# CusToM Workshop

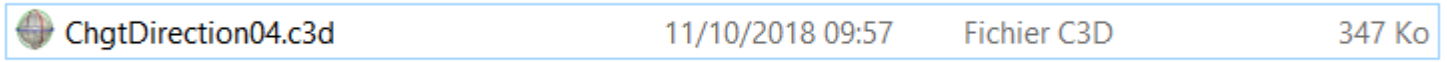
## Kinematic tutorial

Charles Pontonnier, Pierre Puchaud

# Pre-Work

Go in `Examples\1_SideStep_Kinematic\SideStep_Anthropo`

It contains :



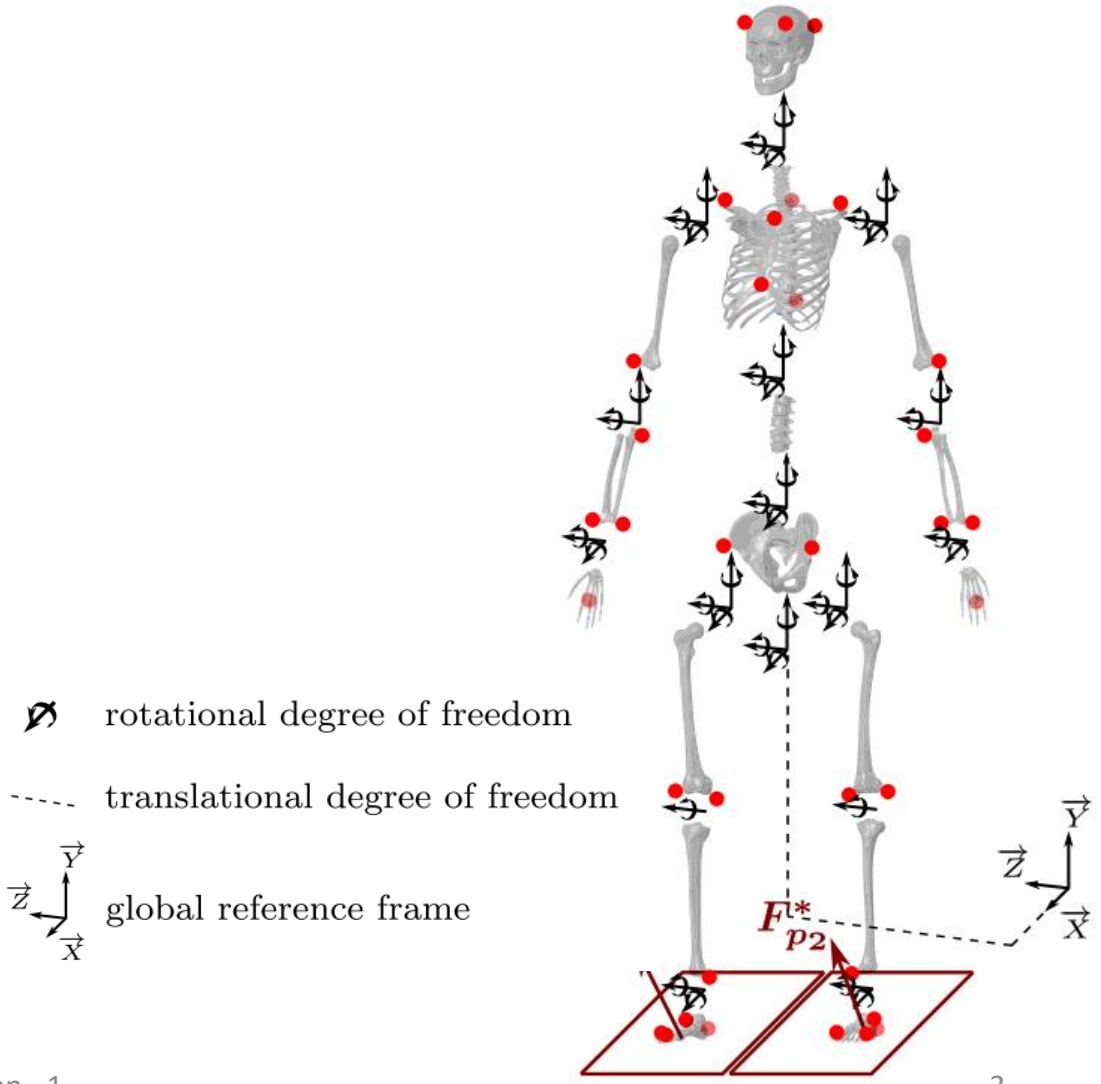
# Generate Parameters of the Model

```
>> GenerateParameters
```

- Size : 1.755 m
- Mass : 70 Kg

- Osteo-articular model – full body
  - Pelvis
  - Pelvis LowerTrunk
  - Leg
  - Arms
- Marker Set
  - MarkerSet_2 (M2S makerset)
  - 2 markers on hand

- No Muscles



# AnalysisParameters

Only Inverse Kinematic Active Step

- Levenberg-marquardt
- 5Hz filter butterworh $2^{nd}$ order zero lag

# What CusToM is Doing ?

```
Anthropometric Model Generation ...
... Anthropometric Model Generation done
```

The osteoarticular model comes from cadaveric data.

Anthropometric scaling:

- Segments lengths
- Anatomical landmarks

$$k_0 = \frac{size\ of\ the\ subject}{size\ of\ the\ cadaver}$$

# What CusToM is Doing ?

```
Preliminary Computations ...
... Preliminary Computations done
```

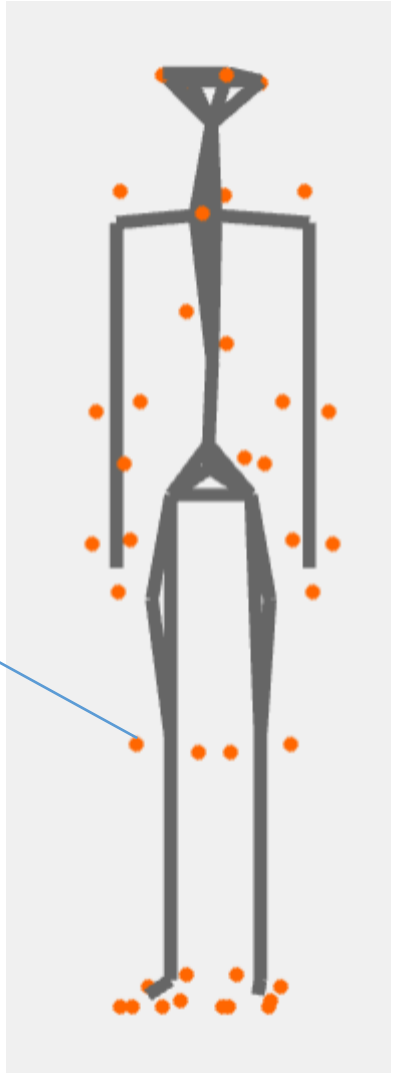
A priori known location of anatomical landmarks are computed in the global reference frame $R_0$ function of joint coordinates $\boldsymbol{q}$

$$^{R_0}\boldsymbol{X}_{\boldsymbol{marker}} = f(\boldsymbol{q})$$

Jacobian matrix $\boldsymbol{J}$ are computed analytically

- For Inverse kinematics using Levenberg-Marquardt algorithms

$$J_{\boldsymbol{f},\boldsymbol{q}}$$
$$J_{\boldsymbol{f},\boldsymbol{cut}}$$
$$J_{\boldsymbol{cut},\boldsymbol{q}}$$
$$J_{\boldsymbol{cut},\boldsymbol{cut}}$$



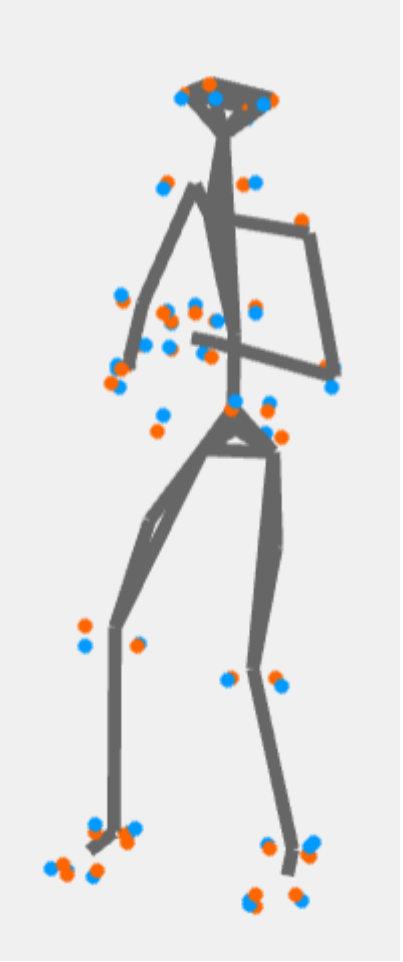
# What CusToM is Doing ?

```
Inverse kinematics (ChgtDirection04) ...
... Inverse kinematics (ChgtDirection04) done
```

Euclidian distance minization between experimental markers ${}^{R_0}\boldsymbol{X}_{exp,i}$ and *a priori* know location of anatomical landmarks ${}^{R_0}\boldsymbol{X}_{mod,m}(\boldsymbol{q})$ in the global frame $R_0$

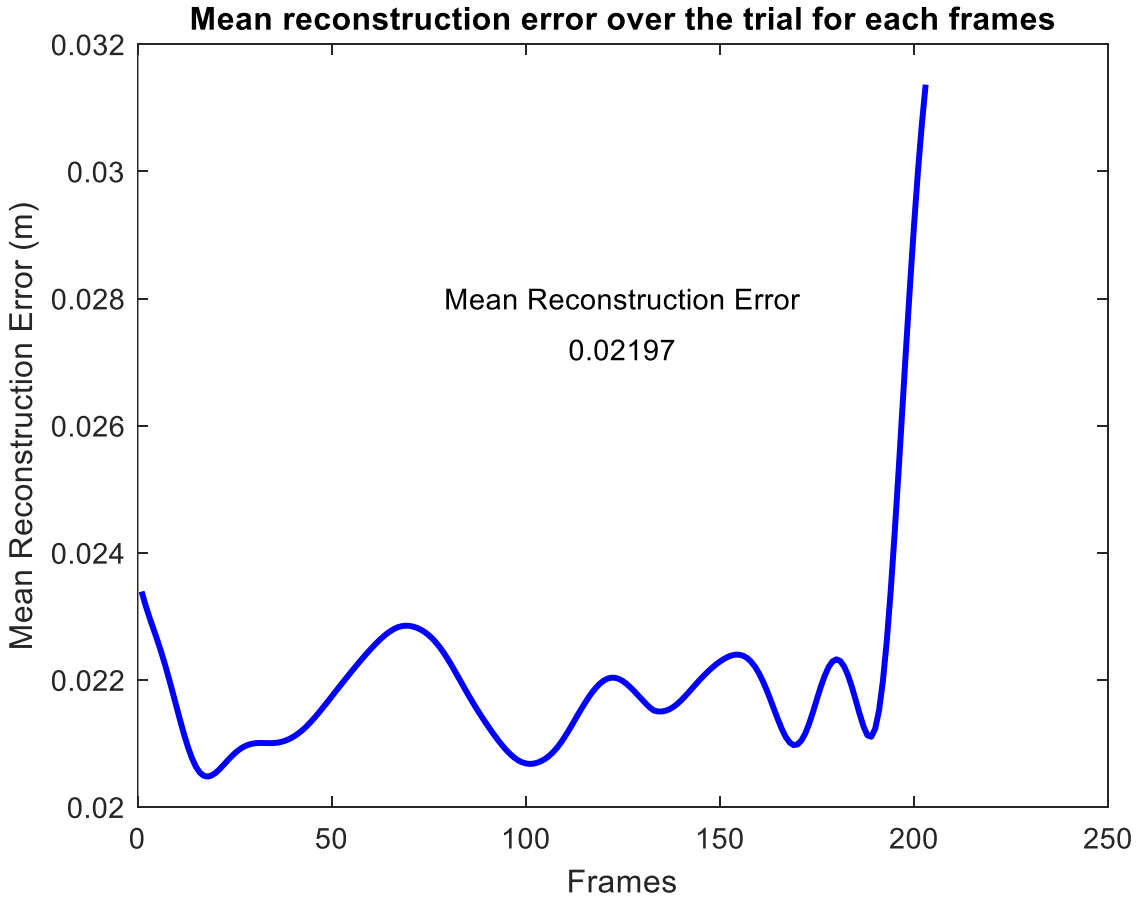
$$\min_{\boldsymbol{q}} \sum_{i}^{N_{markers}} \left\| {}^{R_0}\boldsymbol{X}_{exp,i} - {}^{R_0}\boldsymbol{X}_{mod,m}(\boldsymbol{q}) \right\|^2$$

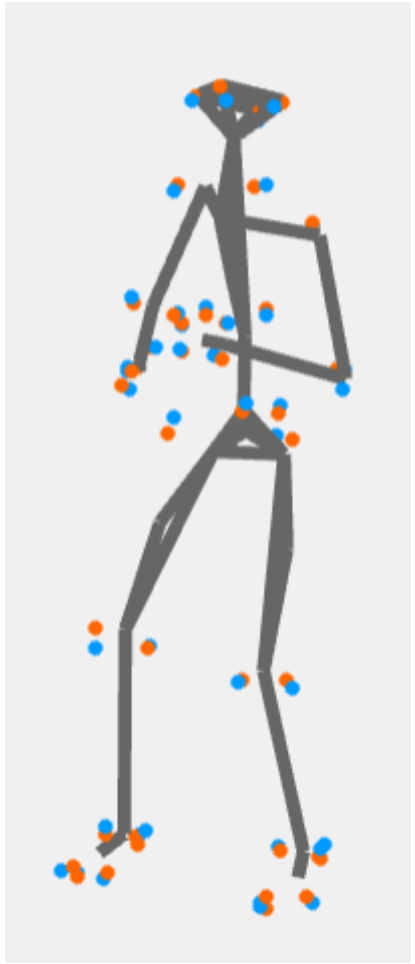
We get the joint coordinates $\boldsymbol{q}$.



# First results – Kinematic residuals

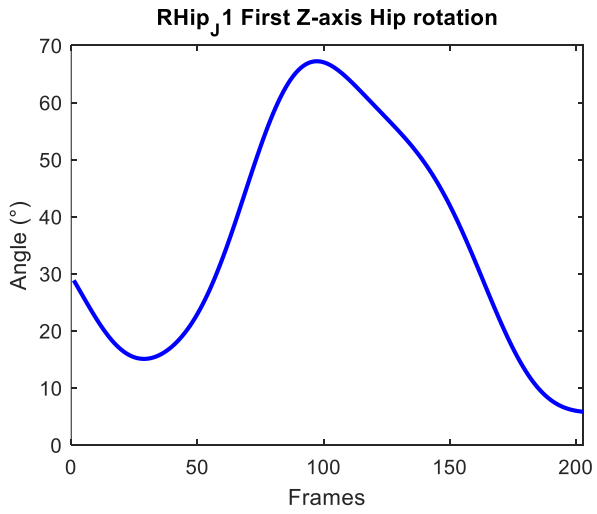
```
>> PostProcessingKinematic_Anthropo
```

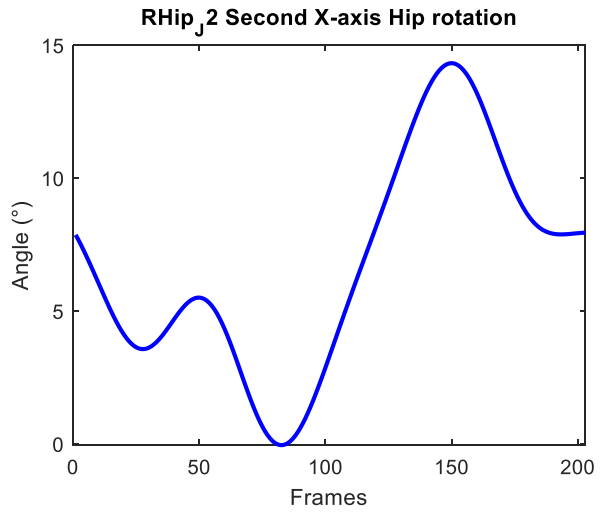


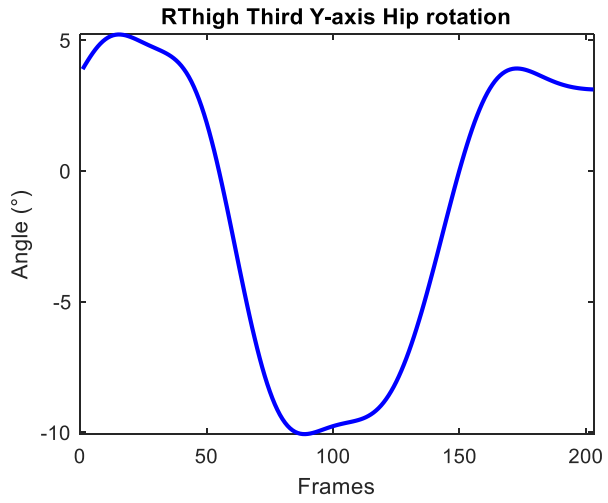



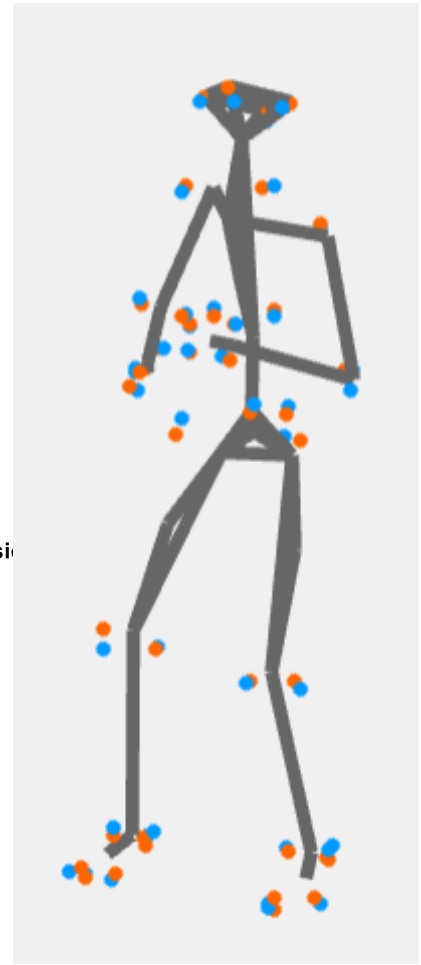
# First results – Joint coordinates

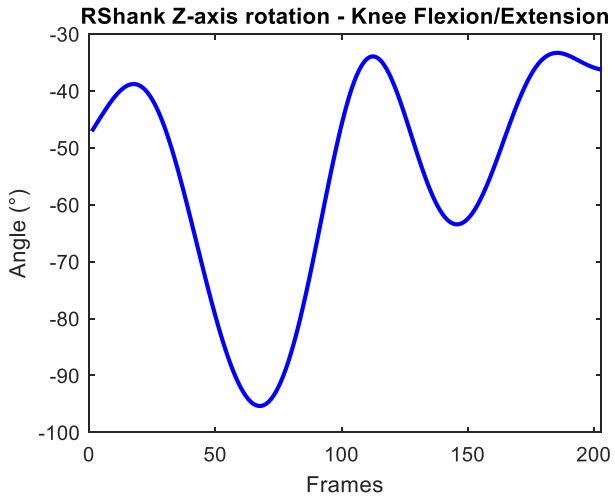
```
>> PostProcessingKinematic_Anthropo
```

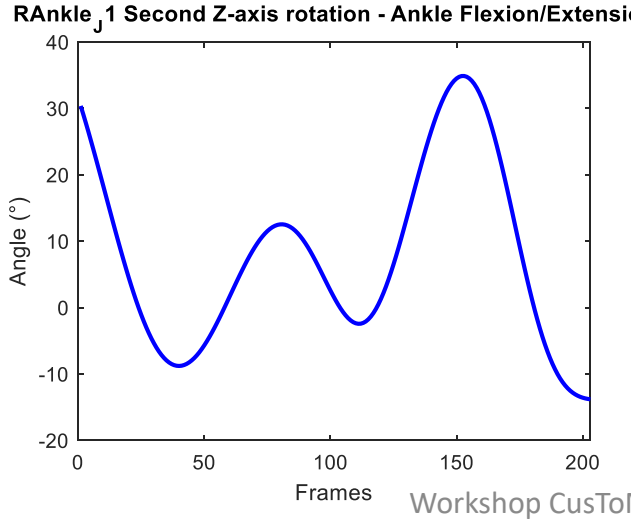


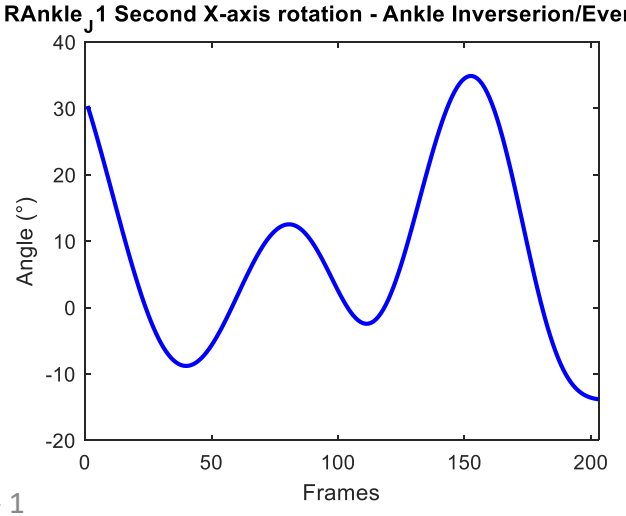



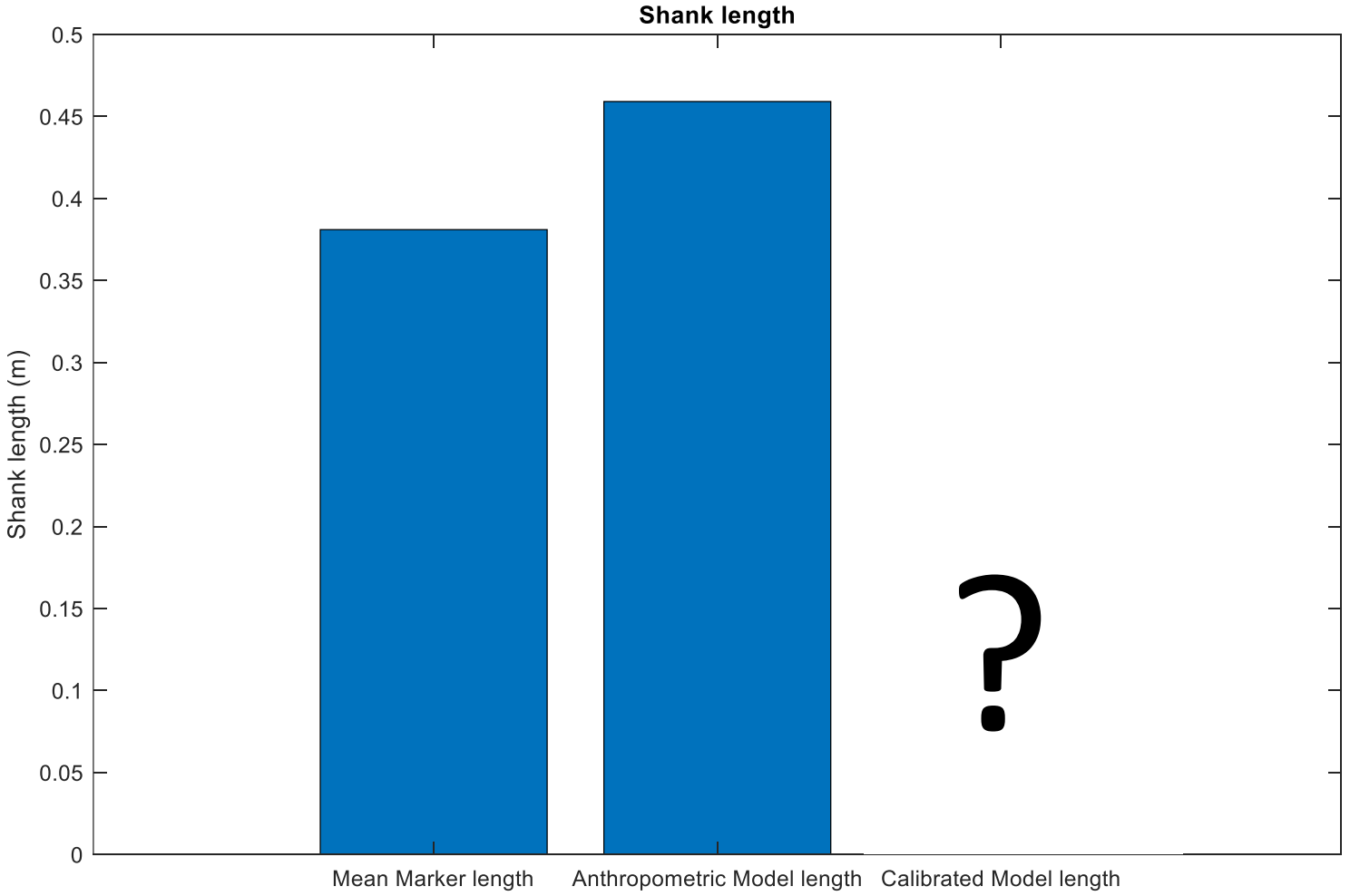


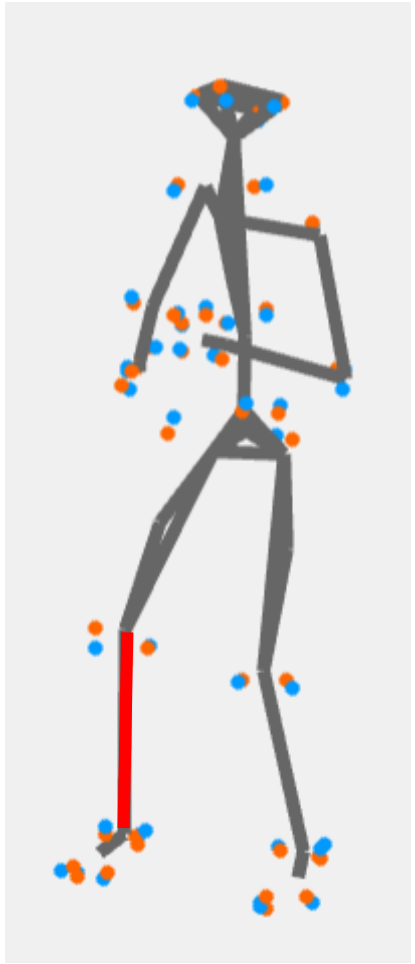



# What about the quality of the model ? – Right Shank length

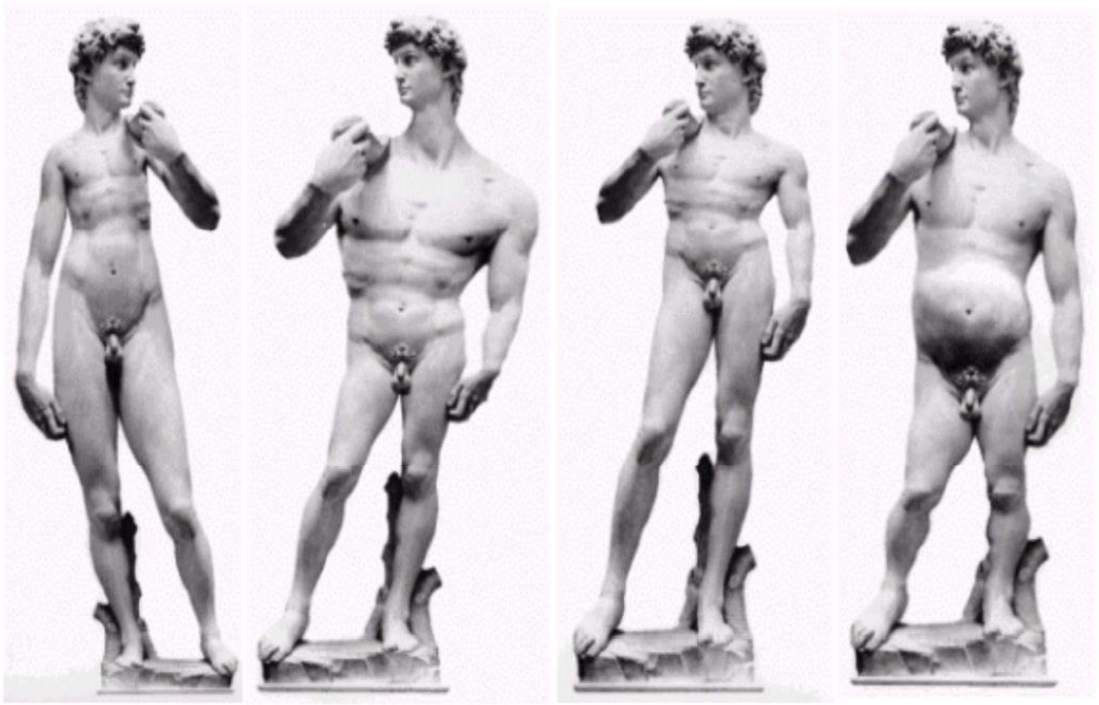
```
>> PostProcessingKinematic_Anthropo
```



# What about the quality of the model ?

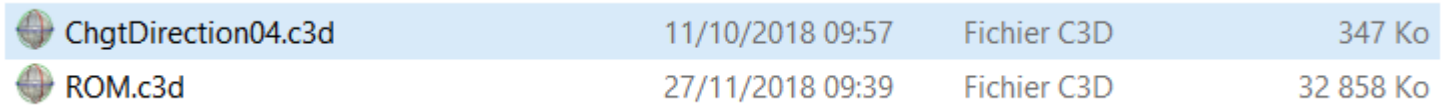
For a same size, segment lengths can vary between subjects.



# Pre-Work

Go in `Examples\1_SideStep_Kinematic\SideStep_Geometric_Calibration`

It contains :




We will add a geometric calibration step

Same previous steps, except for AnalysisParameters.

# Geometrical Calibration step

- Frames used
  - Selection method of frames : UniformlyDistributed
  - Number of frames : 20
- Body length
  - Homethetic factors of Clavicles are linked to homothetic factor of the Thorax
- Marker Position
  - Direction of markers to optimize in local frames ( Z is medio-lateral )
- Axis of rotation
  - Orientation of Joint axis can be optimized to fit subject-specific joint axis.
  - For example knee axis. Two rotation angles have to be introduced.

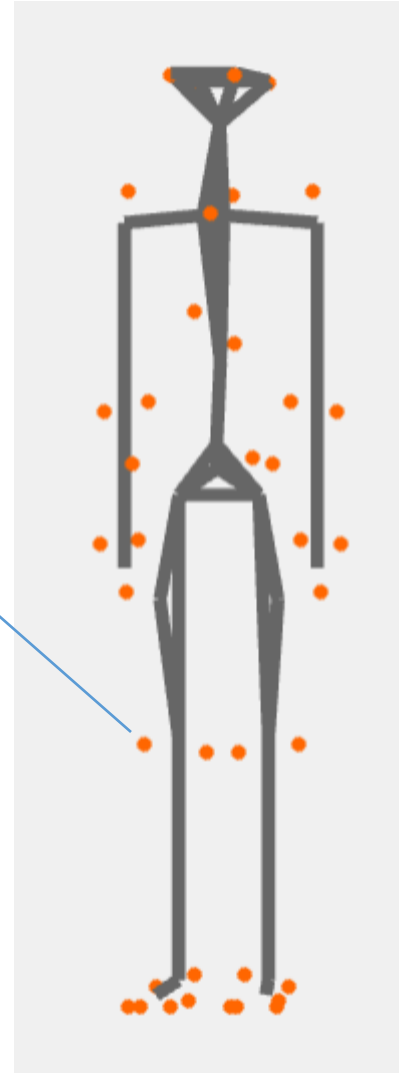
# What is CusToM Doing ?

```
Geometrical Calibration ...
... Geometrical Calibration done
```

A priori known location of anatomical landmarks are computed in the global reference frame $R_0$,function of:

- joint coordinates $\boldsymbol{q}$,
- homothetic factors $\boldsymbol{k}$,
- variation of marker position $\Delta\boldsymbol{p}$,
- rotation of joint axis $\boldsymbol{\alpha}$.

$$^{R_0}\boldsymbol{X}_{\boldsymbol{marker}} = f(\boldsymbol{q}, \boldsymbol{k}, \Delta\boldsymbol{p}, \boldsymbol{\alpha})$$

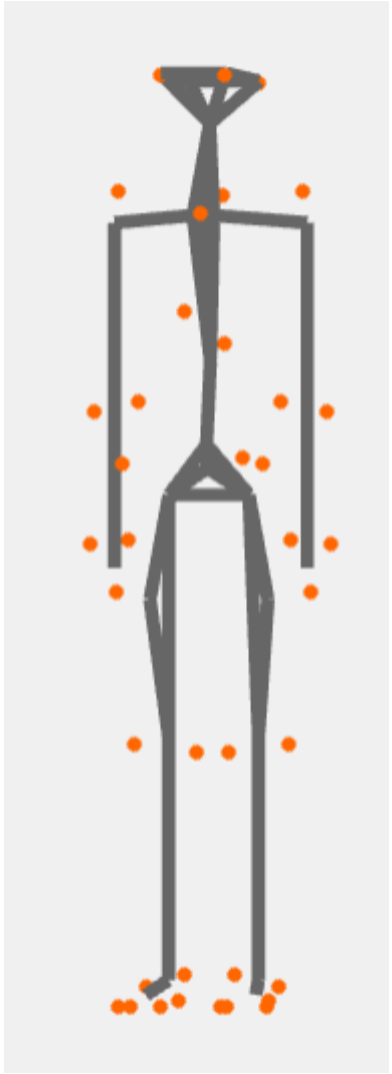


# What is CusToM Doing ?

```
Geometrical Calibration ...
... Geometrical Calibration done
```

**Uniformely distributed frames**

Frames are chosen equally spaced in ROM.c3d



# What is CusToM Doing ?

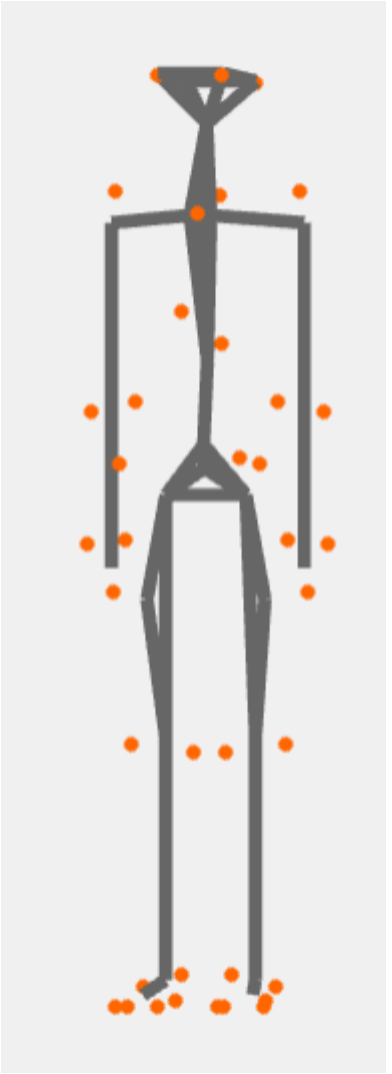
```
Geometrical Calibration ...
... Geometrical Calibration done
```

| | | | |
|---|---|---|---|
| RClavicle ▼ | Linked to | Thorax ▼ |
| LClavicle ▼ | Linked to | Thorax ▼ |

**Body Length**

Linear Constraints of homothetic factors.

$$\begin{cases} k_{R_{Clavicle}} - k_{Thorax} = 0 \\ k_{L_{Clavicle}} - k_{Thorax} = 0 \end{cases}$$

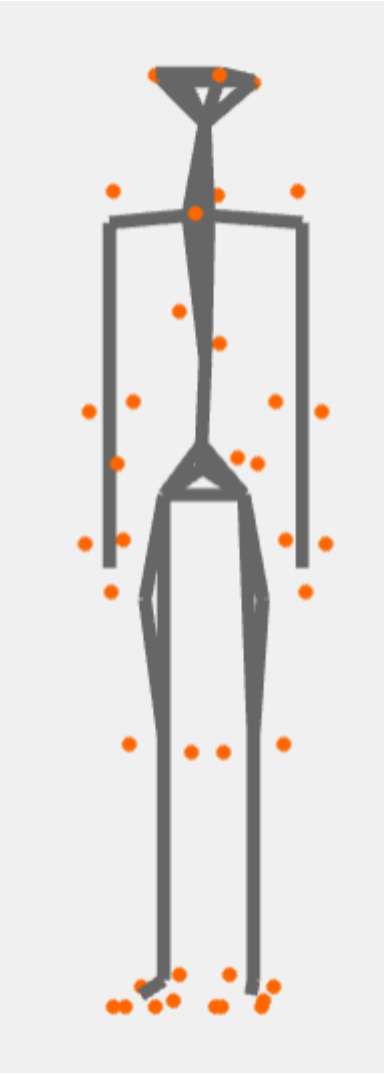


# What is CusToM Doing ?

```
Geometrical Calibration ...
... Geometrical Calibration done
```

**Axis of rotation**

$$^{R_i}\boldsymbol{X}_{\boldsymbol{marker}} = {}^{R_i}\boldsymbol{p}_A + {}^{R_i}\Delta\boldsymbol{p}$$



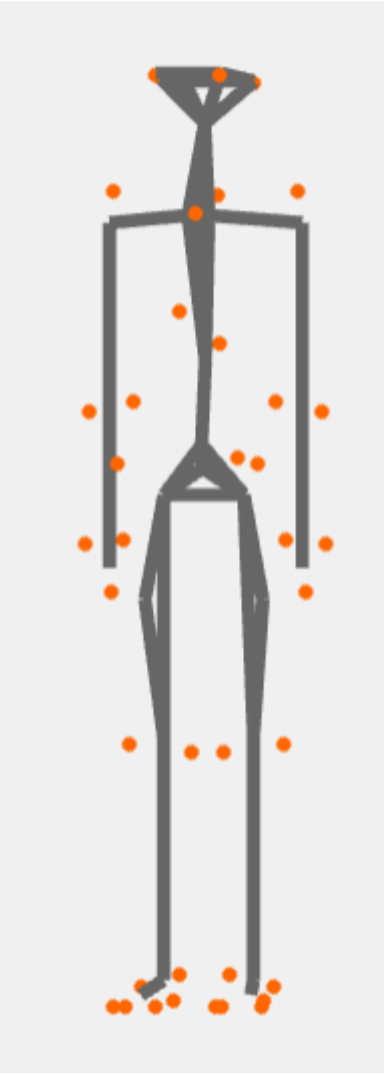
# What is CusToM Doing ?

```
Geometrical Calibration ...
... Geometrical Calibration done
```

**Axis of rotation**

$$^{R_i}\boldsymbol{X}_{\boldsymbol{marker}} = {}^{R_i}\boldsymbol{p}_A + {}^{R_i}\Delta\boldsymbol{p}$$

Some location of markers are optimized
In this case :



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Geometrical Calibration ...
... Geometrical Calibration done
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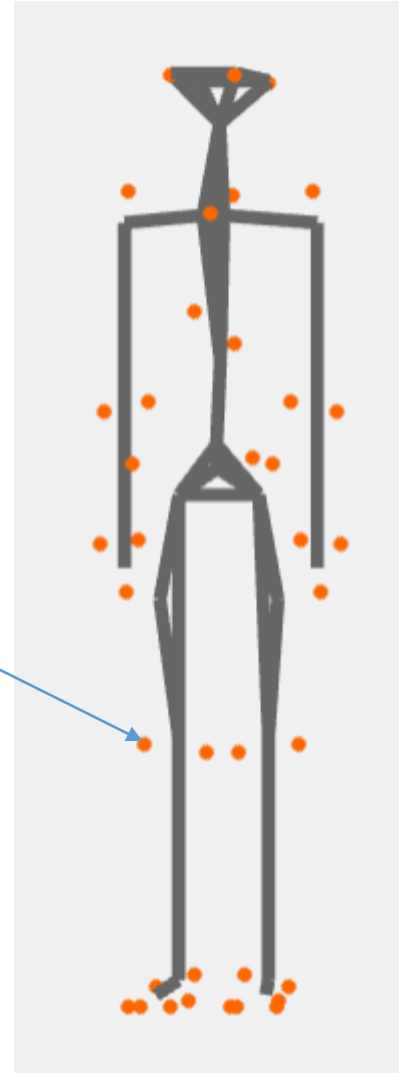

# What is CusToM Doing ?

```
Geometrical Calibration ...
... Geometrical Calibration done
```

**Axis of rotation**

$$^{R_i}\boldsymbol{X}_{\boldsymbol{marker}} = {}^{R_i}\boldsymbol{p}_A + {}^{R_i}\Delta\boldsymbol{p}$$

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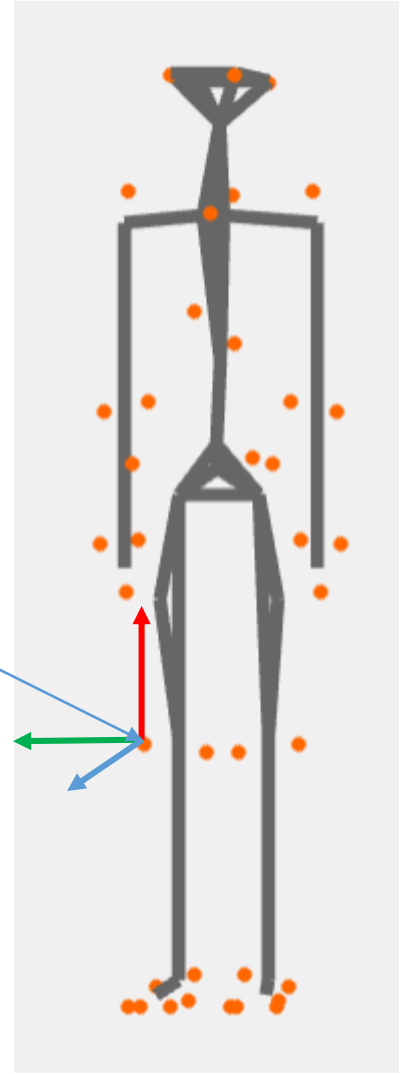

# What is CusToM Doing ?

```
Geometrical Calibration ...
... Geometrical Calibration done
```

**Axis of rotation**

$$^{R_i}\boldsymbol{X}_{\boldsymbol{marker}} = {}^{R_i}\boldsymbol{p}_A + {}^{R_i}\Delta\boldsymbol{p}$$

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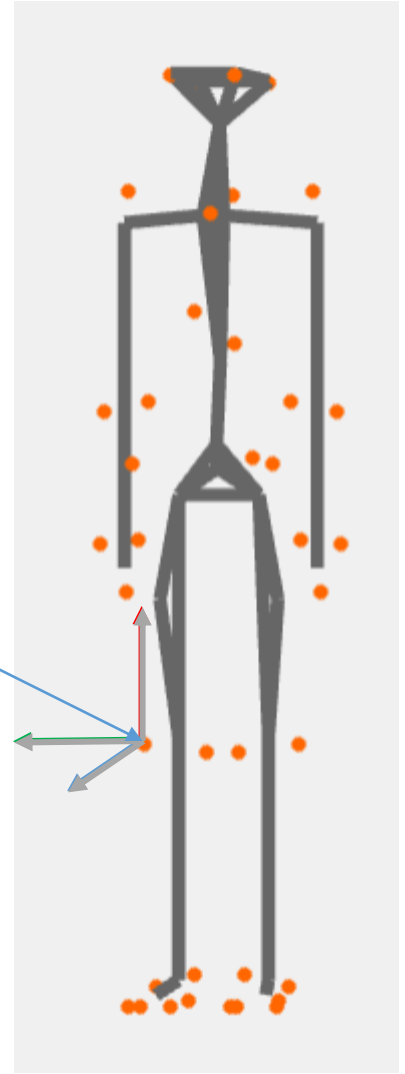


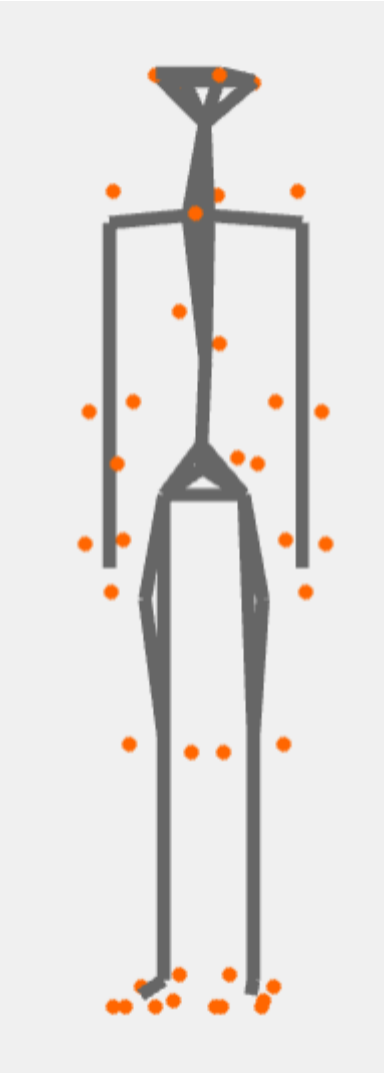
# What is CusToM Doing ?

```
Geometrical Calibration ...
... Geometrical Calibration done
```

**Axis of rotation**

$$^{R_i}\boldsymbol{X}_{\boldsymbol{marker}} = {}^{R_i}\boldsymbol{p}_A + {}^{R_i}\Delta\boldsymbol{p}$$

Some location of markers are optimized
In this case :



# What is CusToM Doing ?

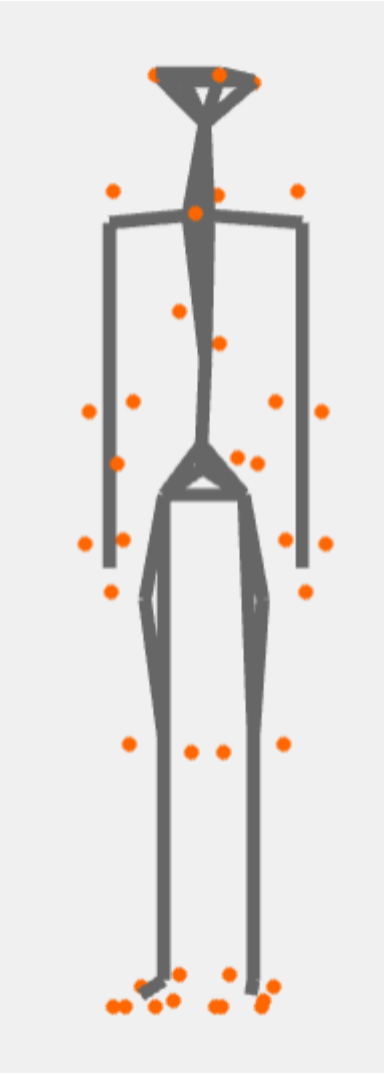
```
Geometrical Calibration ...
... Geometrical Calibration done
```

**Axis of rotation**

$$^{R_i}\boldsymbol{X}_{\boldsymbol{marker}} = {}^{R_i}\boldsymbol{p}_A + {}^{R_i}\Delta\boldsymbol{p}$$

Some location of markers are optimized
In this case :
•RKNE is trusted for x,y,z direction

RKNE ☐☐☐



# What is CusToM Doing ?

```
Geometrical Calibration ...
... Geometrical Calibration done
```

**Axis of rotation**

$$^{R_i}\boldsymbol{X}_{\boldsymbol{marker}} = {}^{R_i}\boldsymbol{p}_A + {}^{R_i}\Delta\boldsymbol{p}$$

Some location of markers are optimized
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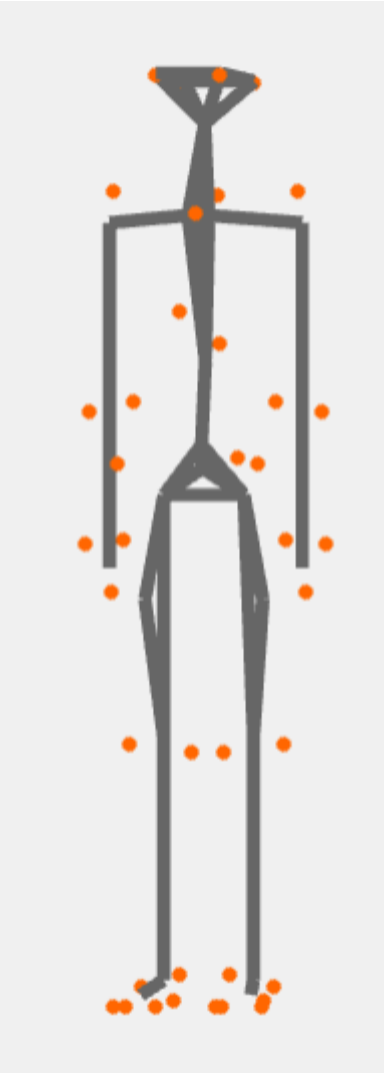
RKNE ☐☐☐



# What is CusToM Doing ?

```
Geometrical Calibration ...
... Geometrical Calibration done
```

**Axis of rotation**

$$^{R_i}\boldsymbol{X}_{\boldsymbol{marker}} = {}^{R_i}\boldsymbol{p}_A + {}^{R_i}\Delta\boldsymbol{p}$$

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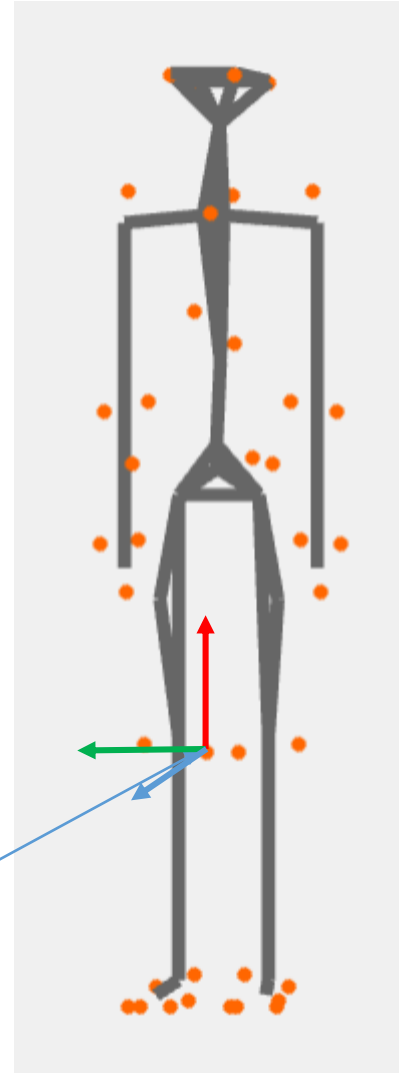
RKNE ☐☐☐



# What is CusToM Doing ?

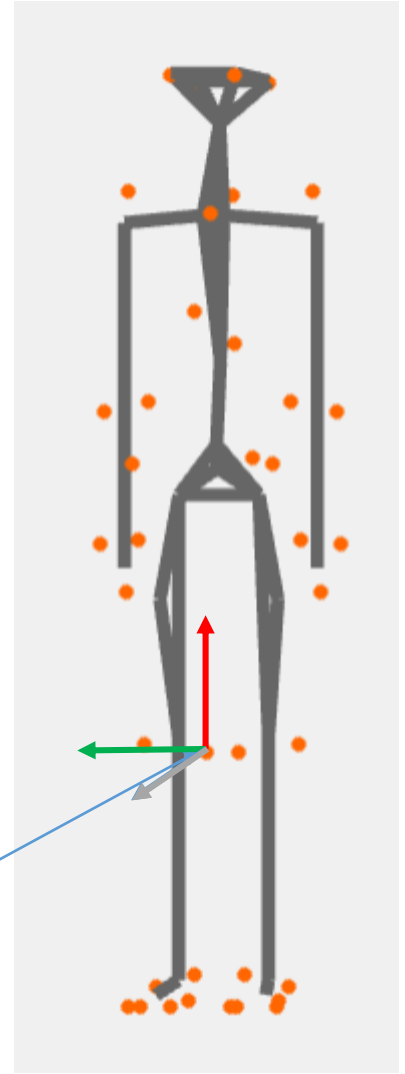
```
Geometrical Calibration ...
... Geometrical Calibration done
```

**Axis of rotation**

$$^{R_i}\boldsymbol{X}_{\boldsymbol{marker}} = {}^{R_i}\boldsymbol{p}_A + {}^{R_i}\Delta\boldsymbol{p}$$

Some location of markers are optimized
In this case :
•RKNE is trusted for x,y,z direction

RKNE ☐☐☐



# What is CusToM Doing ?

```
Geometrical Calibration ...
... Geometrical Calibration done
```

**Axis of rotation**

$$^{R_i}\boldsymbol{X}_{\boldsymbol{marker}} = {}^{R_i}\boldsymbol{p}_A + {}^{R_i}\Delta\boldsymbol{p}$$

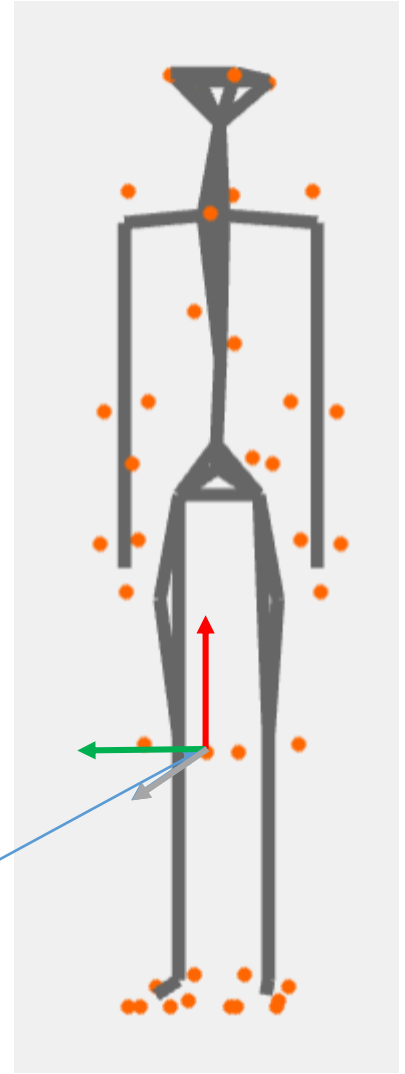
Some location of markers are optimized
In this case :

- RKNE is trusted for x,y,z direction

- RKNI is trusted and optimized for y and z direction

RKNE ☐ ☐ ☐

RKNI ☐ ☑ ☑



# What is CusToM Doing ?

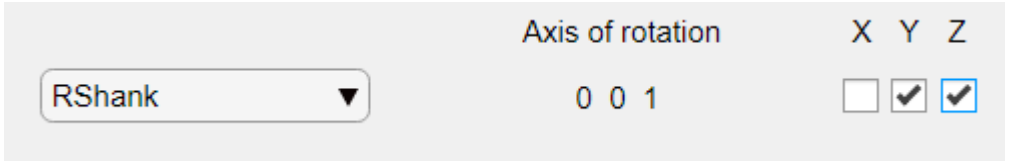
```
Geometrical Calibration ...
... Geometrical Calibration done
```

**Axis of rotation**

$$\overrightarrow{a_z}' = Rot(\alpha_1, \overrightarrow{a_x}) * \overrightarrow{a_0}$$

$$\overrightarrow{a_z}'' = Rot(\alpha_2, \overrightarrow{a_y}') * \overrightarrow{a_z}'$$

$$\overrightarrow{a_z}'' = Rot(\alpha_2, \overrightarrow{a_y}') * Rot(\alpha_1, \overrightarrow{a_x}) * \overrightarrow{a_0}$$




# What is CusToM Doing ?

```
Geometrical Calibration ...
... Geometrical Calibration done
```

**Axis of rotation**

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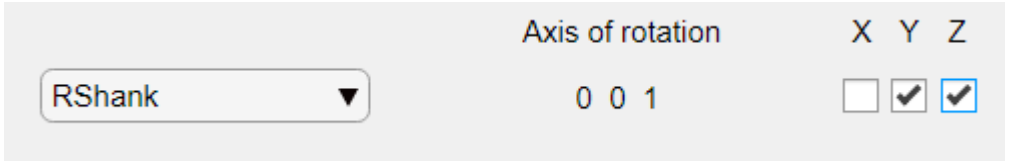


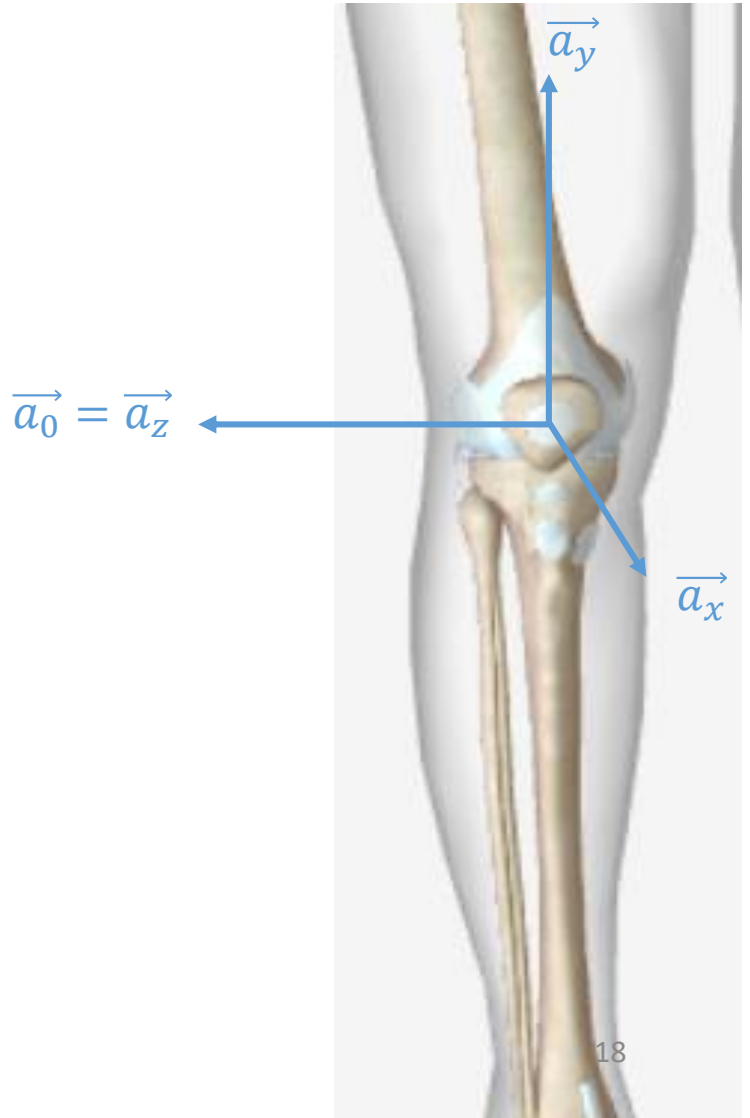

# What is CusToM Doing ?

```
Geometrical Calibration ...
... Geometrical Calibration done
```

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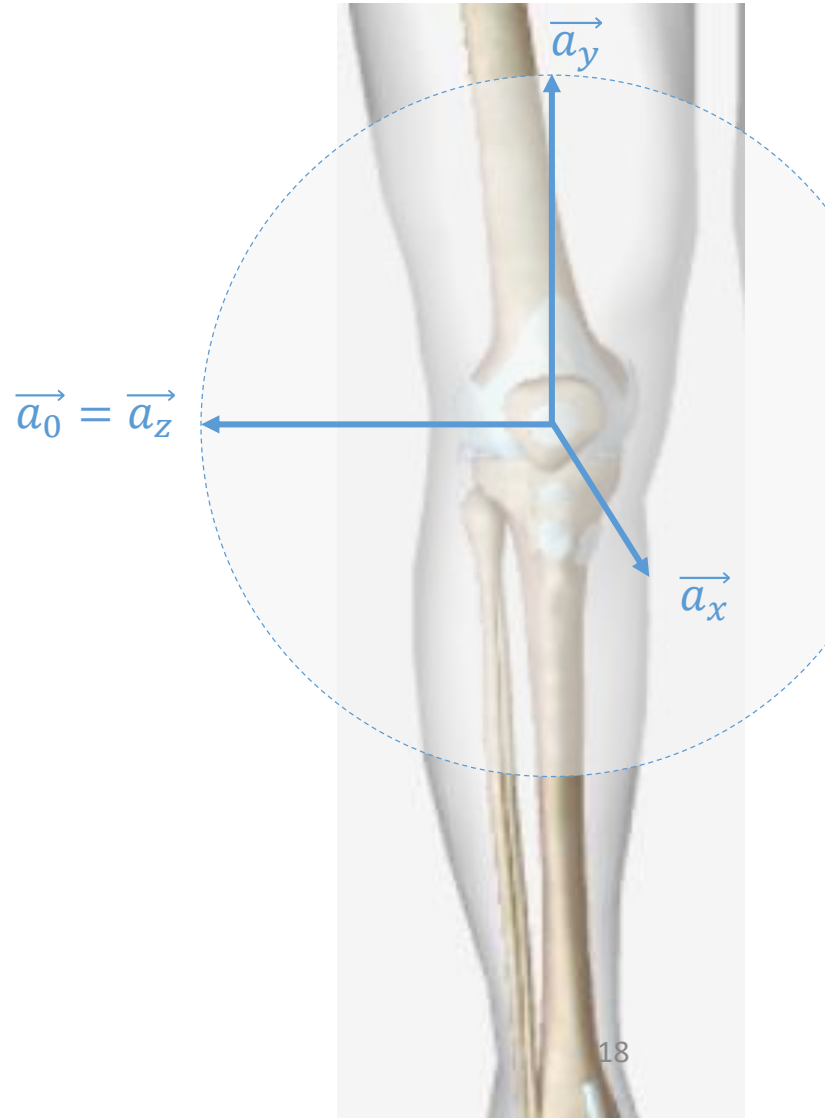



| | Axis of rotation | X | Y | Z |
|---|---|---|---|---|
| RShank | 0 0 1 | ☐ | ☑ | ☑ |

# What is CusToM Doing ?

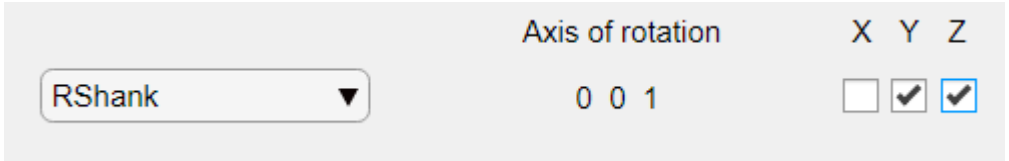
```
Geometrical Calibration ...
... Geometrical Calibration done
```

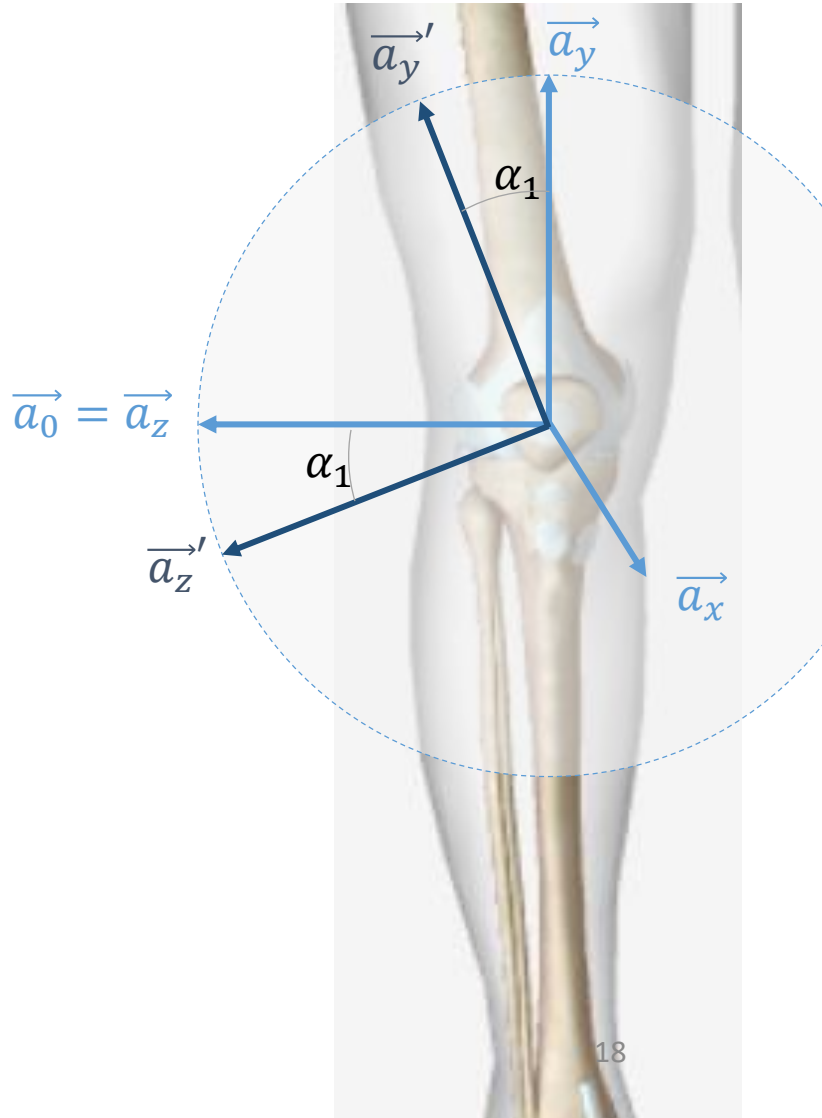
**Axis of rotation**

$$\overrightarrow{a_z}' = Rot(\alpha_1, \overrightarrow{a_x}) * \overrightarrow{a_0}$$

$$\overrightarrow{a_z}'' = Rot(\alpha_2, \overrightarrow{a_y}') * \overrightarrow{a_z}'$$

$$\overrightarrow{a_z}'' = Rot(\alpha_2, \overrightarrow{a_y}') * Rot(\alpha_1, \overrightarrow{a_x}) * \overrightarrow{a_0}$$



# What is CusToM Doing ?

```
Geometrical Calibration ...
... Geometrical Calibration done
```

**Axis of rotation**

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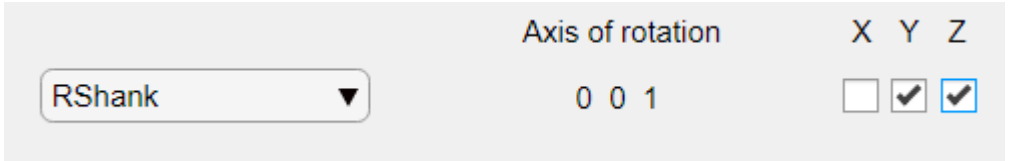
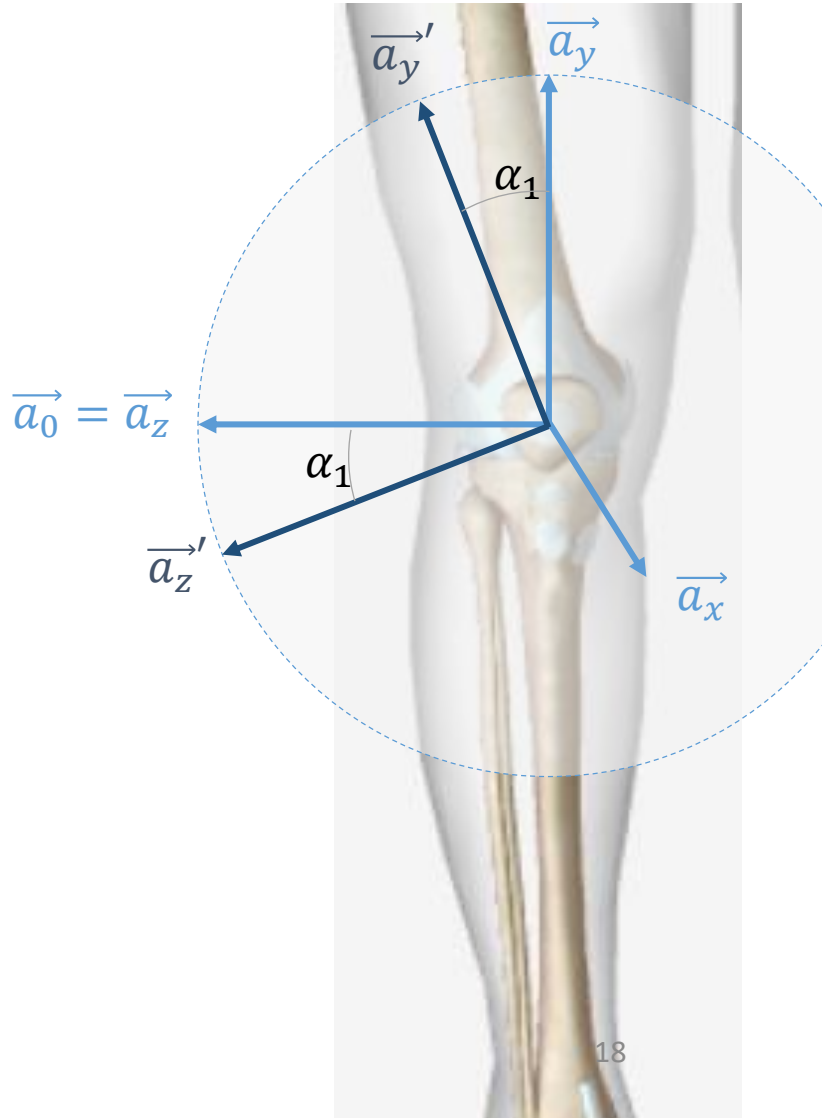
$$\overrightarrow{a_z}'' = Rot(\alpha_2, \overrightarrow{a_y}') * \overrightarrow{a_z}'$$

$$\overrightarrow{a_z}'' = Rot(\alpha_2, \overrightarrow{a_y}') * Rot(\alpha_1, \overrightarrow{a_x}) * \overrightarrow{a_0}$$



# What is CusToM Doing ?

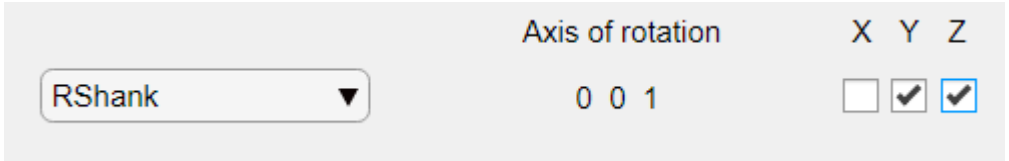
```
Geometrical Calibration ...
... Geometrical Calibration done
```

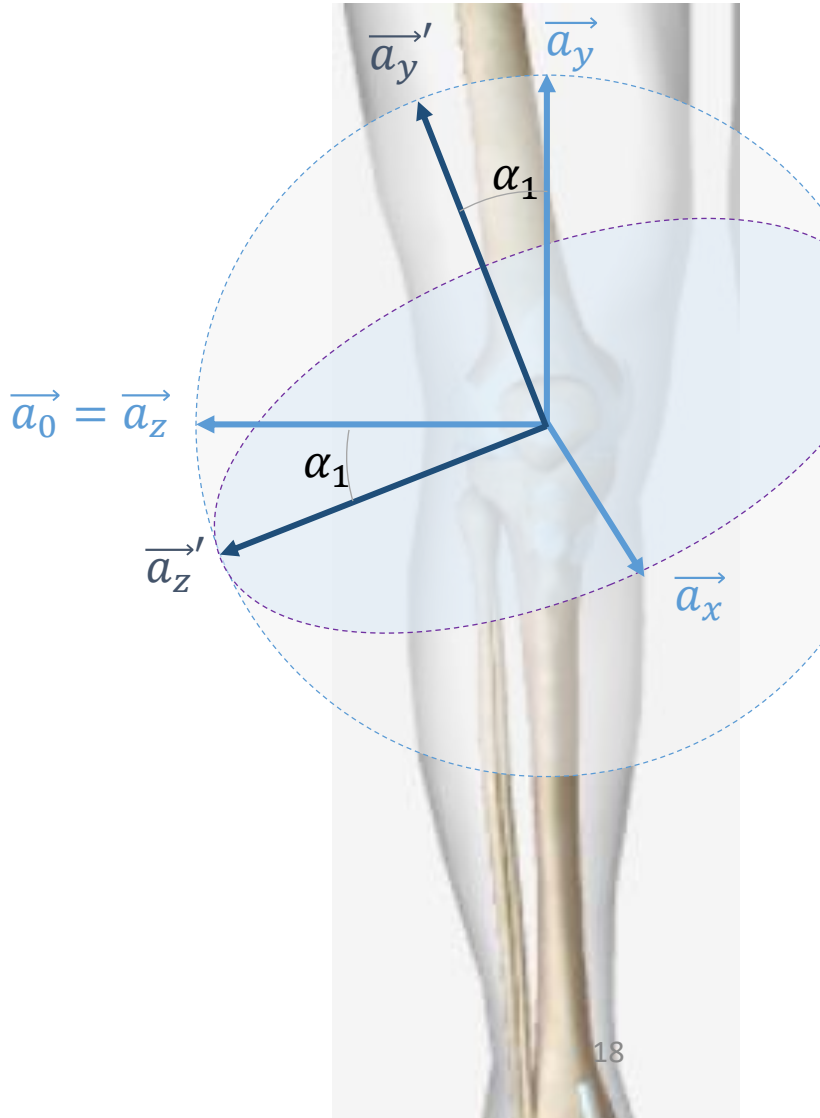
**Axis of rotation**

$$\overrightarrow{a_z}' = Rot(\alpha_1, \overrightarrow{a_x}) * \overrightarrow{a_0}$$

$$\overrightarrow{a_z}'' = Rot(\alpha_2, \overrightarrow{a_y}') * \overrightarrow{a_z}'$$

$$\overrightarrow{a_z}'' = Rot(\alpha_2, \overrightarrow{a_y}') * Rot(\alpha_1, \overrightarrow{a_x}) * \overrightarrow{a_0}$$



# What is CusToM Doing ?

```
Geometrical Calibration ...
... Geometrical Calibration done
```

**Axis of rotation**

$$\overrightarrow{a_z}' = Rot(\alpha_1, \overrightarrow{a_x}) * \overrightarrow{a_0}$$

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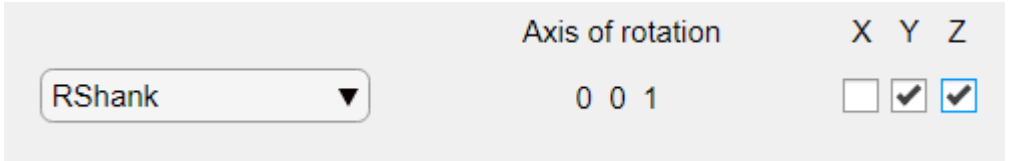
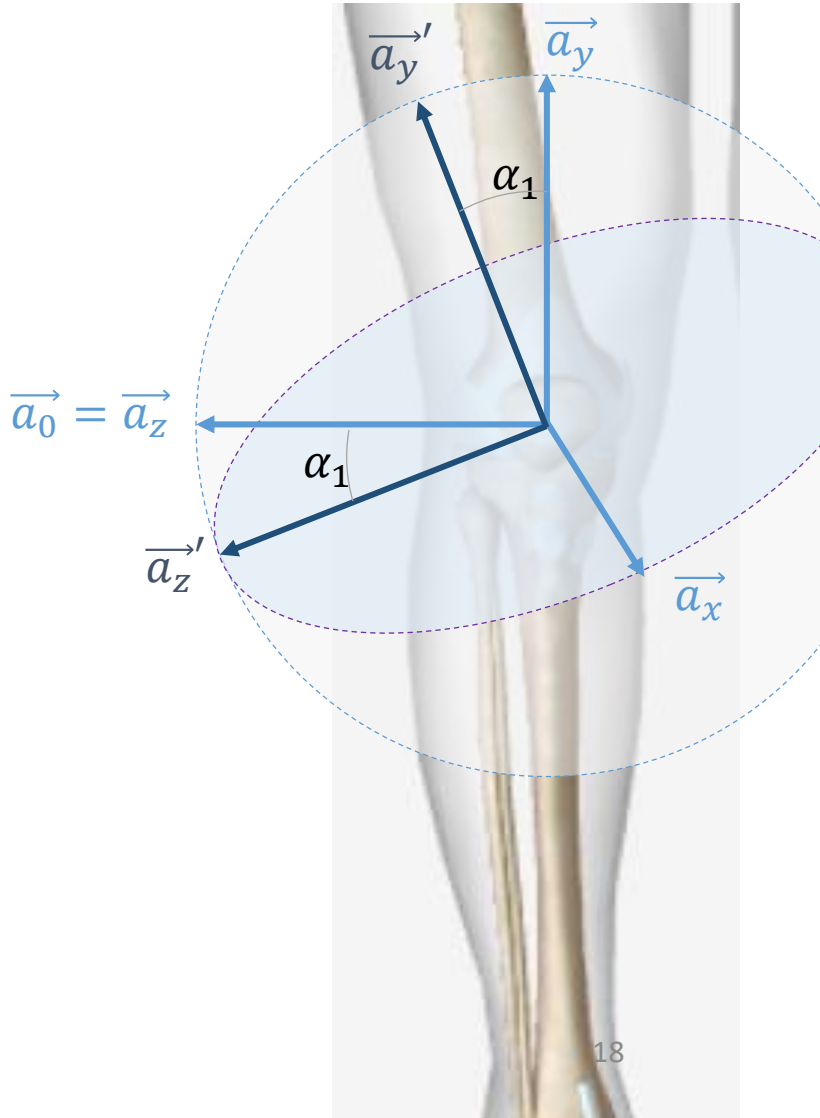
$$\overrightarrow{a_z}'' = Rot(\alpha_2, \overrightarrow{a_y}') * Rot(\alpha_1, \overrightarrow{a_x}) * \overrightarrow{a_0}$$



# What is CusToM Doing ?

```
Geometrical Calibration ...
... Geometrical Calibration done
```

**Axis of rotation**

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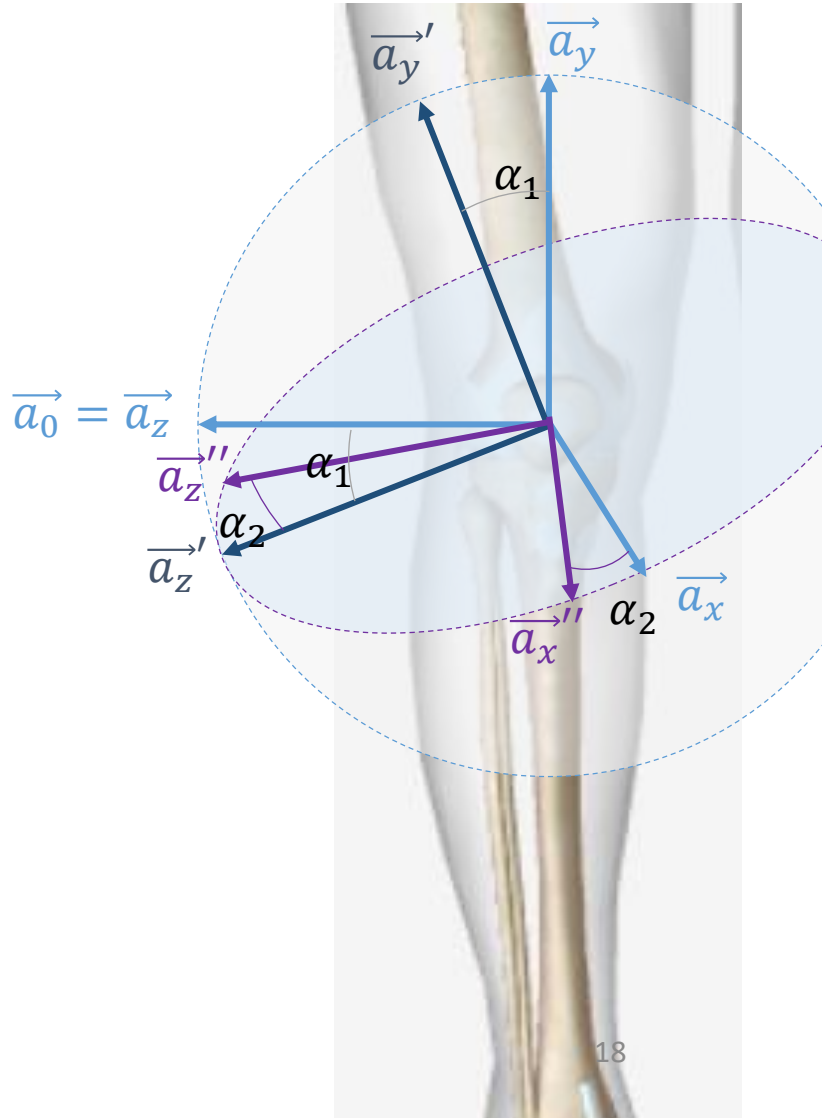



| | Axis of rotation | X | Y | Z |
|---|---|---|---|---|
| RShank | 0 0 1 | ☐ | ☑ | ☑ |

# What is CusToM Doing ?

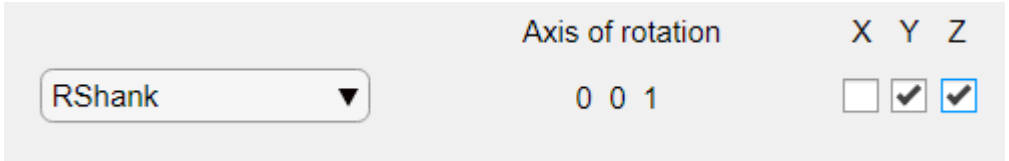
```
Geometrical Calibration ...
... Geometrical Calibration done
```

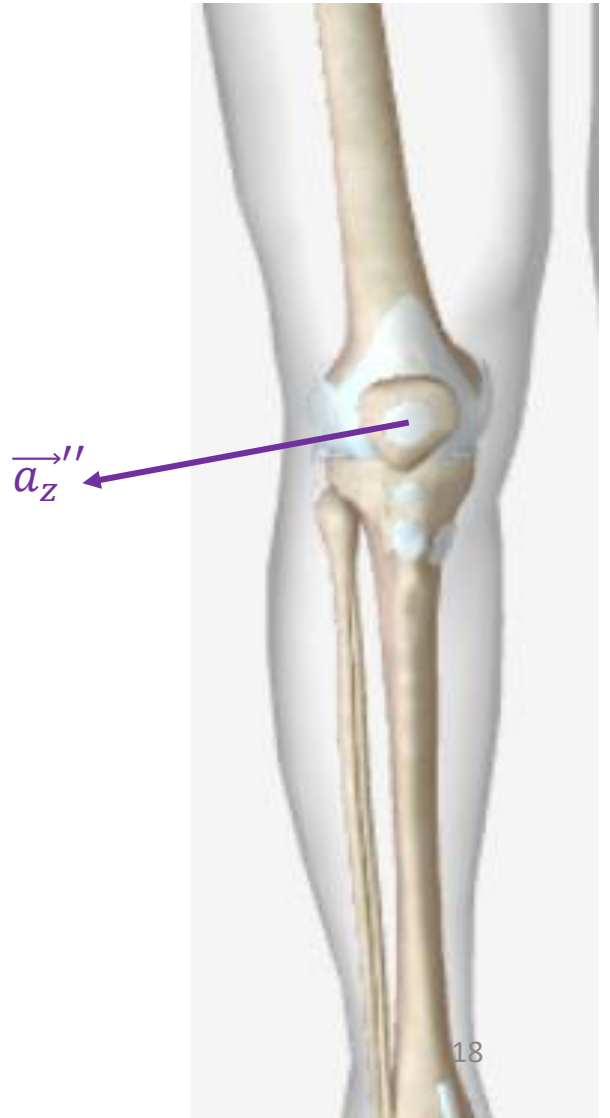
**Axis of rotation**

$$\overrightarrow{a_z}' = Rot(\alpha_1, \overrightarrow{a_x}) * \overrightarrow{a_0}$$

$$\overrightarrow{a_z}'' = Rot(\alpha_2, \overrightarrow{a_y}') * \overrightarrow{a_z}'$$

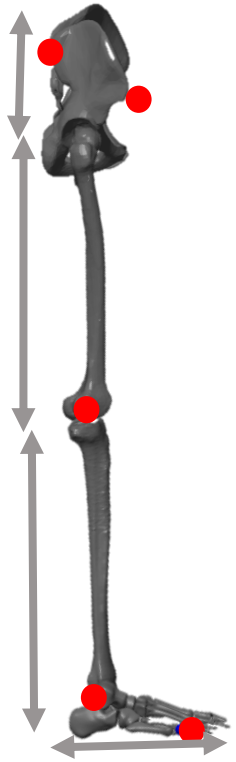
$$\overrightarrow{a_z}'' = Rot(\alpha_2, \overrightarrow{a_y}') * Rot(\alpha_1, \overrightarrow{a_x}) * \overrightarrow{a_0}$$



# What is CusToM Doing ? – Geometrical Calibration Process

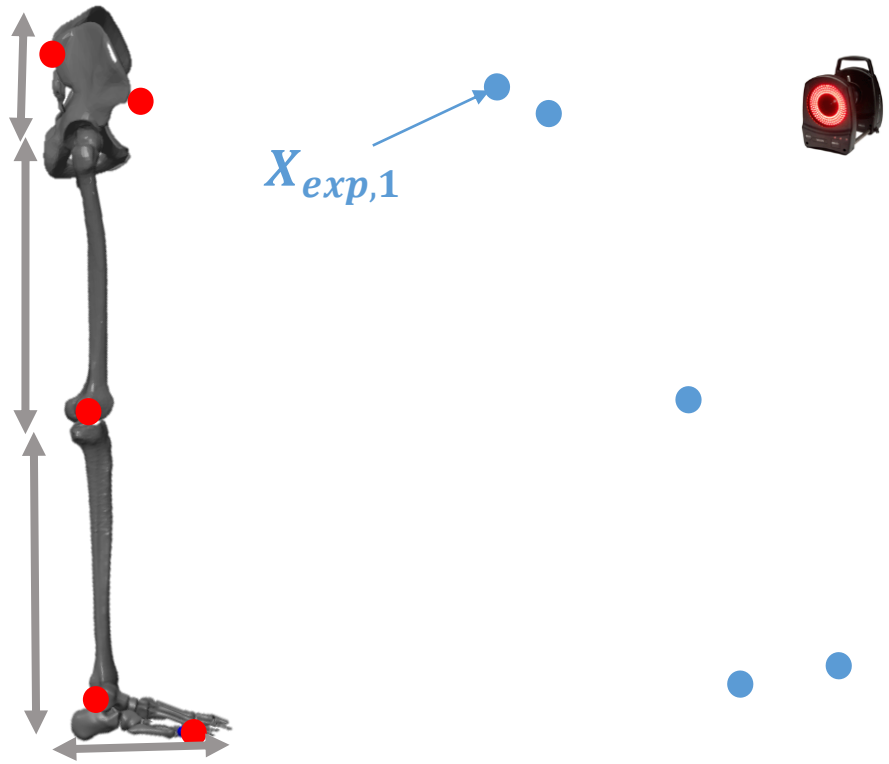
```
Geometrical Calibration ...
... Geometrical Calibration done
```



Regression method
Based on height
RM

# What is CusToM Doing ? – Geometrical Calibration Process

```
Geometrical Calibration ...
... Geometrical Calibration done
```

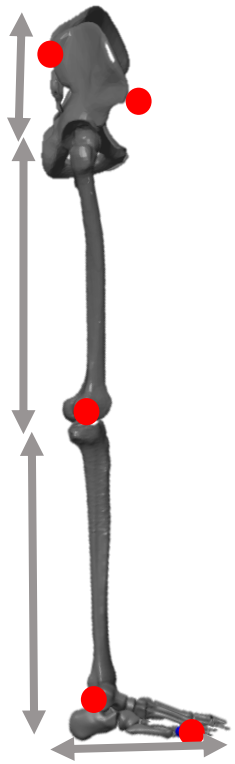


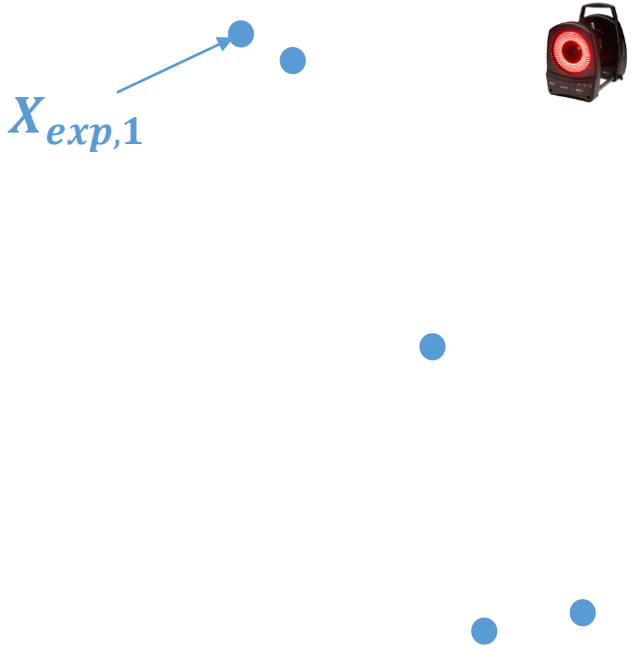
# What is CusToM Doing ? – Geometrical Calibration Process

```
Geometrical Calibration ...
... Geometrical Calibration done
```

Equally spaced sets of frames:

$N_f$

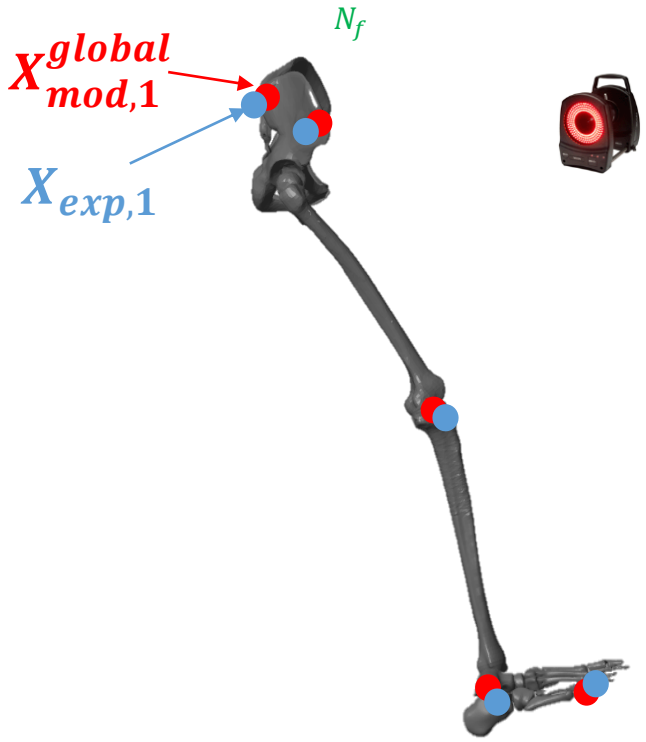




# What is CusToM Doing ? – Geometrical Calibration Process

```
Geometrical Calibration ...
... Geometrical Calibration done
```

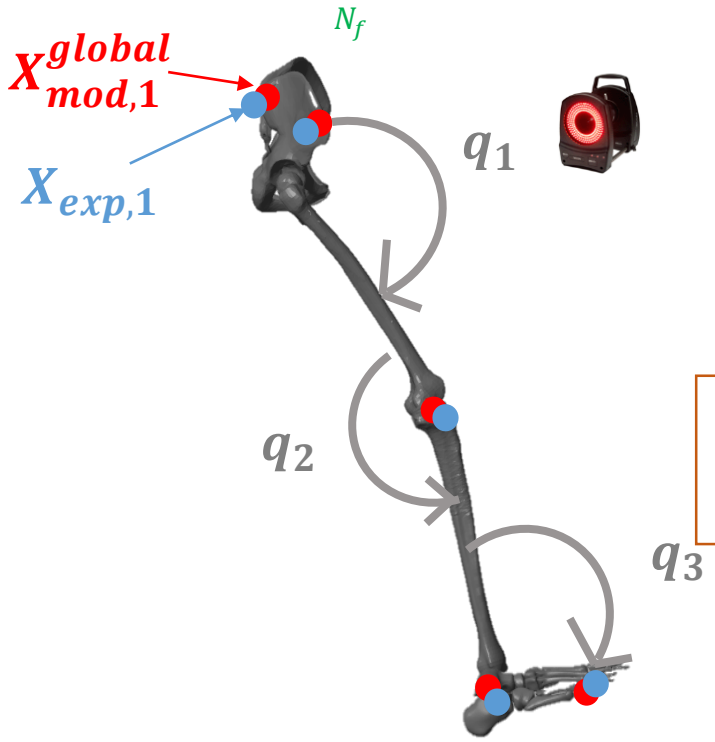
Equally spaced sets of frames:



# What is CusToM Doing ? – Geometrical Calibration Process

```
Geometrical Calibration ...
... Geometrical Calibration done
```

Equally spaced sets of frames:



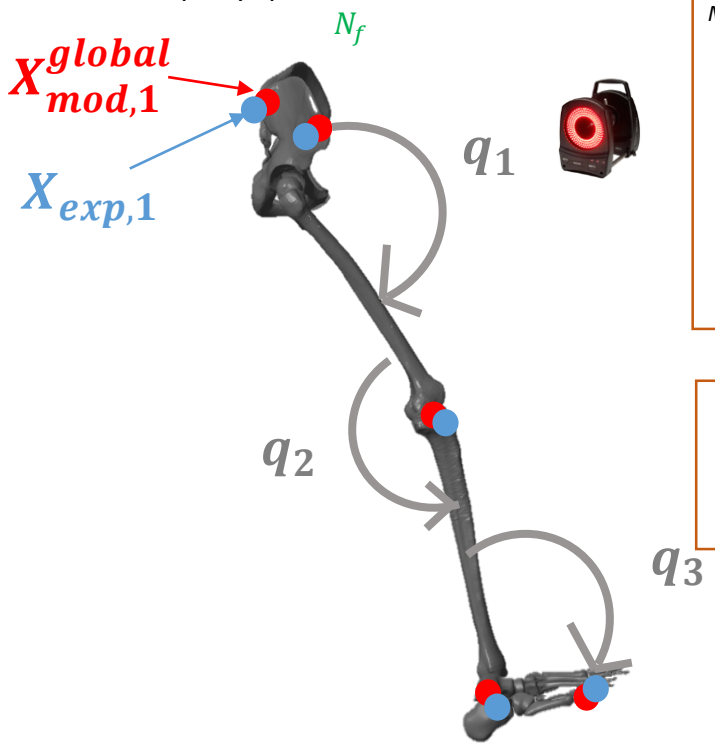

Inverse kinematics

*Lu and O'Connor et al. 1999*

# What is CusToM Doing ? – Geometrical Calibration Process

```
Geometrical Calibration ...
... Geometrical Calibration done
```

Equally spaced sets of frames:




*Muller et al. 2015*

## Parameters identification

At each iteration i

$$\min_{k,\Delta p,\alpha} \phi_i = \sum_{f}^{N_f} \sum_{m}^{N_m} \left\| X_{exp,m}(t_f) - X_{mod,m}^{global}(t_f, k, \Delta p, \alpha) \right\|^2$$

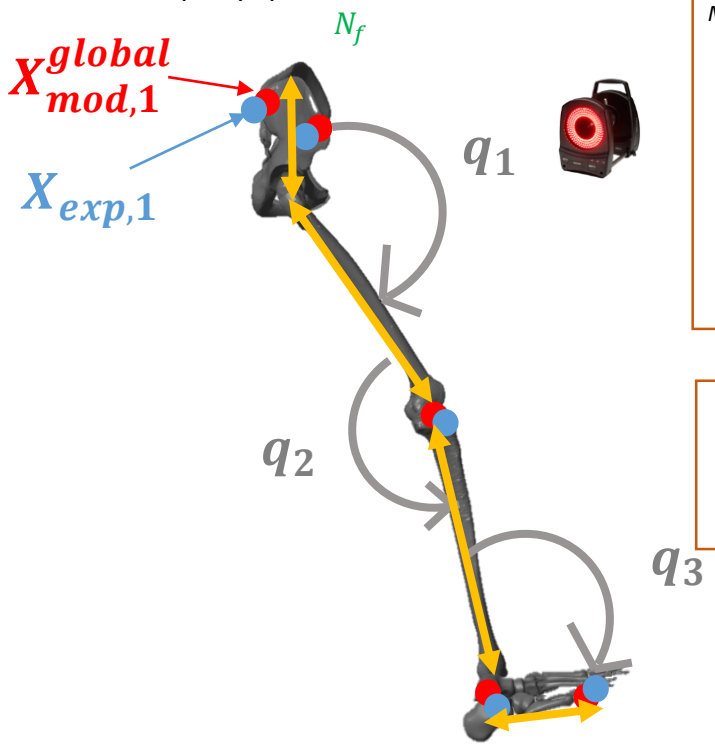
## Inverse kinematics

*Lu and O'Connor et al. 1999*

# What is CusToM Doing ? – Geometrical Calibration Process

```
Geometrical Calibration ...
... Geometrical Calibration done
```

Equally spaced sets of frames:




*Muller et al. 2015*

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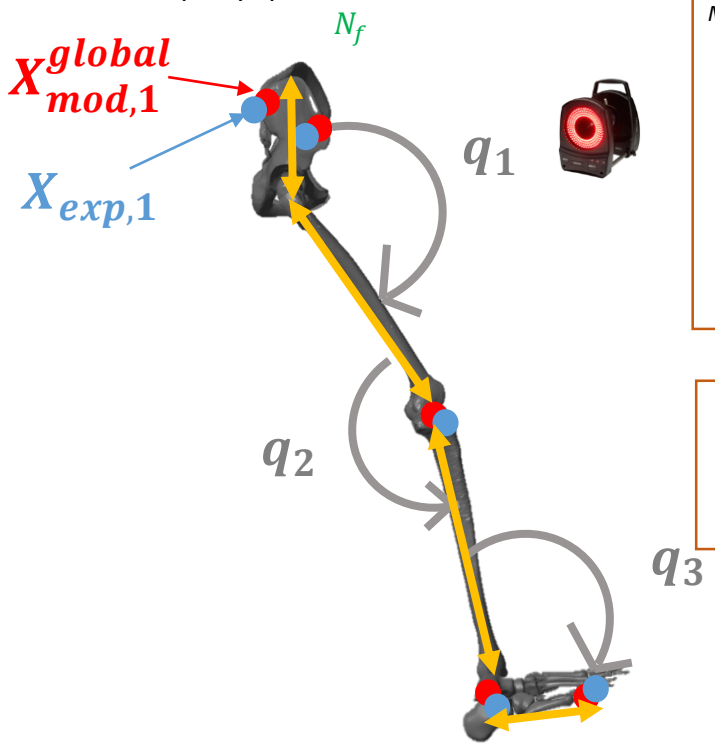
## Inverse kinematics

*Lu and O'Connor et al. 1999*

# What is CusToM Doing ? – Geometrical Calibration Process

```
Geometrical Calibration ...
... Geometrical Calibration done
```

Equally spaced sets of frames:




*Muller et al. 2015*

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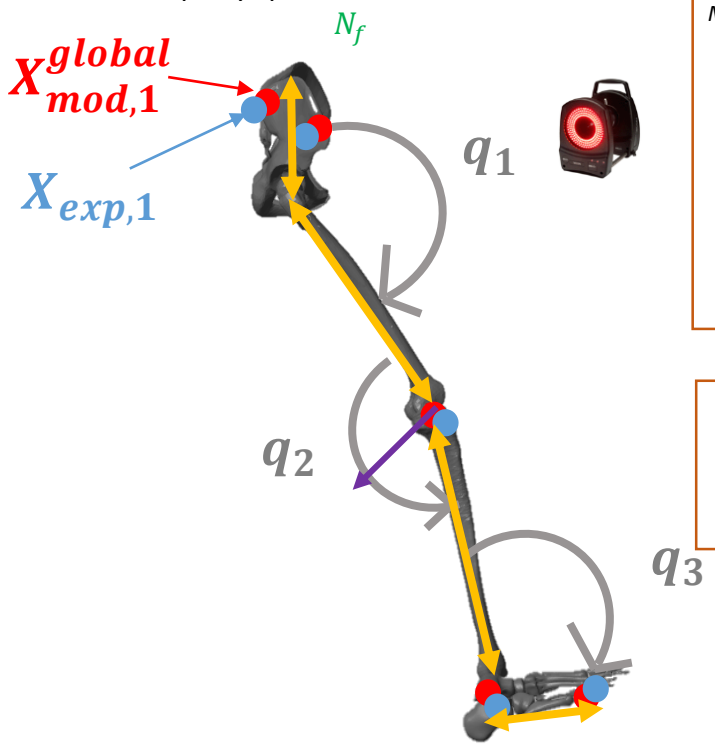
## Inverse kinematics

*Lu and O'Connor et al. 1999*

# What is CusToM Doing ? – Geometrical Calibration Process

```
Geometrical Calibration ...
... Geometrical Calibration done
```

Equally spaced sets of frames:




*Muller et al. 2015*

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At each iteration i

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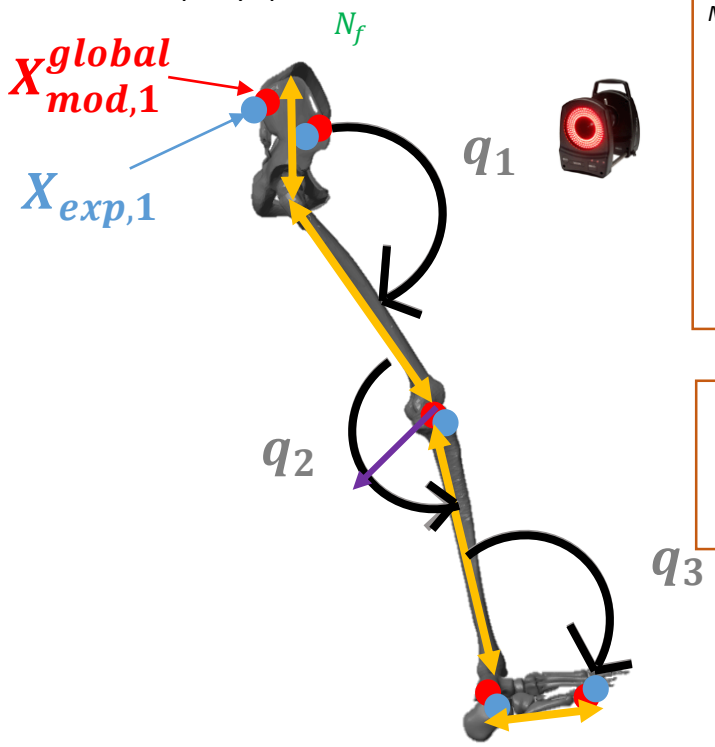
## Inverse kinematics

*Lu and O'Connor et al. 1999*

# What is CusToM Doing ? – Geometrical Calibration Process

```
Geometrical Calibration ...
... Geometrical Calibration done
```

Equally spaced sets of frames:




*Muller et al. 2015*

## Parameters identification

At each iteration i

$$\min_{k,\Delta p,\alpha} \phi_i = \sum_{f}^{N_f} \sum_{m}^{N_m} \left\| X_{exp,m}(t_f) - X_{mod,m}^{global}(t_f, k, \Delta p, \alpha) \right\|^2$$

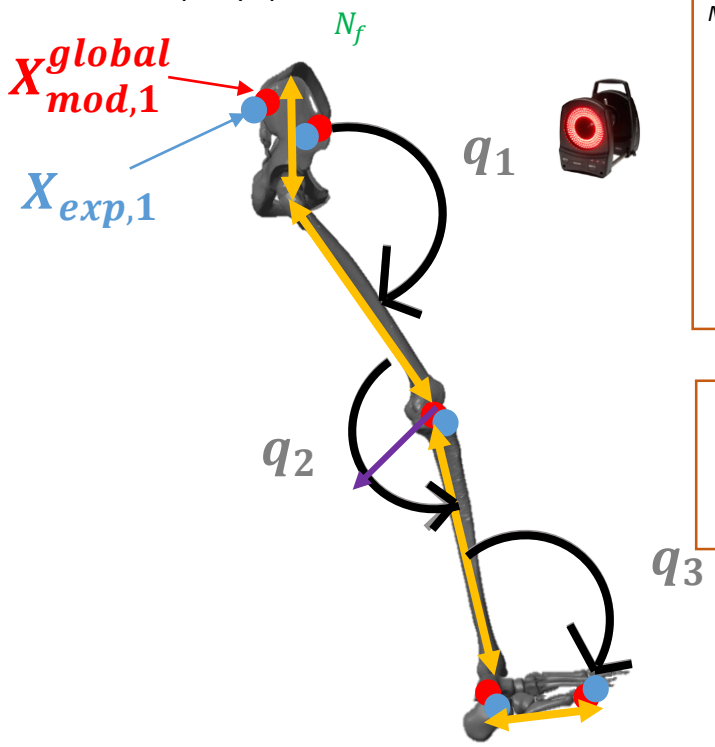
## Inverse kinematics

*Lu and O'Connor et al. 1999*

# What is CusToM Doing ? – Geometrical Calibration Process

```
Geometrical Calibration ...
... Geometrical Calibration done
```

Equally spaced sets of frames:




*Muller et al. 2015*

## Parameters identification

At each iteration i

$$\min_{k,\Delta p,\alpha} \phi_i = \sum_{f}^{N_f} \sum_{m}^{N_m} \left\| X_{exp,m}(t_f) - X_{mod,m}^{global}(t_f, k, \Delta p, \alpha) \right\|^2$$

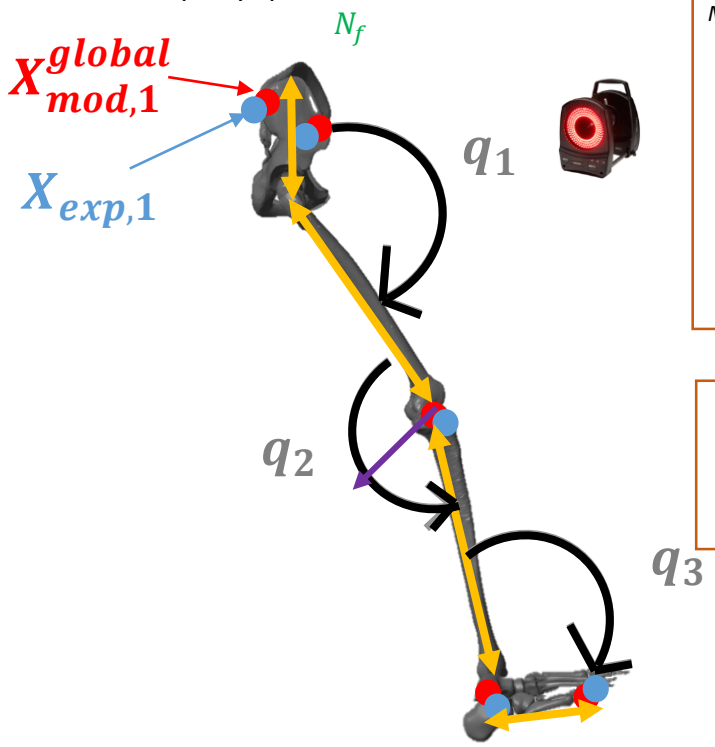
## Inverse kinematics

*Lu and O'Connor et al. 1999*

# What is CusToM Doing ? – Geometrical Calibration Process

```
Geometrical Calibration ...
... Geometrical Calibration done
```

Equally spaced sets of frames:




*Muller et al. 2015*

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At each iteration i

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## Inverse kinematics

*Lu and O'Connor et al. 1999*

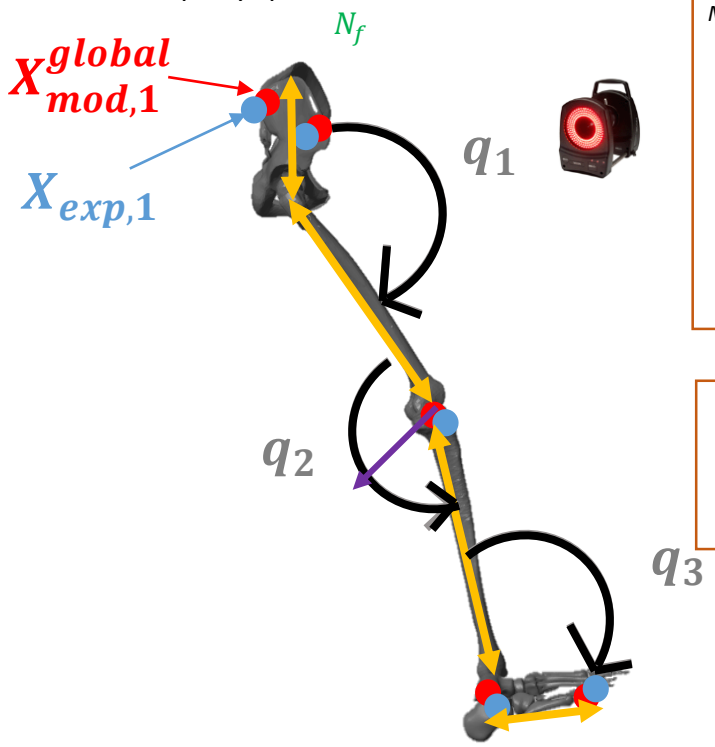
Criterion satisfied ?

$$\frac{\phi_i - \phi_{i-1}}{\phi_{i-1}} < 5\%$$

# What is CusToM Doing ? – Geometrical Calibration Process

```
Geometrical Calibration ...
... Geometrical Calibration done
```

Equally spaced sets of frames:




*Muller et al. 2015*

## Parameters identification

At each iteration i

$$\min_{k,\Delta p,\alpha} \phi_i = \sum_{f}^{N_f} \sum_{m}^{N_m} \left\| X_{exp,m}(t_f) - X_{mod,m}^{global}(t_f, k, \Delta p, \alpha) \right\|^2$$

## Inverse kinematics

*Lu and O'Connor et al. 1999*

Criterion satisfied ?

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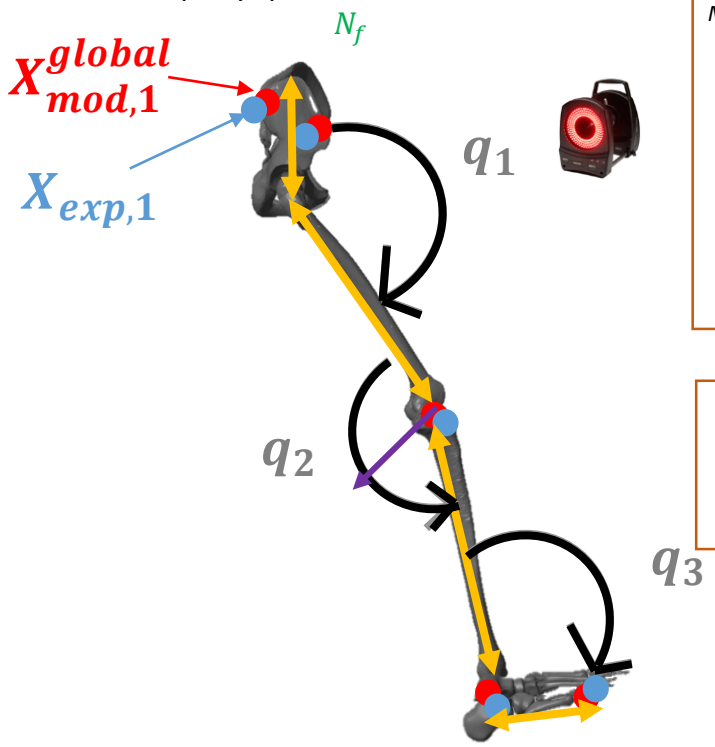
# What is CusToM Doing ? – Geometrical Calibration Process

```
Geometrical Calibration ...
... Geometrical Calibration done
```

Equally spaced sets of frames:




*Muller et al. 2015*

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At each iteration i

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## Inverse kinematics

*Lu and O'Connor et al. 1999*

Criterion satisfied ?

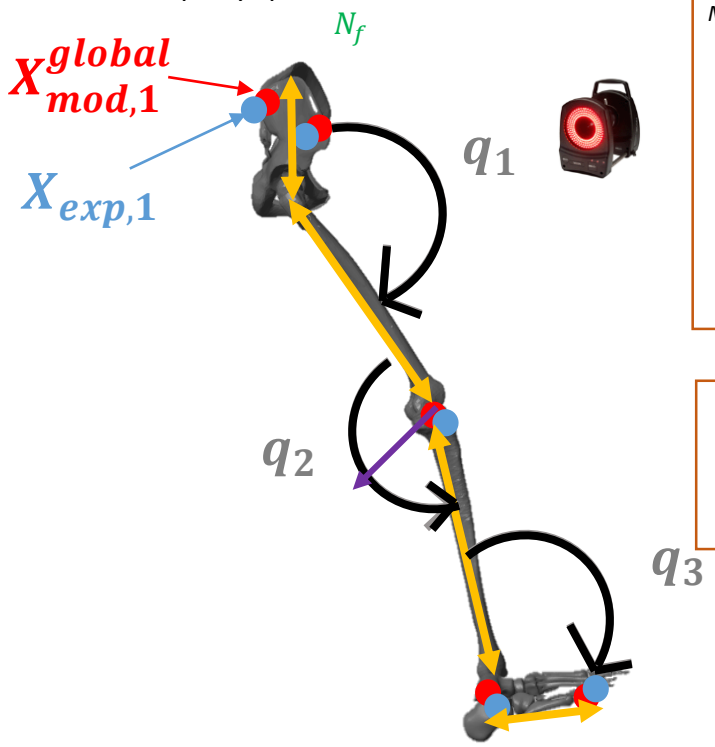
$$\frac{\phi_i - \phi_{i-1}}{\phi_{i-1}} < 5\%$$

No

# What is CusToM Doing ? – Geometrical Calibration Process

```
Geometrical Calibration ...
... Geometrical Calibration done
```

Equally spaced sets of frames:




*Muller et al. 2015*

## Parameters identification

At each iteration i

$$\min_{k,\Delta p,\alpha} \phi_i = \sum_{f}^{N_f} \sum_{m}^{N_m} \left\| X_{exp,m}(t_f) - X_{mod,m}^{global}(t_f, k, \Delta p, \alpha) \right\|^2$$

## Inverse kinematics

*Lu and O'Connor et al. 1999*

Criterion satisfied ?

$$\frac{\phi_i - \phi_{i-1}}{\phi_{i-1}} < 5\%$$

$No$

$Yes$

$Stop$

# What is CusToM Doing ?

```
Geometrical Calibration ...
... Geometrical Calibration done
```

$$\Phi = \sum_{f}^{N_f} \sum_{m}^{N_m} ||\mathbf{X}_{exp,m}(t_f) - \mathbf{X}_{mod,m}^{R_{global}}(\mathbf{q}(t_f), \mathbf{k}, \boldsymbol{\alpha}, \boldsymbol{\Delta}\mathbf{p})||^2$$

$$\begin{aligned} \min_{\mathbf{k},\boldsymbol{\alpha},\boldsymbol{\Delta}\mathbf{p}} \quad & \Phi(\mathbf{q}(t_f), \mathbf{k}, \boldsymbol{\alpha}, \boldsymbol{\Delta}\mathbf{p}) \\ \text{s.t.} \quad & \forall\ s\ \in [\![1; N_s]\!],\ |\frac{k_s}{k_s^0} - 1| < 20\ \% \\ & \forall\ a\ \in [\![1; N_\alpha]\!],\ \alpha_{a,min} < \alpha_a < \alpha_{a,max} \\ & \forall\ m \in [\![1; N_m]\!],\ |\Delta p_m| < 0.05\ m \end{aligned}$$

$$\epsilon = \frac{\Phi_i - \Phi_{i-1}}{\Phi_{i-1}}$$

# Geometrical Calibration Results

```
>> PostProcessingCalibration
```

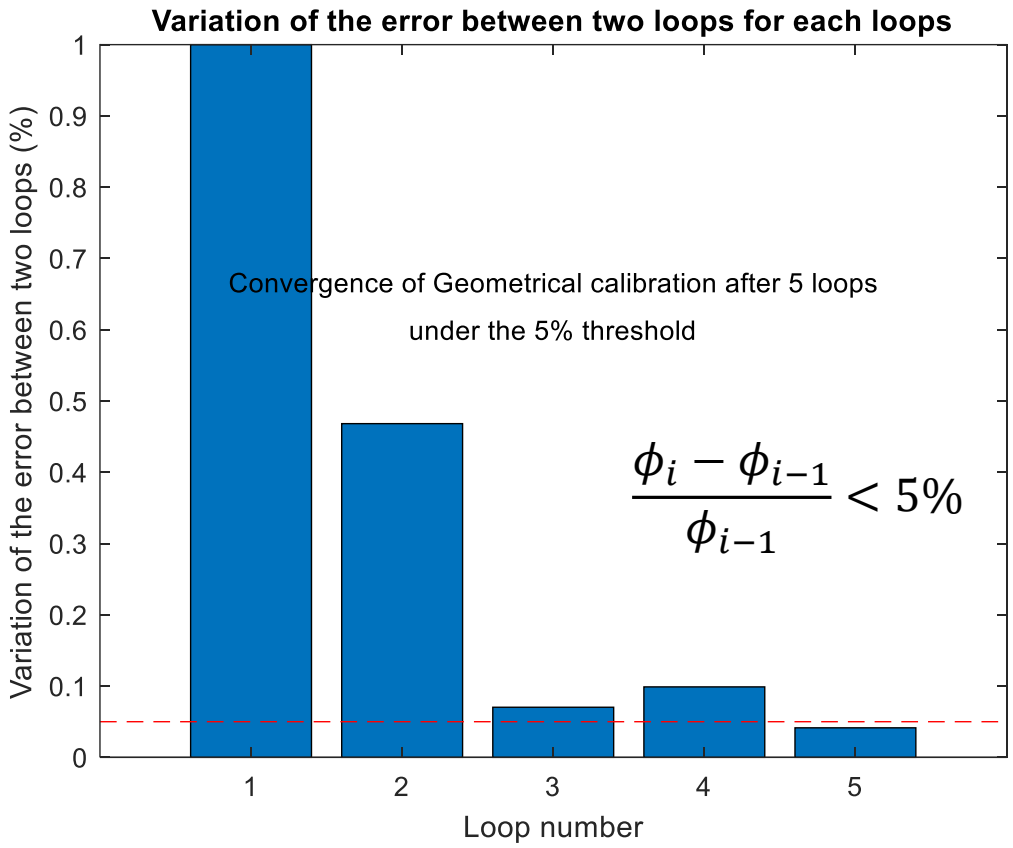
All contained in a struct :

BiomechanicalModel.GeometricalCalibration

| Field | Value |
|---|---|
| frame_calib | *1x20 double* |
| crit | [1 0.4682 0.0703 0.0989 0.0414] |
| errorm | *1x5 cell* |
| k_calib | *48x1 double* |
| p_calib | *126x1 double* |
| alpha_calib | *[ ]* |

`BiomechanicalModel.GeometricalCalibration`

`« .Crit »`



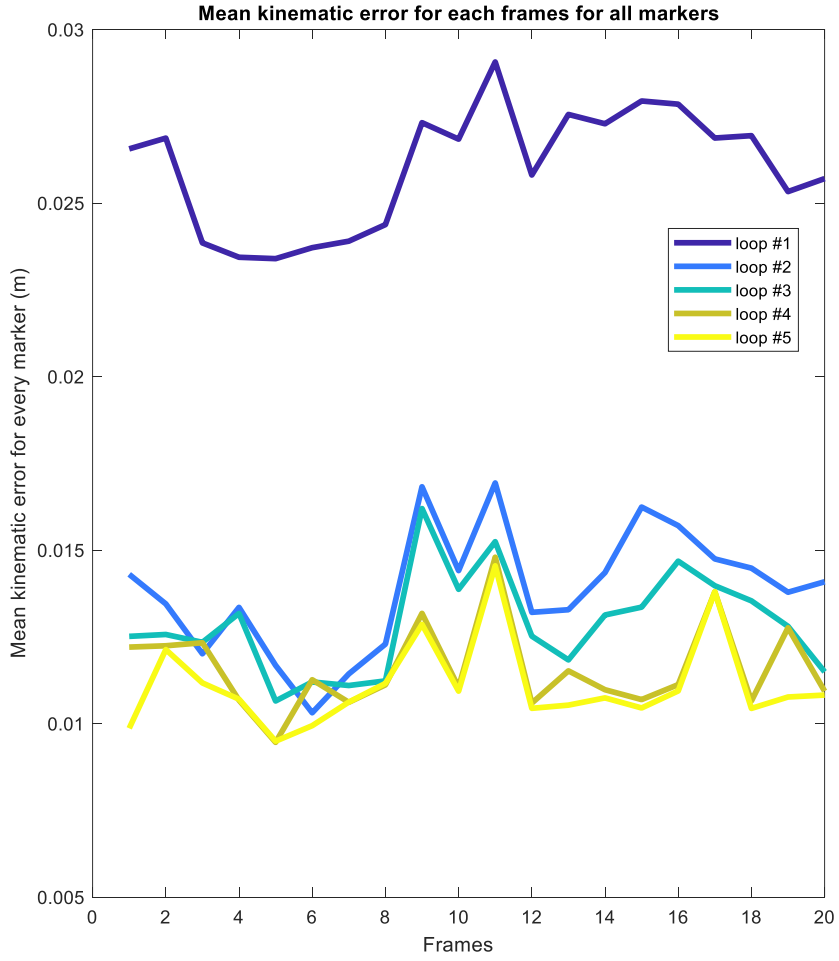
# Geometrical Calibration Results

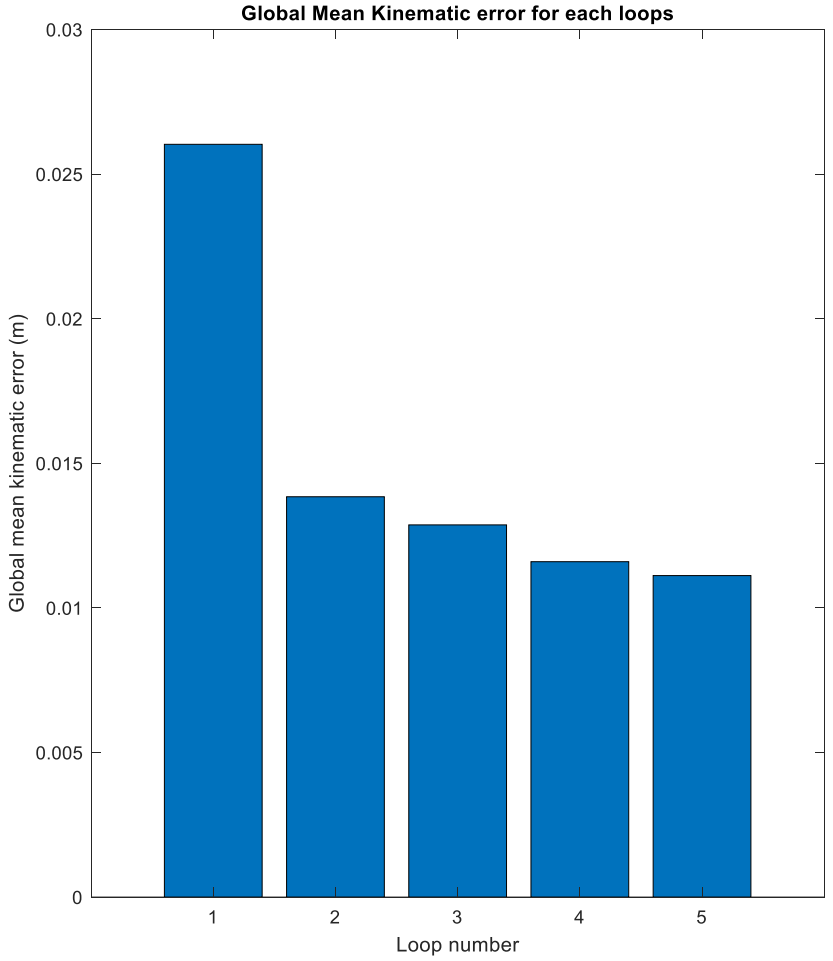
```
>> PostProcessingCalibration
```

```
BiomechanicalModel.GeometricalCalibration
```

« .errorm »

errorm 1x5 cell



# Geometrical Calibration Results

```
>> PostProcessingCalibration
```

`BiomechanicalModel.GeometricalCalibration`

`« .calib_k »`

Variation of the homothetic coefficient from the anthopometric estimation.

Reminder:

$$k_0 = \frac{size\ of\ the\ subject}{size\ of\ the\ cadaver}$$

From the initial musculoskeletal model:

$$k_{final} = k_0 * k_{calib}$$

k_calib — 48x1 double

BiomechanicalModel.GeometricalCalibration.k_calib

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1 | 0.9646 | | | |
| 2 | 1 | | | |
| 3 | 1 | | | |
| 4 | 1 | | | |
| 5 | 1 | | | |
| 6 | 1 | | | |
| 7 | 0.9487 | | | |
| 8 | 1 | | | |
| 9 | 1 | | | |
| 10 | 0.9487 | | | |
| 11 | 1 | | | |
| 12 | 1 | | | |
| 13 | 0.9487 | | | |
| 14 | 1 | | | |
| 15 | 1 | | | |
| 16 | 0.9336 | | | |

BiomechanicalModel.OsteoArticularModel

| Fields | name | sister | child |
|---|---|---|---|
| 1 | 'PelvisSacr... | 0 | 2 |
| 2 | 'LowerTrun... | 17 | 3 |
| 3 | 'LowerTrun... | 0 | 4 |
| 4 | 'LowerTrunk' | 0 | 5 |
| 5 | 'UpperTrun... | 0 | 6 |
| 6 | 'UpperTrun... | 0 | 7 |
| 7 | 'Thorax' | 0 | 8 |
| 8 | 'RClavicle_J... | 11 | 9 |
| 9 | 'RClavicle_J... | 0 | 10 |
| 10 | 'RClavicle' | 0 | 29 |
| 11 | 'LClavicle_J1' | 14 | 12 |
| 12 | 'LClavicle_J2' | 0 | 13 |
| 13 | 'LClavicle' | 0 | 36 |
| 14 | 'ThoraxSkul... | 0 | 15 |
| 15 | 'ThoraxSkul... | 0 | 16 |

# Geometrical Calibration Results

```
>> PostProcessingCalibration
```

`BiomechanicalModel.GeometricalCalibration`

`« .calib_p »`

Displacement of the marker in local frames.

p_calib 126x1 double

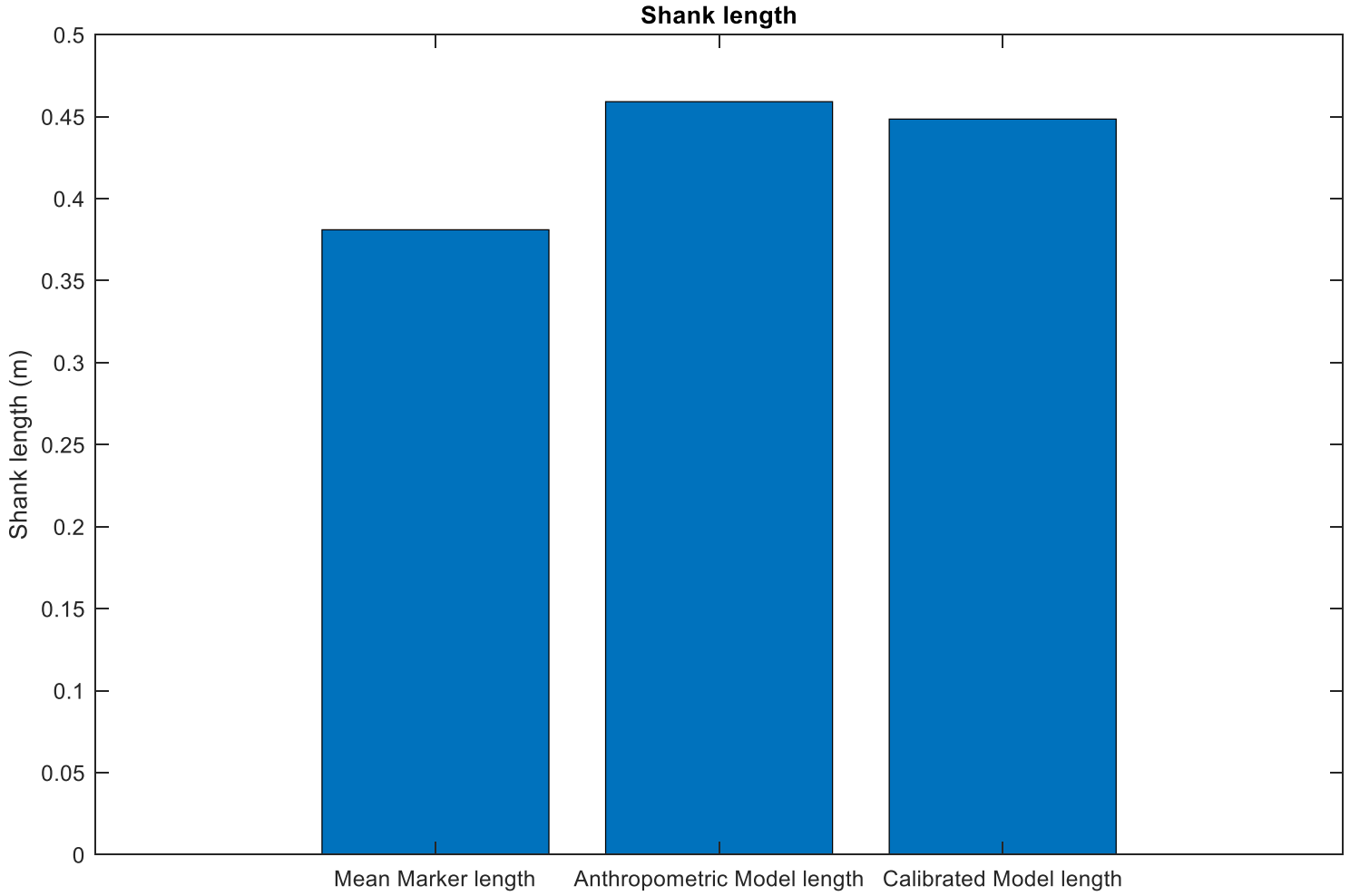
BiomechanicalModel.GeometricalCalibration.p_calib

| | 1 | 2 | 3 |
|---|---|---|---|
| 1 | 0 | $\vec{x}$ | |
| 2 | -0.0037 | $\vec{y}$ | |
| 3 | 0 | $\vec{z}$ | |
| 4 | 0.0210 | | |
| 5 | 0 | | |
| 6 | 0 | | |
| 7 | 0 | | |
| 8 | -0.0271 | | |
| 9 | 0 | | |
| 10 | -0.0181 | | |
| 11 | -0.0111 | | |
| 12 | 0 | | |
| 13 | 2.8682e-04 | | |
| 14 | 0 | | |
| 15 | 0.0218 | | |
| 16 | 0.0067 | | |

BiomechanicalModel.Markers

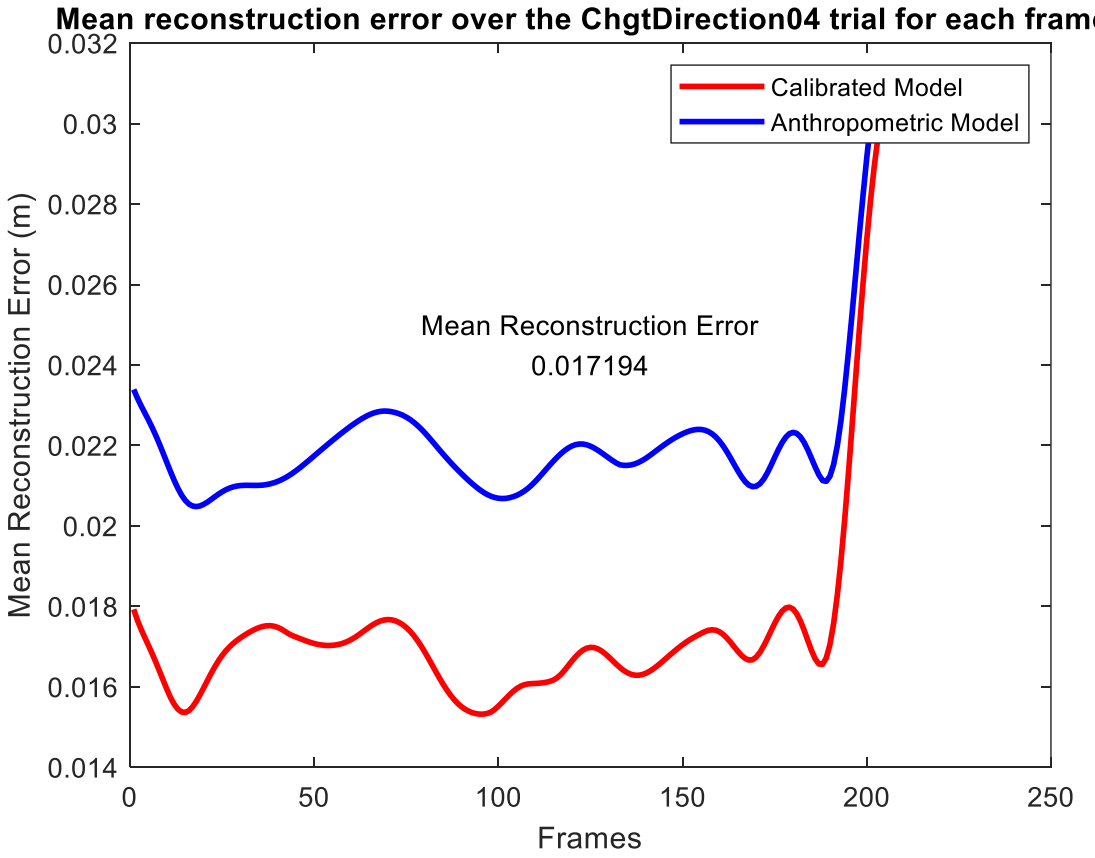
| | name | anat_position | calib_ |
|---|---|---|---|
| 1 | 'STRN' | 'STRN' | 3x1 cell |
| 2 | 'CLAV' | 'CLAV' | 3x1 cell |
| 3 | 'T10' | 'T10' | 3x1 cell |
| 4 | 'C7' | 'C7' | 3x1 cell |
| 5 | 'RSHO' | 'RSHO' | 3x1 cell |
| 6 | 'LSHO' | 'LSHO' | 3x1 cell |
| 7 | 'RFWT' | 'RFWT' | 3x1 cell |
| 8 | 'LFWT' | 'LFWT' | 3x1 cell |
| 9 | 'RBWT' | 'RBWT' | 3x1 cell |
| 10 | 'LBWT' | 'LBWT' | 3x1 cell |
| 11 | 'RFHD' | 'RFHD' | 3x1 cell |
| 12 | 'LFHD' | 'LFHD' | 3x1 cell |
| 13 | 'RBHD' | 'RBHD' | 3x1 cell |
| 14 | 'LBHD' | 'LBHD' | 3x1 cell |
| 15 | 'RKNE' | 'RKNE' | 3x1 cell |
| 16 | 'RANE' | 'RANE' | 3x1 cell |

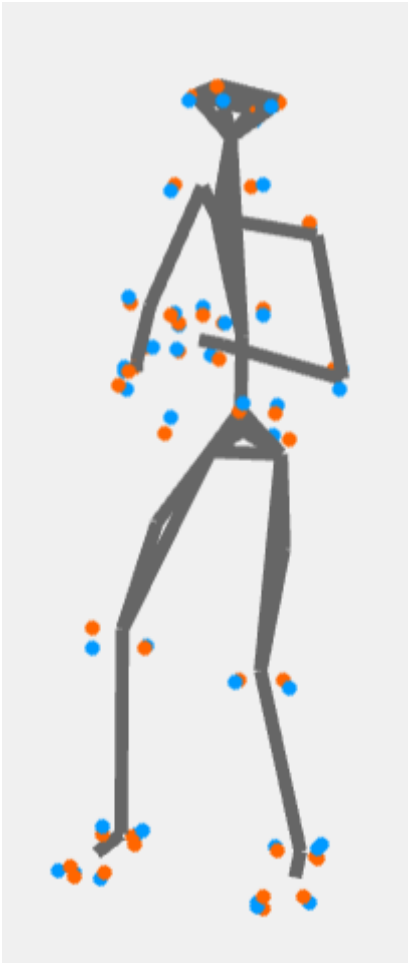
# What about the quality of the model ?
# Geometrical Calibration Results - Right Shank length



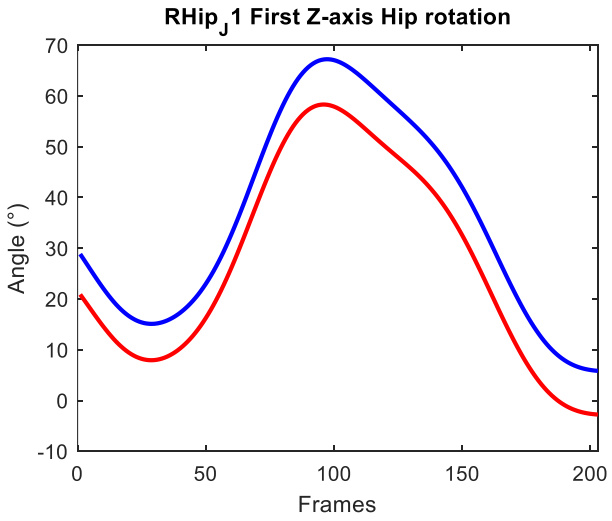
# Kinematical Results

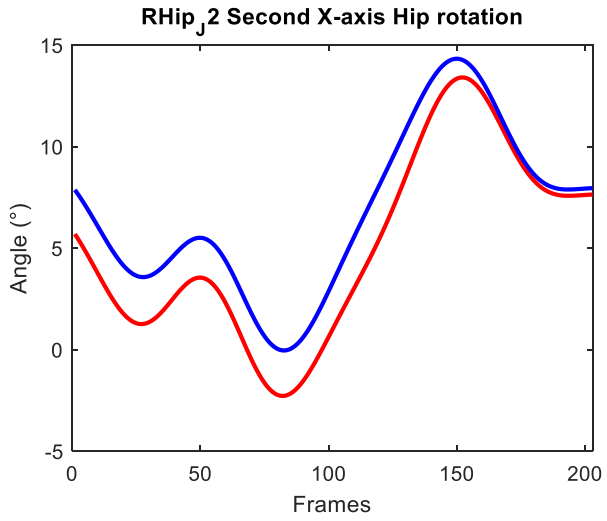
Decreasing of the mean reconstruction error over the side step trial.

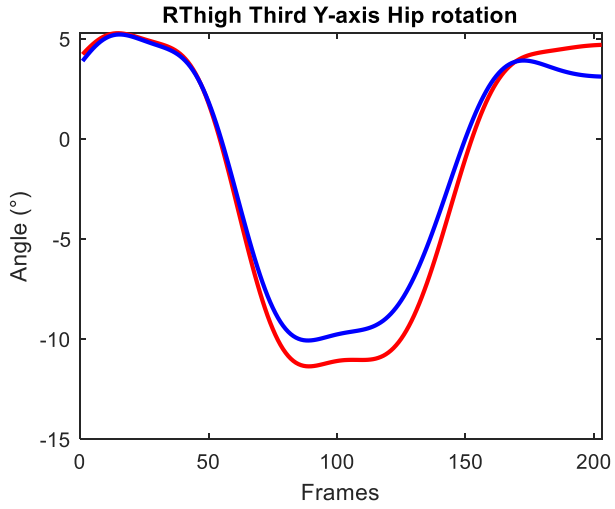


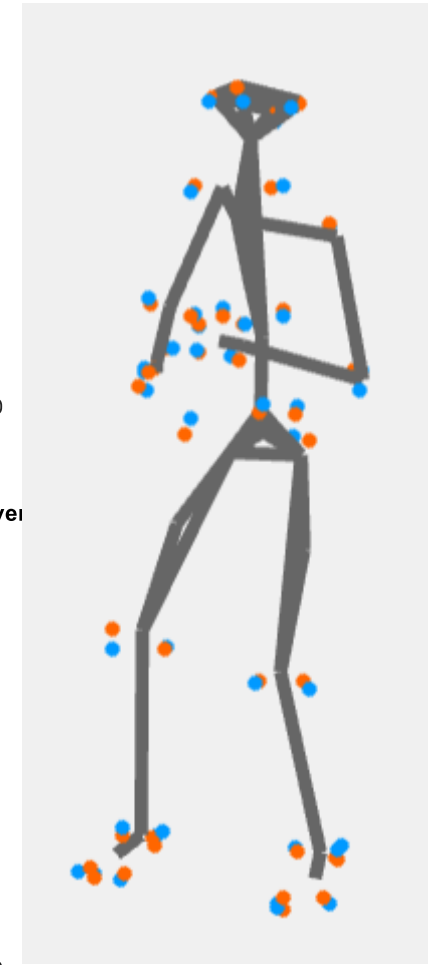



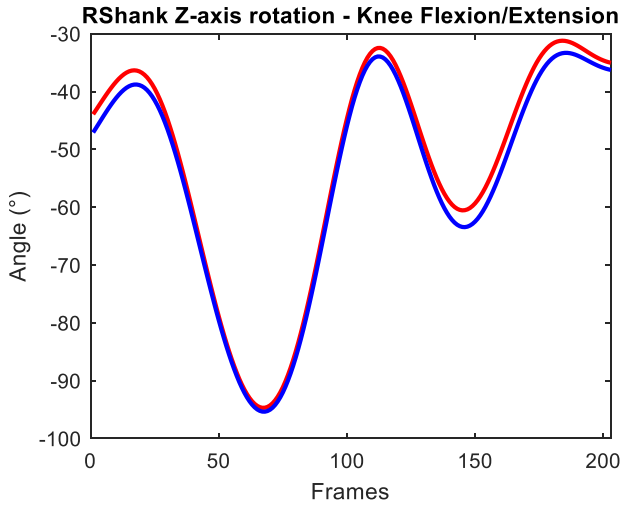
# Kinematical Results

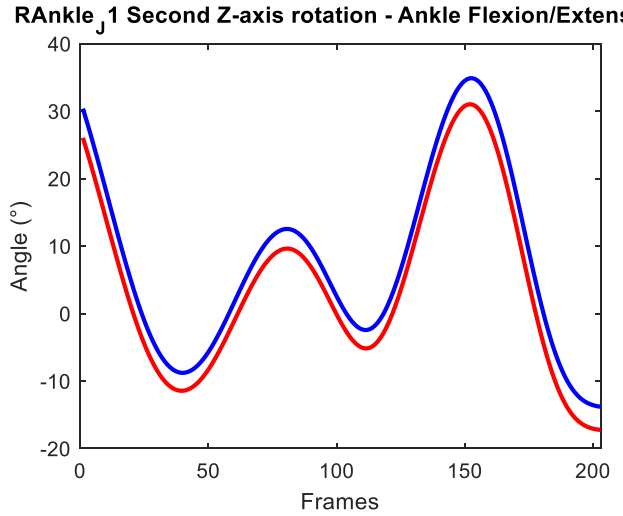


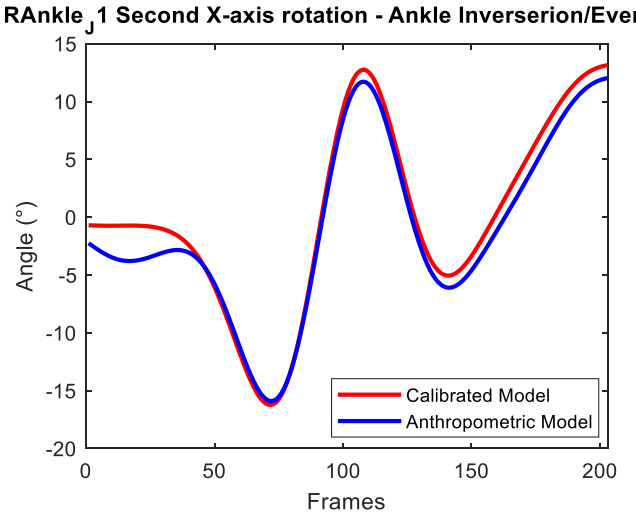



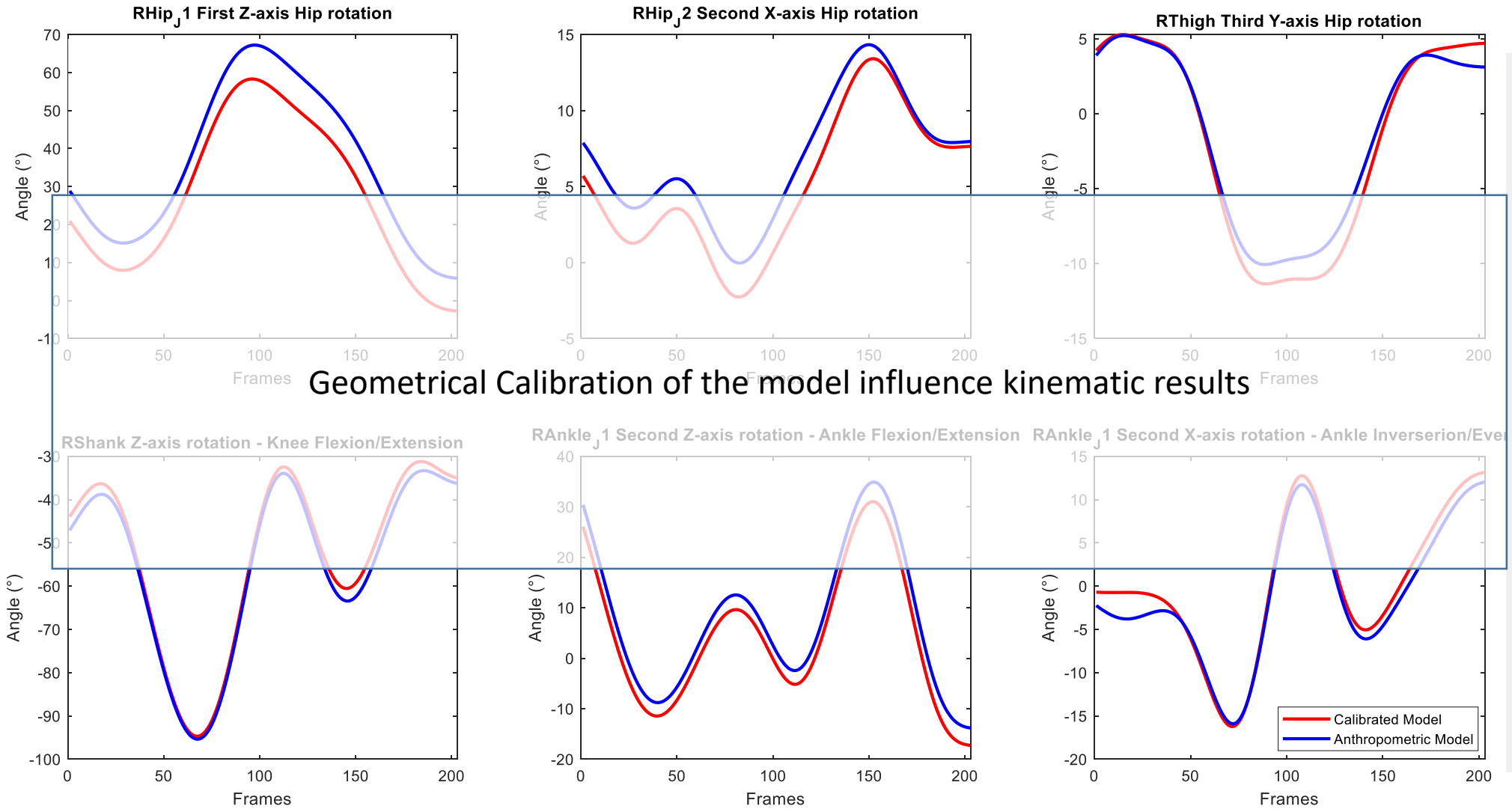





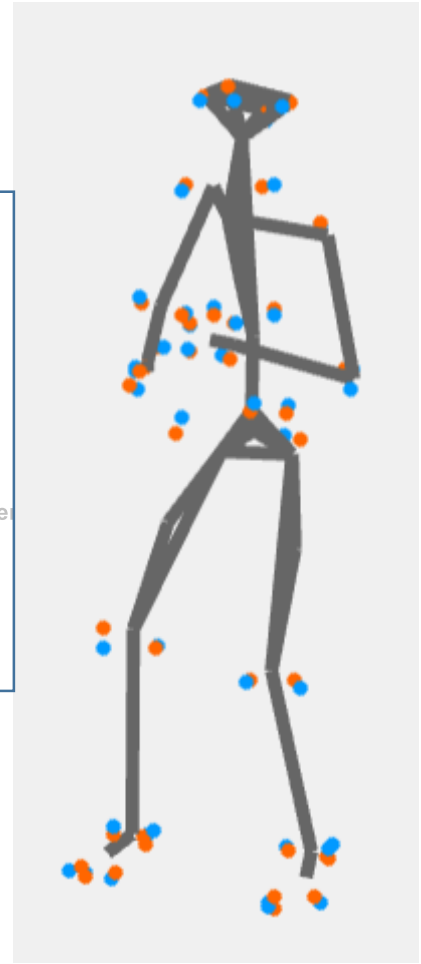



# Kinematical Results




Geometrical Calibration of the model influence kinematic results



# Take home message

To ensure the quality of the model and kinematic results

- Check your reconstruction errors
  - on your calibration trial
  - on your inverse kinematic trials
  - 4 to 40 mm reconstruction error mean have been reported. [Begon et al. 2017]

*Begon, M., Andersen, M.S., Dumas, R., 2017. Multibody kinematic optimization for the estimation of upper and lower limb human joint kinematics: a systematic review. J. Biomech. Eng. 140, 1–11.*

- Be sure you chose the right constraints to ensure the geometrical calibration
  - Enough frames (20-100)
  - Homothetic constraints (equality)
  - Displacement of markers
  - Rotation of joint axis