the CAMS-knee datasets were updated to version 1.1. This new release includes the following changes:

- The sign of the free vertical torque (Tz_lab and Tz_lab_IfB) measured using the fixed (FP1-FP6) force plates has been corrected for all subjects. Originally, the Tz values described the free vertical torque acting on the force plate, but for consistency, Tz now defines the free vertical torque acting on the foot. Signs for the mobile force plates (FP7-FP8) have not been corrected as these were already consistent with the forces.
- The location of the centres of pressure (COPy_lab_6 and COPy_lab_IfB_6) in the lab coordinate system (CSLAB) for the sit-to-stand-to-sit activity of the K7L subject have been corrected by -12.0mm (i.e. new_value = old_value - 12.0mm).

Subjects' details

Six subjects (5 m, 1f, aged 75 ± 5 years, body mass 89 ± 13 kg, height 172 ± 4 cm) each with an instrumented knee implant from the Julius Wolff Institute (JWI, Charité - Universitätsmedizin Berlin, Germany), were measured in the Laboratory for Movement Biomechanics (LMB) at ETH Zurich, 64-87 months postoperatively.

Anthropometry data

Some important anthropometric data extracted from the skin-marker trajectories in the standing trials for the subjects are listed in Table 1:

Table 1: Anthropometry data for the subjects

		K1L	K2L	K3R	K5R	K7L	K8L
General	Height [cm]	175	169	173	174	165	175
	Body mass [kg]	101.5	90.8	100.3	95.6	66.5	78.8
	Gender	m	m	m	m	f	m
	Shoe size	43	44	41/42	43	41	41
	Age	70	78	77	65	80	76
	Dominant leg r/l	r	l	r	r	l	r
	Implanted leg r/l	l	l	r	r	l	l
Overall leg	Leg length l (LLMA - LASIS) [cm]	92	91.5	100	94.5	91.5	95
	Leg length r (RLMA - RASIS) [cm]	91	90.5	100	95	91	95
Thigh	Circumference below the hip joint l [cm]	53	53	54	54	50	48.5
	Circumference middle of the thigh l [cm]	48.5	50	50	49	46	43
	Circumference above the knee joint l [cm]	42	42	42	41.5	37.5	37
	Circumference below the hip joint r [cm]	55	53	54	56	49	50
	Circumference middle of the thigh r [cm]	50	48	50.5	51	47.5	44
	Circumference above the knee joint r [cm]	42	43	41	44	38.5	37
Shank	Circumference just below the left knee joint [cm]	35.5	34	34.5	35	32	32.5
	Circumference at the thickest point of the left calf [cm]	39.5	39	39	38	345	34
	Circumference above the left ankle [cm]	22.5	24	23.5	24	21	24
	Circumference just below the right knee joint [cm]	34	34	35.5	35	32.5	31.5
	Circumference at the thickest point of the right calf [cm]	39	39	39.5	40	35.5	34.5
	Circumference above the right ankle [cm]	22.5	24	24.5	25	21.5	22
Foot	Circumference at the level of the left metatarsus [cm]	27.5	27	25	26.5	24	25
	Left foot length [cm]	23.5	24	22.2	24	22	25.5
	Height of left lateral malleolus [cm]	6.5	7.0	7.0	7.0	6.0	7.0
	Circumference at the level of the right metatarsus [cm]	27.5	27.5	26	26	24	25.5
	Right foot length [cm]	23.5	24	23.3	24	22.5	25.5
	Height of right lateral malleolus [cm]	6.5	7.0	7.0	7.0	6.0	7.0
Pelvis	Pelvis circumference (approximately where the belt sits) [cm]	108	104.5	104.5	101.5	94	95
	Waist circumference (at the level of the belly button) [cm]	117	114.5	117	109.5	85	102
Implant	Inlay	M10	M10	M10	M10	M10	M10
	Femoral component	M+	M+	M+	M+	M	M+
	Tibial component	JWI instrumented tibial tray					

Anatomy data

The positions of important anatomical landmarks are listed in the CT coordinate system (CS_{CT}) (Table 2):

Table 2: Position of anatomical landmarks obtained from postop CT images.

	K1L	K2L	K3R	K5R	K7L	K8L
l_hip_center [mm]	100.2 -157.2 -316.1	90.5 -154.3 880.0	88.0 -141.7 -431.0	87.3 -160.5 998.1	78.9 -131.1 906.9	96.9 -136.0 896.5
r_hip_center [mm]	-79.5 -145.5 -314.3	-71.1 -145.9 873.7	-88.9 -134.4 -428.5	-79.9 -142.6 997.6	-103.3 -150.6 917.1	-79.1 -142.1 894.0
l_med_epicondyle [mm]	73.7 -128.3 -753.3	59.0 -142.3 479.0	35.1 -124.2 -845.0	67.7 -156.2 571.9	60.5 -138.3 509.3	60.0 -131.8 473.9
l_lat_epicondyle [mm]	158.8 -126.9 -750.0	141.5 -125.3 489.0	120.0 -106.5 -836.0	151.3 -143.2 577.9	145.0 -132.0 513.3	142.8 -127.1 474.3
r_med_epicondyle [mm]	-42.8 -118.0 -749.1	-48.1 -160.4 470.5	-49.9 -128.2 -843.0	-45.6 -150.8 577.9	-75.5 -149.3 520.1	-49.7 -141.0 475.7
r_lat_epicondyle [mm]	-130.0 -116.6 -742.5	-130.9 -144.9 480.5	-138.5 -117.4 -843.0	-129.4 -131.9 578.9	-154.4 -121.3 523.1	-129.8 -136.4 475.7
l_gr_trochanter [mm]	155.4 -140.6 -313.4	135.2 -121.9 893.3	-	131.1 -155.6 1000.7	123.1 -99.7 919.8	138.3 -114.7 900.0
r_gr_trochanter [mm]	-	-124.2 -129.9 888.5	-	-129.0 -115.1 995.2	-164.8 -154.0 935.8	-128.6 -116.8 898.0
l_knee_center [mm]	116.3 -127.6 -751.6	100.3 -133.8 484.0	-	113.3 -155.9 546.0	102.8 -135.2 511.3	101.4 -129.4 474.1
r_knee_center [mm]	-	-89.5 -152.6 475.5	-94.19 -122.82 -843.0	-84.8 -132.1 556.5	-114.9 -135.3 521.6	-89.7 -138.7 475.7
l_ankle_center [mm]	126.3 -91.5 -1170.6	83.5 -114.9 49.3	63.3 -66.5 -1293.0	166.1 -118.6 113.5	68.7 -130.2 104.0	67.1 -116.5 52.5
r_ankle_center [mm]	-97.4 -84.3 -1162.8	-87.8 -118.3 55.9	-61.5 -67.8 -1295.4	-71.8 -113.3 149.3	-98.0 -128.5 103.6	-69.0 -114.6 51.560
l_med_maleolus [mm]	82.5 -95.1 -1136.5	53.9 -134.1 72.4	36.6 -87.7 -1271.2	56.2 -132.7 177.9	42.2 -135.5 127.7	46.5 -137.3 73.6
l_lat_maleolus [mm]	169.5 -73.2 -1152.5	116.9 -102.3 52.1	93.9 -52.5 -1282.0	116.6 -96.2 167.9	102.1 -115.1 104.8	89.8 -86.3 53.1
r_med_maleolus [mm]	-65.8 -95.6 -1140.2	-56.7 -129.1 73.1	-22.7 -88.9 -1280.5	-46.4 -129.4 168.6	-71.9 -144.9 131.1	-38.2 -119.6 77.2
r_lat_maleolus [mm]	-130.5 -63.9 -1150.0	-122.0 -99.9 56.3	-97.7 -32.9 -1288.5	-99.7 -83.5 155.4	-130.1 -109.6 124.1	-98.9 -96.7 56.8
l_med_metatarsus [mm]	132.0 -184.1 -1246.6	66.9 -241.0 2.4	-	39.3 -240.2 77.9	13.9 -207.6 7.2	59.5 -230.7 -11.7
l_lat_metatarsus [mm]	196.1 -144.2 -1243.6	144.0 -211.1 -2.7	-	109.4 -206.0 57.9	96.2 -198.7 3.1	111.8 -181.0 -37.6
r_med_metatarsus [mm]	-	-47.8 -247.0 10.6	-63.9 -155.5 -1372.7	-41.2 -234.5 81.6	-88.0 -200.2 40.8	-58.0 -220.7 -23.3
l_med_metatarsus [mm]	-	-126.2 -227.6 -8.0	-123.1 -113.3 -1378.3	-113.2 -194.6 55.7	-156.9 -168.6 45.6	-126.5 -176.6 -40.3
r_heel [mm]	-	-93.3 -63.4 26.5	-41.4 -1.7 -1300.6	-51.0 -63.2 143.0	-95.3 -42.861 118.5	-51.4 -66.7 57.7
l_heel [mm]	119.8 -29.08 -1174.7	72.9 -68.7 30.8	-	72.5 -72.0 151.9	71.5 -78.0 109.4	48.1 -69.4 47.7

Important: Two different coordinate systems have been used for the tibial and femoral implants within the CAMS-Knee project due to the complexities of different measurement modalities and combining measurement data from two collaborating labs. For the sake of clarity, we provide consistent notation throughout the datasets, which henceforth will be named CS_{JWI} and CS_{LMB}. The tibial CS_{JWI} (CS_{JWI_TIB}) is used to describe all the measured joint contact force and moment data acting on the tibial implant. However, the kinematics of the implants are presented using CS_{LMB_TIB} and CS_{LMB_FEM}. As a result, when combining implant kinematics and internal forces/moments, a transformation between the two systems is required, as described below (see also Supplementary Material for a full description of the transformations):

CS_{JWI} for instrumented knee implant

The instrumented knee implant measures the three components of the contact forces and contact moments, which are presented in the CS_{JWI_TIB}. Its design is based on the INNEX FIXUC total knee system (Zimmer GmbH, Winterthur, Switzerland) with an ultra-congruent tibial insert and a standard femoral component. *In-vivo* contact forces as well as the 3D pose of the implant components in the CS_{CT} are based on the JWI convention for implant coordinate systems, which are described as follows:

CS_{JWI_TIB}: As described by Kutzner et al. 2010, the origin of the CS_{JWI_TIB} is at the intersection between the axis of the tibial component stem and a plane perpendicular to the stem axis at the level of the lowest contact points on the upper surface of the inlay (Fig 1).

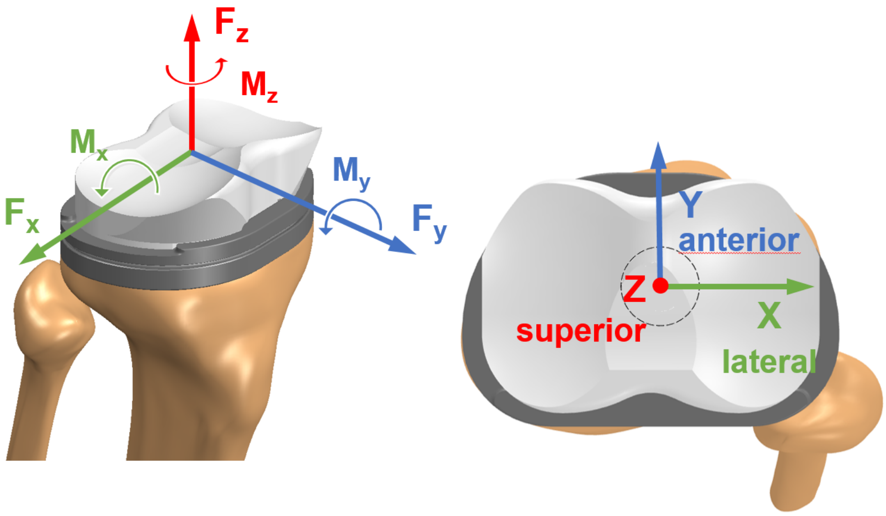


Figure 1: Definition of the orthogonal axes of the instrumented tibial component (right leg), where the actual origin is slightly distal than depicted.

Important: Forces and moments are presented according to anatomical directions. This is equivalent to a right-handed coordinate system for the right knees, and a left-handed coordinate system for the left knees (with associated left-hand thumb rule for the left knee moments). The result is that a medial to lateral force has a positive X-axis component for both left and right knees. A posterior to anterior force always has a positive Y-component, and an inferior to superior force always has a positive Z-component. Similarly, moments are presented in an anatomical format: extension (X), adduction (Y) and internal rotation (Z) moments all have a positive sign for both left and right knees. In addition, the axes are aligned orthogonally with the symmetry axis of the inlay. Please see https://cams-knee.orthoload.com/instrumented-knee-implant/ for further details.

CS_{JWI_FEM}: The orientation of CS_{JWI_FEM} is defined based on the posterior vertical cut plane of the femoral component (Fig 2). The Z-axis is parallel to the femoral pegs, while the X-axis is parallel to the line connecting the lowest points on the condyles and is directed towards the lateral side. Therefore, the X-, Y-, and Z-axes represent the lateral, anterior, and proximal directions of the femoral component respectively. The origin of the CS_{JWI_FEM} is defined based on the boundaries of the component, where:

$$X_{JWI\_ORIGIN\_FEM} = \frac{X_{min} + X_{max}}{2}$$

$$Y_{JWI\_ORIGIN\_FEM} = Y_{min} + 0.36(Y_{max} - Y_{min})$$

$$Z_{JWI\_ORIGIN\_FEM} = Z_{min} + 0.30(Y_{max} - Y_{min})$$

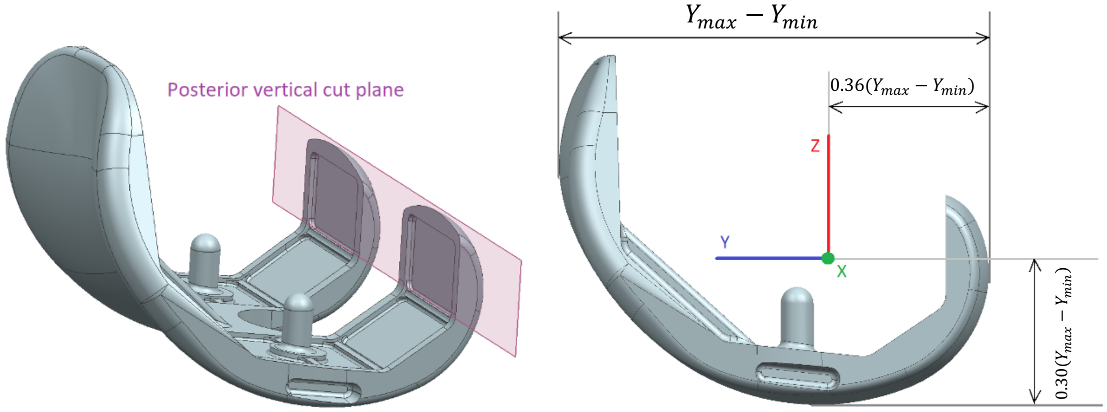


Figure 2: Definition of CS_{JWI_FEM}

CS_{LMB} for implant kinematics

The fluoroscopy-based kinematics presented in the CAMS-Knee datasets are based on CS_{LMB_FEM} and CS_{LMB_TIB}, which are orthogonal right-handed coordinate systems for both left and right knees, defined as follows:

CS_{LMB_TIB}: The Y-axis is parallel to the tibial stem axis in the superior direction. The Z-axis is parallel to a line connecting the centres of the two tibial pegs and is directed medially. The X-axis is orthogonal to Y and Z, and is defined based on the right-hand rule (direction depends on the implanted side: posterior for the right leg, and anterior for left-legged implants). The origin is located centrally at the most distal point of the tibial stem (Fig 3, left).

CS_{LMB_FEM}: The Y-axis is aligned with the axial axis of the pegs. The Z-axis is parallel to a line connecting the most superior points of the pegs, and is directed medially. The X-axis is orthogonal to Y and Z, and is defined based on the right-hand rule (direction depends on the implanted side: posterior for the right leg and anterior for left-legged implants). The origin is located at the intersection of the lines perpendicular to the horizontal and vertical tangent surfaces (Fig 3, right) and midway between the two femoral pegs.

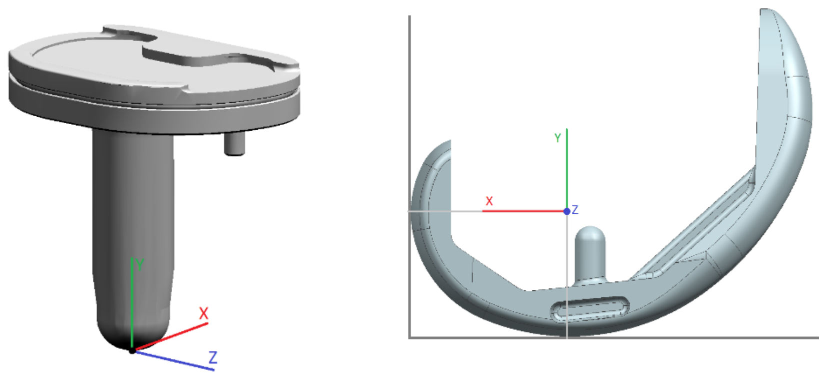


Figure 3: CS_{LMB_TIB} (left) and CS_{LMB_FEM} (right) for a right knee implant

Relative transformation from CS_{JWI} to CS_{LMB}

To transform from CS_{JWI} into CS_{LMB} the following transformation matrices can be used (Table 3, see also appendix example 4):

Table 3: Relative transformation matrix from CS_{JWI} to CS_{LMB} ($T_{JWI \to LMB}$) for each component.

	Right knees	Left knees
Femur M	No Subject	$\begin{bmatrix} 0 & 1 & 0 & -3.8592 \\ 0 & 0 & 1 & -1.6910 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
Femur M+	$\begin{bmatrix} 0 & -1 & 0 & 2.3724 \\ 0 & 0 & 1 & -0.4520 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 & 1 & 0 & -2.3724 \\ 0 & 0 & 1 & -0.4520 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
Tibia	$\begin{bmatrix} 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 72.1100 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 72.1100 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

Subject-specific implantation

To describe the subject-specific implantation, the origin as well as the unit vectors of the CS_{JWI} are provided in the CS_{CT} (Table 4, consistent with that used for defining the anatomical landmarks).

Table 4: Subject-specific implantation data in CS_{CT}

		K1L	K2L	K3R	K5R	K7L	K8L
CS_{JWI_FEM} in CS_{CT}	**Origin [mm]**	119.5260 -128.9620 -752.6720	101.297 -124.986 472.930	-94.771 -111.721 -855.238	-86.445425 -135.172358 568.472927	103.126627 -131.110057 502.012840	100.152242 -125.782290 469.639016
	Unit vector along X axis	0.99965 -0.007616 0.0254367	0.992702 0.120182 -0.0100327	-0.98971 0.137963 -0.0379556	-0.973897 0.225451 0.0264166	0.997405 0.0716995 0.00643948	0.987754 0.1553 -0.0150367
	Unit vector along Y axis	-0.00243316 -0.980234 -0.197823	0.116578 -0.977577 -0.175364	-0.129912 -0.977562 -0.165811	-0.226912 -0.970066 -0.0865152	0.0717133 -0.997423 -0.00195904	0.152606 -0.981672 -0.114165
	Unit vector along Z axis	-0.0264409 -0.197691 0.979905	0.0308833 -0.172915 0.984453	-0.0599801 -0.159174 0.985423	0.00612095 -0.0902531 0.995898	-0.0062824 -0.00241572 0.999977	0.0324913 -0.110474 0.993347
CS_{JWI_TIB} in CS_{CT}	**Origin [mm]**	119.820084 -137.935540 -773.672877	103.206022 -142.28882 453.6557	-96.186991 -126.435802 -876.344584	-88.769255 -144.785120 548.024264	103.409011 -142.323896 484.917609	102.268343 -140.304643 449.560131
	Unit vector along X axis	0.999427 0.006972 0.033122	0.990450 0.135526 -0.025277	-0.991545 0.127620 -0.023489	-0.973696 0.227635 0.010014	0.997785 0.065533 -0.011403	0.988289 0.150247 -0.026602
	Unit vector along Y axis	0.009055 -0.997961 -0.063184	0.137586 -0.983335 0.118840	-0.127195 -0.991700 -0.018790	-0.227686 -0.973725 -0.004271	0.066045 -0.996433 0.052522	0.151956 -0.984949 0.082370
	Unit vector along Z axis	-0.032614 -0.063448 0.997452	0.008750 0.121183 0.992590	-0.025692 -0.0130 0.999547	0.008778 -0.006439 0.999937	0.007920 0.053159 0.998553	0.013826 0.085448 0.996246

To construct each full transformation matrix, these components should be used within the matrix structure presented in Supplementary Material (Eq 6). This implantation resulted in an approximate posterior tibial slope of K1L: 5°, K2L: 11°, K3R: 10°, K5R:7°, K7L: 7°, and K8L: 11°.

Lab and equipment details

All subjects were measured in the Laboratory for Movement Biomechanics, ETH Zürich, Switzerland in June 2014. Complete details about the lab setup and the equipment used for measuring the database are reported in Taylor et al., 2017. However, the following description may simplify understanding and practical use of the database contents.

Eight force plates (FP1 and FP2, type 9281B, 400 × 600 mm; FP3 and FP4, type 9285, 400 × 600 mm; FP5, type 9281C, 400 × 600 mm; FP6, type 9287B, 600 × 900 mm; and FP7 and FP8, type 9286AA, 600 x 900 mm; 2000 Hz; all Kistler, Switzerland), were used to measure the ground reaction forces (GRFs) during the captured trials (Fig 4). Please note that FP7 and FP8 were mobile force plates, and were only used during stair descent and downhill walking.

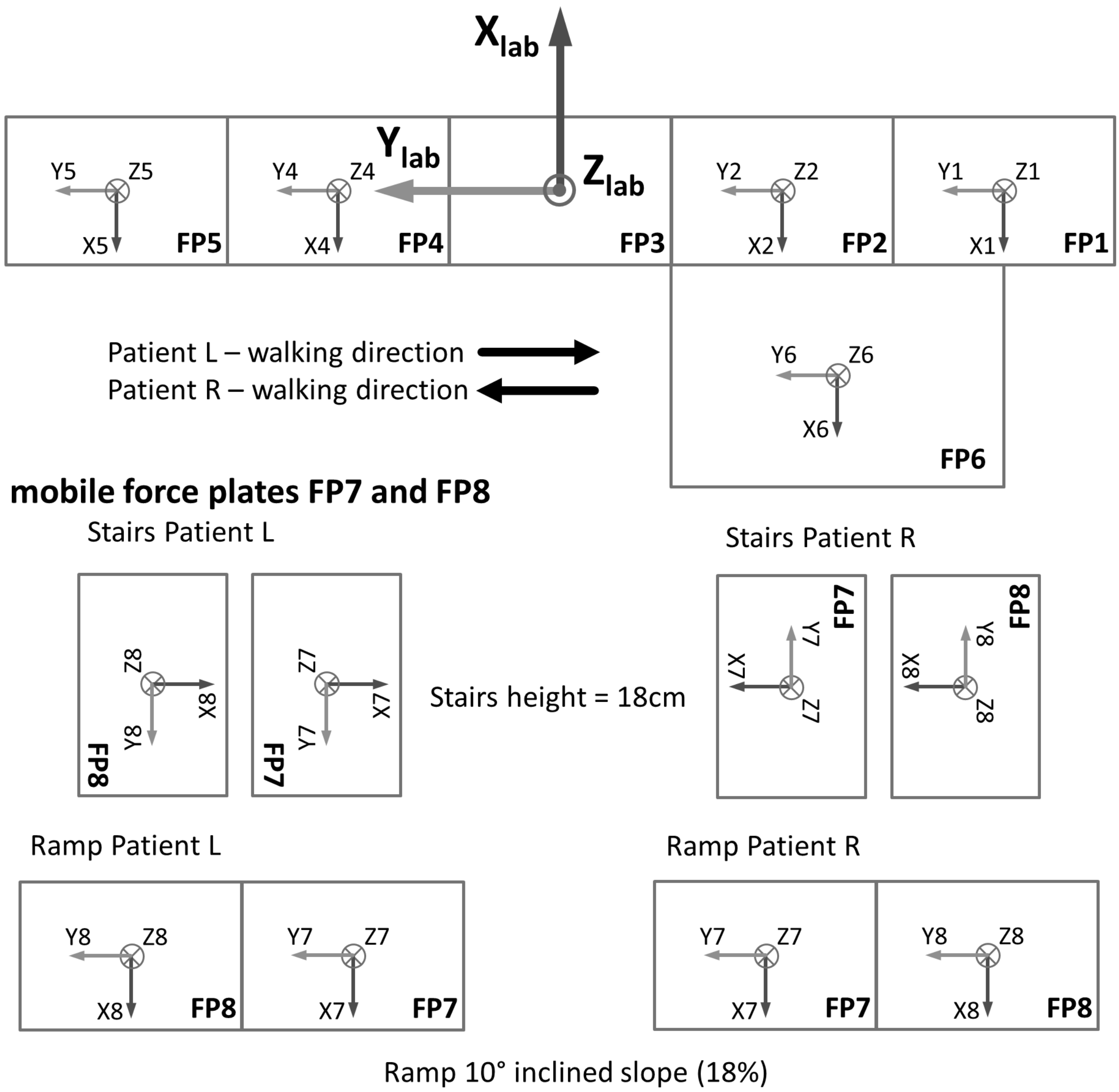


Figure 4: Arrangement of the force plates within the laboratory

All the processed kinematic and ground reaction force data are reported in CS_{LAB} (not *in-vivo* joint contact forces, which are presented in CS_{JWI_TIB} as described previously!).

Important: The data from all force plates (including FP7 and FP8) have already been transformed into the lab coordinate system (CS_{LAB}), so no further manipulation of the forces and centre of pressure (CoP) are required.

CS_{LAB} is an orthogonal right-handed coordinate system with its origin defined at the centre of FP3. The Y-axis is aligned with the walkway pointing from FP1 to FP5, the Z-axis is perpendicular to the force plates and pointing upwards, while the X-axis is orthogonal and defined based on the right-hand rule.

Notes on Activities

A full description of the activities can be found in Taylor et al. 2017. However, the following points may be helpful:

- All subjects with the implant in the right knee walked from FP1 towards FP5 (right to left in Fig 4) while subjects with implants in their left knees walked from FP5 towards FP1.
- For the sit-stand-sit activity, subjects with a left knee implantation were positioned such that the left foot was placed on FP1, while the right foot was positioned on FP6. Here, the stool was located on FP2. Subjects with a right knee implantation were positioned such that the right foot was placed on FP2, while the left foot was positioned on FP6. Here, the stool was located on FP1.
- For the squat activity, subjects with a left knee implantation were positioned such that the left foot was placed on FP1, while the right foot was positioned on FP6. Subjects with a right knee implantation were positioned such that the right foot was placed on FP2, while the left foot was positioned on FP6.

Data capture

The equipment used in the measurements had different sampling frequencies, which varied from 25Hz to 2000Hz (fluoroscope: 25Hz, instrumented implant: 90-100Hz, Vicon: 100Hz, EMG and ground reaction forces: both 2000Hz). All the processed kinematic and kinetic data reported in the database were synchronized using TTL trigger signals and reported based on the highest sampling frequency (2000Hz). As a result, the parameters obtained from systems with lower frequencies include some rows filled with 'NaN' to indicate that no measurement occurred at that time point.

Structure of the Database

The database is subdivided into documentation, tools, implant geometry files and subjects' folders (K1L, K2L, …) data, including the different activity data (Fig 5):

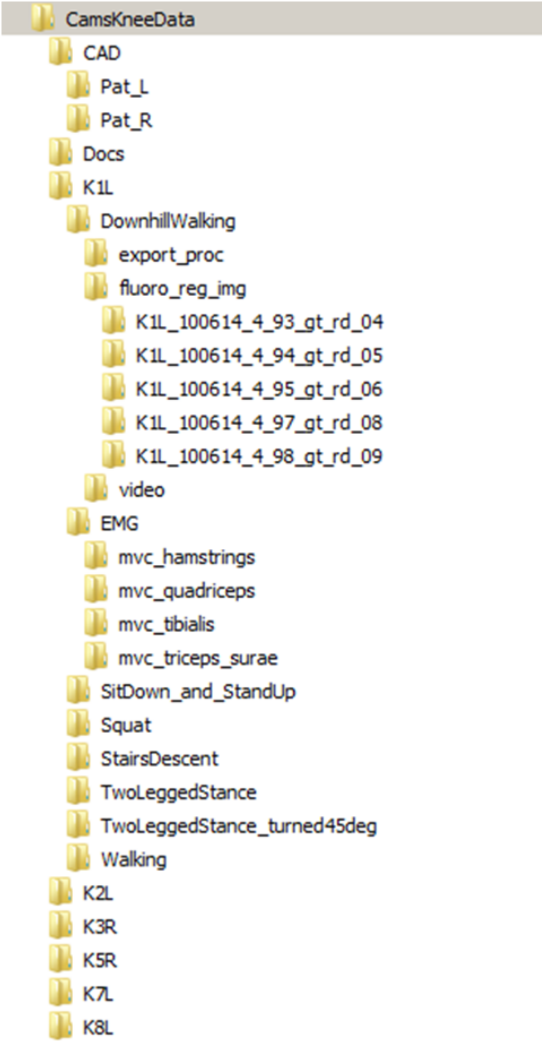


Figure 5: Structure of the CAMS-Knee full data database

1. CAD: Implant geometry files

Geometry of the implant components are presented in the STL format. The folder 'CamsKneeData\CAD' contains all STL files representing geometries of the tibial tray, tibial inlay, and the femoral components (size M, and femoral component size M+) in both the CS_{JWI} and CS_{LMB} conventions. The type and size of the implant components can be seen in Table 1.

2. Processed data

All the processed kinematic, kinetic, telemetric and video data captured from individual subjects are presented according to activity (**task**). For example, 'CamsKneeData\K8L\level_walking\' contains all the data related to gait trials captured from the subject K8L, while 'CamsKneeData\K8L\squat\' comprises all the data measured during squat trials performed by the same subject. The directory for processed data for every subject includes:

2.1. export_proc

All the processed trial data are reported in 'CamsKneeData*subject**task*\export_proc\', in .csv format, which includes the following data:

- ***Gait events***
  - Heel-strike and toe-off of the sequential gait cycles included in the trial (in seconds).

- ***Time***
  - starting from 0, in seconds.

- ***Sampling***
  - The ratio between the analog and video sample rate is 20 (2000Hz/100Hz)
  - **frame_a**; analog frame number, starting from 0
  - **frame_v**; video frame number, starting from 0

- ***Marker trajectories***
  - **Marker_X, Marker_Y and Marker_Z**; coordinates of the labelled markers (in mm), presented in CS_{LAB} (Fig. 4)
  - No filtering or gap filling was performed on the processed marker trajectories
  - See Taylor et al., (2017) for more details about the marker set used in the experiment.

- ***Force plate data***
  - **Ref_X_lab, Ref_Y_lab and Ref_Z_lab**; position of the centre of each force plate in the CS_{LAB} (in mm).
  - **Fx_lab, Fy_lab and Fz_lab**; components of the ground reaction force vector acting on the foot and presented in the CS_{LAB} (in N). The force level was set to zero when the force plate was not loaded (i.e. <15N) or was set to NaN when the force plate was not used in the measurement. All force plates were reset to zero before each trial measurement.
  - **COPx_lab, COPy_lab and COPz_lab**; location of the centre of pressure (CoP) in the CS_{LAB} (in mm). The CoP was calculated using the equation provided by the manufacturer (Kistler, Switzerland).
  - **Tz_lab**; free vertical torque (in Nm) acting on the foot and presented in the CS_{LAB}.
  - **COPx_lab_IfB, COPy_lab_IfB and COPz_lab_IfB**; location of the corrected centre of pressure (CoP) in the CS_{LAB} (in mm). The CoP was corrected using an in-situ point-of-force application based on the calibration method described by List et al., (2017).
  - **Tz_lab_IfB**; corrected free vertical torque (in Nm) acting on the foot and presented in the CS_{LAB}. This torque was calculated after correction of the CoP based on the calibration method described by List et al., (2017) (i.e. corresponding to COPx_lab_IfB, COPy_lab_IfB and COPz_lab_IfB).

- ***EMG data***
  - Sixteen columns reporting the output of 16 EMG sensors used during the measurements (see Taylor et al. 2017 for more details about placement of the sensors on the target muscles).
  - EMG signals are reported without any post-processing.
  - A delay of 48ms (according to DELSYS) was present in the wireless transmission of the EMG data, which has not been corrected for.

- ***In-vivo joint loads***
  - All force data was synchronised with the motion data
  - **F_x, F_y, F_z, and F_{res}**; three components and the resultant contact force (in N) measured by the instrumented implant and reported in CS_{JWI_TIB} (Fig 1) and described by Kutzner et al. 2010.

- **M_x, M_y, M_z, and M_{res}**; three components and the resultant contact moment (in Nm) measured by the instrumented implant and reported in CS_{JWI_TIB} (Fig 1) and described by Kutzner et al. 2010.

- **Transformation matrix of the tibial component**
- $T_{11\_tib\text{-}lab}$ … $T_{44\_tib\text{-}lab}$; the sixteen elements of a 4x4 transformation matrix describe the translation and rotation from the tibial component CS_{LMB} (coinciding with the coordinate system of the corresponding tibial component STL file) into the CS_{LAB}:

$$T_{tib\rightarrow lab} = \begin{bmatrix} T_{11\_tib-lab} & \cdots & T_{14\_tib-lab} \\ \vdots & \ddots & \vdots \\ T_{41\_tib-lab} & \cdots & T_{44\_tib-lab} \end{bmatrix}$$

- **Transformation matrix of the femoral component**
- $T_{11\_fem\text{-}lab}$ … $T_{44\_fem\text{-}lab}$; sixteen elements of a 4x4 transformation matrix describe the translation and rotation from the femoral component CS_{LMB} (coinciding with the coordinate system of the corresponding femoral component STL file) into the CS_{LAB}.

$$T_{fem\rightarrow lab} = \begin{bmatrix} T_{11\_fem-lab} & \cdots & T_{14\_fem-lab} \\ \vdots & \ddots & \vdots \\ T_{41\_fem-lab} & \cdots & T_{44\_fem-lab} \end{bmatrix}$$

- **SYNC_fluoro**
- Is a binary signal, where a '1' indicates the time point when the fluoroscope captures images.

2.2. fluoro_reg_img

The folder 'CamsKneeData*subject**task*\fluoro_reg_img\' contains fluoroscopic captured images/video including the 3D implant components, registered according to the process described in Burckhardt et al., (2005). In addition, there is a video of the fluoroscopic image series.

2.3. video

This directory contains synchronised videos of the patients performing the measured activities, as well as the registered implant videos.

References:

Burckhardt, K., et al. "Submillimeter measurement of cup migration in clinical standard radiographs." IEEE Trans. Med. Imaging. 24 (2005): 676–688.

Kutzner, I., et al. "Loading of the knee joint during activities of daily living measured in vivo in five subjects." *Journal of biomechanics* 43.11 (2010): 2164-2173.

List, R., et al. "In-situ force plate calibration: 12 years' experience with an approach for correcting the point of force application." Gait & Posture 58 (2017): 98-102.

Taylor, W.R., et al. "A Comprehensive Assessment of the Musculoskeletal System: The CAMS-Knee Data Set. Journal of Biomechanics (2017), pre-print: DOI: 10.1016/j.jbiomech.2017.09.022

Terms and conditions:

1. The data may be used only for scientific purposes without any commercial benefit
2. The data may be used only at the registered institute or facility and may not be passed on to third parties
3. In any scientific publication (e.g. journals, conference abstracts, poster, or oral presentation) reporting use of the data, the CAMS-Knee database must be cited as follows: CAMS-Knee (2017): 'filename', retrieved from https://CAMS-Knee.orthoload.com, 'Date of access (day, month, and year)'

and

Taylor W.R., Schütz P., Bergmann G., List R., Postolka B., Hitz M., Dymke J., Damm P., Duda G., Gerber H., Schwachmeyer V., Hamed Hosseini Nasab S., Trepczynski A., Kutzner I.; "A Comprehensive Assessment of the Musculoskeletal System: The CAMS-Knee Data Set"; Journal of Biomechanics 2017; http://dx.doi.org/10.1016/j.jbiomech.2017.09.022; https://cams-knee.orthoload.com/

Contact:

A user forum has been created on the SLACK platform (www.slack.com) with a workspace-URL at https://cams-knee.slack.com. Please feel free to join in discussions, propose changes, add information or associated models, or ask questions.

For questions regarding possible collaborations or sponsorship: contact@cams-knee.orthoload.com

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Supplementary Material: Coordinate Systems and Transformations in the CAMS-Knee Datasets

The CAMS-Knee datasets form an ideal example for a biomechanics course for two reasons: 1) They are free and publicly available, 2) They are transformation and coordinate system hell.

Nomenclature

Coordinate System:

CS_A

Point:

$$\bar{p}_A = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix}_A$$

The point, $\bar{p}_A$, is comprised of three x, y, z components expressed in CS_A.

Coordinate System Origin:

$$\bar{O}_A^B = \begin{bmatrix} O_x^B \\ O_y^B \\ O_z^B \end{bmatrix}_A$$

The origin, $\bar{O}_A^B$, represents the x, y, z coordinates of the origin of CS_B expressed in CS_A.

Vector:

$$\vec{v}_A = \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix}_A$$

The vector, $\vec{v}_A$, is comprised of three x, y, z components expressed in CS_A.

Unit Vector:

$$\hat{u}_A = \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix}_A$$

The unit vector, $\hat{u}_A$, is comprised of three x, y, z components expressed in CS_A.

Coordinate System Unit Vectors:

$$\hat{u}_A^B = \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix}_A \qquad \hat{v}_A^B = \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix}_A \qquad \hat{w}_A^B = \begin{bmatrix} w_x \\ w_y \\ w_z \end{bmatrix}_A$$

Each CS_B has x,y,z axes that are aligned with three unit vectors ($\hat{u}_A^B, \hat{v}_A^B, \hat{w}_A^B$) expressed in CS_A

Matrix:

$$\boldsymbol{M} = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix}$$

Force:

$$\vec{F}_A^B = \begin{bmatrix} F_x^B \\ F_y^B \\ F_z^B \end{bmatrix}_A$$

The force, $\vec{F}$, is composed of x,y,z components expressed in CS_A and applied to the origin of CS_B

Moment:

$$\vec{M}_A^B = \begin{bmatrix} M_x^B \\ M_y^B \\ M_z^B \end{bmatrix}_A$$

The moment, $\vec{M}$, is composed of x,y,z components expressed in CS_A and applied to CS_B

Transformation Definitions

Here, we provide transformation matrices to transform data between different coordinate systems within the CAMS-Knee datasets.

The transformation from an example CS_A to CS_B is described using a 4 x 4 transformation matrix:

$$\boldsymbol{T}_{A\to B} = \begin{bmatrix} R_{11} & R_{12} & R_{13} & t_x \\ R_{21} & R_{22} & R_{23} & t_y \\ R_{31} & R_{32} & R_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

Here the $\boldsymbol{R}$ submatrix is the direction cosine matrix that represents the rotation from CS_A to CS_B, and the $\vec{t}_B$ subvector represents the translation from O^A to O^B expressed in CS_B.

This formulation enables points ($\bar{p}$) and vectors ($\vec{v}$) that are reported in CS_A to be transformed into CS_B using the following matrix multiplications:

Point

$$\begin{bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{bmatrix}_B = \boldsymbol{T}_{A\to B} \begin{bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{bmatrix}_A \tag{2}$$

Vector

$$\begin{bmatrix} v_x \\ v_y \\ v_z \\ 0 \end{bmatrix}_B = \boldsymbol{T}_{A\to B} \begin{bmatrix} v_x \\ v_y \\ v_z \\ 0 \end{bmatrix}_A \tag{3}$$

Note: the padding (1 vs 0) on end of the column vectors changes because the position of a point is affected by the origin and orientation of a coordinate system, whereas a direction vector is unaffected by translational changes to the origin. Also, moments are pseudovectors, thus this equation only holds true for moments if the transformation is between two coordinate systems of the same handedness (no mirroring). In the case of mirroring, the transformed moment vector must also be negated.

Transformations between multiple CSs can be performed by multiplying the transformation matrices. For example, transforming the coordinates of a point defined in CS_A to CS_B to CS_C can be performed using the following:

$$\begin{bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{bmatrix}_C = \boldsymbol{T}_{B\to C}\ \boldsymbol{T}_{A\to B} \begin{bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{bmatrix}_A \tag{4}$$

A transformation can be performed in the opposite direction using the inverse of the transformation matrix.

$$\begin{bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{bmatrix}_A = \boldsymbol{T}_{A\to B}{}^{-1} \begin{bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{bmatrix}_B \tag{5}$$

CAMS-Knee Coordinate Systems

Two local coordinate systems are fixed to the implant components for reporting the dynamic *in vivo* measurements. Additionally, a global lab coordinate system (CS_{LAB}) was used for reporting the dynamic motion analysis measurement, while a local CT coordinate system (CS_{CT}) described the locations of the implants and anatomic landmarks.

CS_{JWI}: The knee contact force and moment measurements are reported in the CS_{JWI_TIB}. The implantation position and orientation of CS_{JWI_TIB} and CS_{JWI_FEM} are reported in CS_{CT}.

CS_{LMB}: The fluoroscopic measurements of implant kinematics are reported as a transformation from CS_{LMB} to CS_{LAB}.

CS_{CT}: The coordinate system of the computed tomography (CT) images. The positions of the bone landmarks, as well as the origin and directional unit vectors of CS_{JWI} are reported in CS_{CT} (Table 4).

CS_{LAB}: The coordinate system of the motion capture lab. All motion capture and GRF measurements are reported in the CS_{LAB}. The fluoroscopic measurements of implant kinematics are reported as a transformation of CS_{LMB} into CS_{LAB}.

The two local implant coordinate systems, CS_{LMB} and CS_{JWI}, are present mainly for historical reasons. The instrumented implant and analysis codes were developed in the Julius Wolff Institute (JWI) at the Charité – Universitätsmedizin Berlin, and the fluoroscopy system and associated analysis codes were developed at the Laboratory for Movement Biomechanics (LMB) at ETH Zürich. The left-handed coordinate system used in the CS_{JWI} (left implants) is convenient because the forces/moments can be reported in anatomic directions and their meaning is easily transferable between the right and left knees. Unfortunately, many visualization and simulation programs only accommodate right handed coordinate systems. Thus, for the registration of the 3D implant geometries to the 2D fluoroscopic images, a right handed CS_{LMB} was necessary for both left and right knees. The implant poses for each time point, reconstructed in the local (and moving!) fluoroscope coordinate system, as well as the ground reaction forces, have all been transformed into CS_{LAB}.

CAMS-Knee Transformations

In the CAMS-Knee datasets, we provide the transformation matrices $\boldsymbol{T}_{JWI \to LMB}$, $\boldsymbol{T}_{JWI \to CT}$, and $\boldsymbol{T}_{LMB \to LAB}$. Using these three transformations and their inverses, data can be transformed between all four CS_{LMB}, CS_{JWI}, CS_{CT}, and CS_{LAB}. $\boldsymbol{T}_{JWI \to LMB}$ and $\boldsymbol{T}_{JWI \to CT}$ are static (for each subject) and thus listed above (Table 3 and Table 4). The transformation between CS_{LAB} and all other coordinate systems is dynamic. $\boldsymbol{T}_{LMB \to LAB}$ is reported for each time step (fluoroscopic image) in the .csv data file (columns: "$T_{xx\_tib\text{-}lab}$", "$T_{xx\_fem\text{-}lab}$").

$\boldsymbol{T}_{JWI \to LMB}$

The transformation matrix from the local implant fixed coordinate systems CS_{JWI} to CS_{LMB} ($T_{JWI \to LMB}$) for each component is presented in Table 3.

$\boldsymbol{T}_{JWI \to CT}$

The origin (O_{CT}^{JWI}) and axis unit vectors ($\hat{u}_{CT}^{JWI}, \hat{v}_{CT}^{JWI}, \widehat{w}_{CT}^{JWI}$) of CS_{JWI} expressed in CS_{CT} for each subject is provided in Table 4. These data can be used to construct the transformation matrix $\boldsymbol{T}_{JWI \to CT}$ using the following equation:

$$\boldsymbol{T}_{JWI \to CT} = \begin{bmatrix} u_x^{JWI} & u_y^{JWI} & u_z^{JWI} & O_x^{JWI} \\ v_x^{JWI} & v_y^{JWI} & v_z^{JWI} & O_y^{JWI} \\ w_x^{JWI} & w_y^{JWI} & w_z^{JWI} & O_z^{JWI} \\ 0 & 0 & 0 & 1 \end{bmatrix}_{CT} \tag{6}$$

Where O_{CT}^{JWI} is the x, y, z coordinates of the origin of the CS_{JWI} in the CS_{CT}, and $(u, v, w)_{x,y,z}^{JWI}$ represent the unit vectors of the CS_{JWI} ($\hat{u}_{CT}^{JWI}, \hat{v}_{CT}^{JWI}, \widehat{w}_{CT}^{JWI}$) expressed in the CS_{CT}.

$\boldsymbol{T}_{LMB \to LAB}$

The transformation matrix $\boldsymbol{T}_{LMB \to LAB}$ is presented in the .csv files, with each component of the transformation matrix reported in separate columns, for example "T11_tib-lab"…

$$\boldsymbol{T}_{LMB \to LAB} = \begin{bmatrix} T_{11} & T_{12} & T_{13} & T_{14} \\ T_{21} & T_{22} & T_{23} & T_{24} \\ T_{31} & T_{32} & T_{33} & T_{34} \\ T_{41} & T_{42} & T_{43} & T_{44} \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & R_{13} & t_x \\ R_{21} & R_{22} & R_{23} & t_y \\ R_{31} & R_{32} & R_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where the translation ($\vec{t}_{LAB}$) is from O^{LAB} to O^{LMB} and expressed in CS_{LAB}.

CAMS-Knee Examples

Ex1: For the left femur M Plus implant, find the origin of the CS_{JWI} in the CS_{LMB}.

Using $\boldsymbol{T}_{JWI\rightarrow LMB}$ from Table 3, and the origin (0,0,0) in CS_{LMB}:

$$\begin{bmatrix} -2.3724 \\ -0.4520 \\ 0 \\ 1 \end{bmatrix}_{LMB} = \boldsymbol{T}_{JWI\rightarrow LMB} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}_{JWI}$$

Ex2: How can you pose the .stl implant geometry files (CS_{JWI}) in the CS_{LAB} throughout an activity trial?

The .stl files store triangulated surface meshes of the implant component geometries. The data contained in the file is a list of points representing the x, y, and z coordinates of the triangle vertices as well as a list of the three vertex indexes that make up each triangle. Thus, we just need to calculate the transformation matrix ($\boldsymbol{T}_{JWI\rightarrow LMB}$) to transform points expressed in CS_{JWI} into CS_{LAB}. This can be found using the $\boldsymbol{T}_{LMB\rightarrow LAB}$ given for each time step in the .csv file and the transformation between the local implant coordinate systems ($\boldsymbol{T}_{JWI\rightarrow LMB}$) given in Table 3.

$$\begin{bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{bmatrix}_{LAB} = \boldsymbol{T}_{LMB\rightarrow LAB} \boldsymbol{T}_{JWI\rightarrow LMB} \begin{bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{bmatrix}_{JWI}$$

Ex3: Transform the bone landmarks from CS_{CT} to CS_{LMB}

The bone landmarks are provided as (x,y,z) points in CS_{CT} in Table 2. These can be transformed using the $\boldsymbol{T}_{JWI\rightarrow CT}$ provided in Table 4 and $\boldsymbol{T}_{JWI\rightarrow LMB}$ provided in Table 3.

$$\begin{bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{bmatrix}_{LMB} = \boldsymbol{T}_{JWI\rightarrow LMB}\, \boldsymbol{T}_{JWI\rightarrow CT}{}^{-1} \begin{bmatrix} p_x \\ p_y \\ p_z \\ 1 \end{bmatrix}_{CT}$$

Ex4: Transform the left knee (K1L, K2L, K7L, K8L) contact force ($\vec{F}_{JWI}^{JWI}$) and moment data ($\vec{M}_{JWI}^{JWI}$) that are expressed in CS_{JWI} into the CS_{LMB} for a right knee.

Reminder: In force/moment notation ($\vec{F}_{JWI}^{JWI}$), the superscript is the CS that the force or moment is acting on (i.e. forces are applied to the CS origin), and the subscript represents the CS that the force/moment is reported in. For example, $\vec{F}_{LMB}^{JWI}$ is applied at the origin of CS_{JWI}, but reported in CS_{LMB}.

The force ($\vec{F}_{JWI}^{JWI}$) and moment ($\vec{M}_{JWI}^{JWI}$) vectors are reported for each time step in the .csv files (column labels: "F_x", "F_y", "F_z", as well as "M_x", "M_y", "M_z").

The left-handed coordinate system of the left CS_{JWI} may be confusing at first. However, the clever design of the left- and right-handed CS_{JWI} enables the left force ($\vec{F}_{JWI}^{JWI}$) and moment ($\vec{M}_{JWI}^{JWI}$) measurements to be directly interpreted in the right CS_{JWI}.

$$\begin{bmatrix} F_x^{JWI} \\ F_y^{JWI} \\ F_z^{JWI} \end{bmatrix}_{left} = \begin{bmatrix} F_x^{JWI} \\ F_y^{JWI} \\ F_z^{JWI} \end{bmatrix}_{right}$$

$$\begin{bmatrix} M_x^{JWI} \\ M_y^{JWI} \\ M_z^{JWI} \end{bmatrix}_{left} = \begin{bmatrix} M_x^{JWI} \\ M_y^{JWI} \\ M_z^{JWI} \end{bmatrix}_{right}$$

Thus, we now only need to transform the ($\vec{F}_{JWI}^{JWI}$) and moment ($\vec{M}_{JWI}^{JWI}$) vectors from the right CS_{JWI} to the right CS_{LMB}.

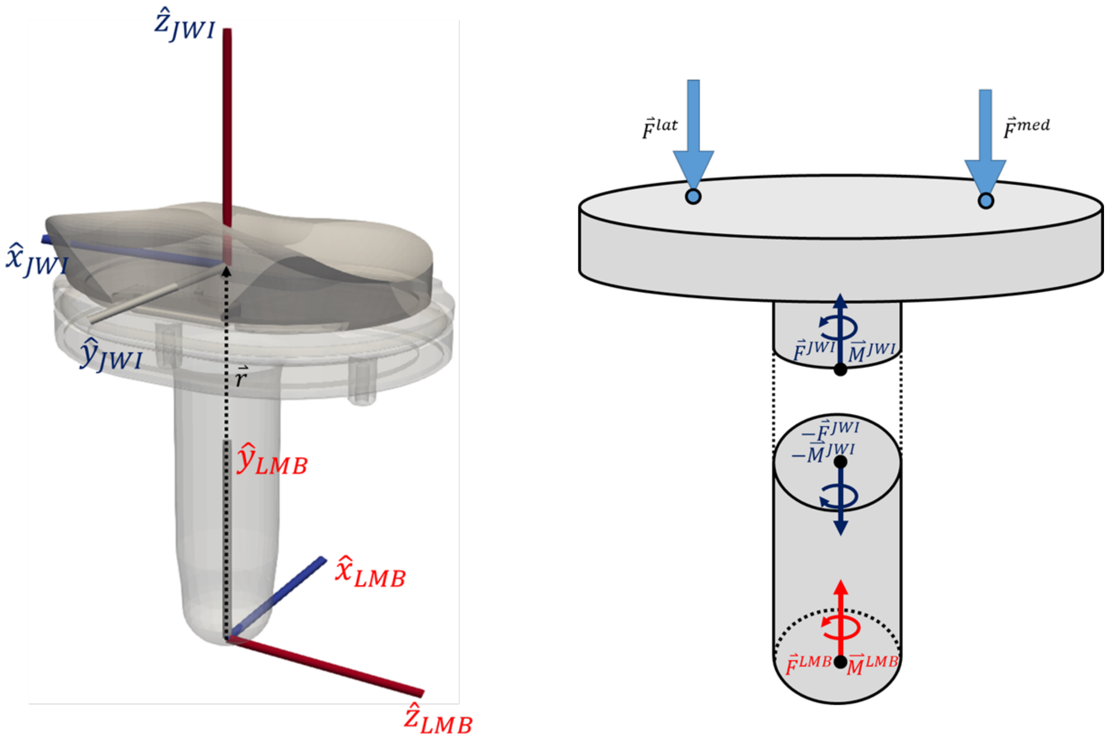

Figure S1: (left) Diagram of the tibial implant with the local implant CS_{LMB} and CS_{JWI}, and vector $\vec{r}$ from $\bar{O}^{LMB}$ to $\bar{O}^{JWI}$ represented. (right) A free body diagram with transections of the tibial implant at $\bar{O}^{JWI}$ and $\bar{O}^{LMB}$ to enable the calculation of the internal resultant forces and moments acting at CS_{JWI} and CS_{LMB}. Note: the instrumented implant measurements are $\vec{F}_{JWI}^{JWI}$ and $\vec{M}_{JWI}^{JWI}$

By assuming that the tibial stem is a rigid body, Newton's second law can be applied to calculate the resultant force ($\vec{F}^{LMB}$) and moment ($\vec{M}^{LMB}$) vectors acting at the origin of CS_{LMB} from the strain gauge measurements of the resultant force ($\vec{F}^{JWI}$) and moment ($\vec{M}^{JWI}$) vectors measured in CS_{JWI}. Note that the force and moment equilibrium equations must be formulated with one consistent reference frame, and here we use CS_{JWI}. We assume the inertial effects ($m\vec{a}$, $I\vec{\alpha}$) are negligible and equal to zero.

The free body diagram reveals that the force components of the two resultant forces acting at CS_{LMB} and CS_{JWI} must be equal:

$$\sum \vec{F}_{JWI} = 0 = \vec{F}_{JWI}^{LMB} - \vec{F}_{JWI}^{JWI}$$

$$\vec{F}_{JWI}^{LMB} = \vec{F}_{JWI}^{JWI}$$

The measured force vector ($\vec{F}_{JWI}^{JWI}$) can then be transformed using Eq 3 to find $\vec{F}_{LMB}^{LMB}$:

$$\begin{bmatrix} F_x^{LMB} \\ F_y^{LMB} \\ F_z^{LMB} \\ 0 \end{bmatrix}_{LMB} = \boldsymbol{T}_{JWI\to LMB} \begin{bmatrix} F_x^{LMB} \\ F_y^{LMB} \\ F_z^{LMB} \\ 0 \end{bmatrix}_{JWI} = \boldsymbol{T}_{JWI\to LMB} \begin{bmatrix} F_x^{JWI} \\ F_y^{JWI} \\ F_z^{JWI} \\ 0 \end{bmatrix}_{JWI}$$

The transformation $\boldsymbol{T}_{JWI\to LMB}$ for the tibia can be found in Table 3.

The moment equilibrium equation about the CS_{LMB} origin expressed in CS_{JWI}, O_{JWI}^{LMB}, can be written as follows:

$$\sum \vec{M}_{\bar{O}_{JWI}^{LMB}} = 0 = \vec{M}_{JWI}^{LMB} - \vec{M}_{JWI}^{JWI} + \vec{r}_{JWI} \times \vec{F}_{JWI}^{JWI}$$

$$\vec{M}_{JWI}^{LMB} = \vec{M}_{JWI}^{JWI} + \vec{r}_{JWI} \times \vec{F}_{JWI}^{JWI}$$

Where $\vec{r}_{JWI}$ is the vector from $\bar{O}_{JWI}^{LMB}$ to $\bar{O}_{JWI}^{JWI}$ reported in CS_{JWI}.

By definition, the cross product of two vectors in the same coordinate system can be rewritten in matrix form:

$$\vec{r}_{JWI} \times \vec{F}_{JWI}^{JWI} = \begin{bmatrix} r_y \ F_z^{JWI} - r_z \ F_y^{JWI} \\ r_z \ F_x^{JWI} - r_x \ F_z^{JWI} \\ r_x \ F_y^{JWI} - r_y \ F_x^{JWI} \end{bmatrix}_{JWI}$$

The origins of CS_{JWI} and CS_{LMB} for the tibial component are only offset by a translation along the z-axis in CS_{JWI}:

$$\begin{bmatrix} r_x \\ r_y \\ r_z \end{bmatrix}_{JWI} = \begin{bmatrix} 0 \\ 0 \\ r_z \end{bmatrix}_{JWI}$$

Hence, we can simplify the cross-product equation to:

$$\vec{r}_{JWI}^{LMB} \times \vec{F}_{JWI}^{JWI} = \begin{bmatrix} -r_z \ F_y^{JWI} \\ r_z \ F_x^{JWI} \\ 0 \end{bmatrix}_{JWI}$$

This relationship can be substituted into the moment equilibrium equation to reveal:

$$\vec{M}_{JWI}^{LMB} = \vec{M}_{JWI}^{JWI} + \begin{bmatrix} -r_z \ F_y^{JWI} \\ r_z \ F_x^{JWI} \\ 0 \end{bmatrix}_{JWI}$$

$$\vec{M}_{JWI}^{LMB} = \begin{bmatrix} M_x^{JWI} - r_z \ F_y^{JWI} \\ M_y^{JWI} + r_z \ F_x^{JWI} \\ M_z^{JWI} \end{bmatrix}_{JWI}$$

$\vec{M}_{JWI}^{LMB}$ in a right-handed CS$_{JWI}$ can be transformed into $\vec{M}_{LMB}^{LMB}$ as using s=1 in the following:

$$\begin{bmatrix} M_x^{LMB} \\ M_y^{LMB} \\ M_z^{LMB} \\ 0 \end{bmatrix}_{JWI} = s\boldsymbol{T}_{JWI\rightarrow LMB}{}^{-1} \begin{bmatrix} M_x^{LMB} \\ M_y^{LMB} \\ M_z^{LMB} \\ 0 \end{bmatrix}_{LMB}$$

Note: Since $\vec{M}_{JWI}^{LMB}$ is a pseudo vector (https://en.wikipedia.org/wiki/Pseudovector), s=1 only when the transformation matrix consists of pure rotations and translations, but not mirroring. Here, this is true because the right knee CS$_{JWI}$ is transformed to the right knee CS$_{LMB}$. However, a transformation from a left-handed CS to a right-handed coordinate system (e.g. left knee CS$_{JWI}$ to left knee CS$_{LMB}$) requires one of the axes to be mirrored. In this case, the transformed moment vector needs to be negated, thus s=-1.

This yields:

$$\begin{bmatrix} M_x^{LMB} \\ M_y^{LMB} \\ M_z^{LMB} \\ 0 \end{bmatrix}_{LMB} = s\boldsymbol{T}_{JWI\rightarrow LMB} \begin{bmatrix} M_x^{JWI} - r_z\ F_y^{JWI} \\ M_y^{JWI} + r_z\ F_x^{JWI} \\ M_z^{JWI} \\ 0 \end{bmatrix}_{JWI}$$

The transformation $\boldsymbol{T}_{JWI\rightarrow LMB}$ for the tibia can be found in Table 3. From Table 3, for both the left and right tibia implants, $r_z = -72.11$ mm.