



# PLUG-IN GAIT REFERENCE GUIDE



## WHAT'S INSIDE?

About this guide	3
Regulatory information	4
Plug-in Gait models and templates	5
Lower body modeling with Plug-in Gait	6
Upper body modeling with Plug-in Gait	21
Full body modeling with Plug-in Gait	30
Plug-in Gait labeling skeleton templates (VSTs) in Vicon Nexus	36
Plug-in Gait bones	38
Complete list of Plug-in Gait bones	39
Plug-in Gait virtual markers	42
Plug-in Gait joint centers	43
Plug-in Gait lower body forces and moments	44
Plug-in Gait kinematic and kinetic calculations	46
About Plug-in Gait processes	47

© Copyright 2016—2023 Vicon Motion Systems Limited. All rights reserved.

Revision 2. For use with Nexus 2.15

Vicon Motion Systems Limited reserves the right to make changes to information or specifications in this document without notice. Companies, names, and data used in examples are fictitious unless otherwise noted. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic or mechanical, by photocopying or recording, or otherwise without the prior written permission of Vicon Motion Systems Ltd.

Vicon® is a registered trademark of Oxford Metrics plc. Vicon Lock Lab™, Vicon Lock Studio™, Vicon Nexus™, Vicon Shōgun™, Vicon Tracker™, T-Series™, Vicon Valkyrie™, Vicon Vantage™, Vicon Vero™, and Vicon Vue™ are trademarks of Oxford Metrics plc.

VESA® is a registered trademark owned by VESA ([www.vesa.org/about-vesa/](http://www.vesa.org/about-vesa/)). Other product and company names herein may be the trademarks of their respective owners. For full and up-to-date copyright and trademark acknowledgements, visit <https://www.vicon.com/vicon/copyright-information>.

Vicon Motion Systems is an Oxford Metrics plc company.

Email: [support@vicon.com](mailto:support@vicon.com) Web: <http://www.vicon.com>





Segment meshes 48

Plug-in Gait internal models 49

Overview of the Plug-in Gait modeling process 50

Static vs. dynamic models 51

The chord function 52

Lower body kinematics 53

Upper body kinematics 69

Angle outputs 75

Kinetic modeling 76

**Plug-in Gait output angles 82**

Angle definitions 83

Plug-in Gait kinematic variables 86

Upper body angles as output from Plug-in Gait 95

Lower body angles as output from Plug-in Gait 98

**Plug-in Gait output specification 101**

Global (laboratory) co-ordinate system 102

Pelvis 103

Femur 104

Tibia 105

Foot 106

Joint kinematic definitions 107

Joint kinetics 109

## About this guide

# About this guide

This guide provides in-depth descriptions of Plug-in Gait models and templates, and details of the calculations performed by Plug-in Gait. For information on how to use Plug-in Gait with Vicon Nexus, see *Modeling with Plug-in Gait* in the *Vicon Nexus User Guide*.

It is assumed that you are familiar with standard motion capture, data processing, and data management in Nexus; and with data visualization, analysis and reporting in Vicon Polygon. For more information on these processes, see the documentation for Nexus and Polygon.

## About this guide

## Regulatory information

For Vicon Nexus regulatory details, see *Vicon Nexus regulatory information* in the Nexus documentation area of the [Vicon website](https://help.vicon.com)<sup>1</sup>.

---

<sup>1</sup> <https://help.vicon.com>

## Plug-in Gait models and templates

# Plug-in Gait models and templates

The following topics contain information on the differences between the Plug-in Gait models, including details of the relevant outputs and marker sets. A description of the labeling skeleton templates that you can use with Plug-in Gait is also available:

- [Lower body modeling with Plug-in Gait, page 6](#)
- [Upper body modeling with Plug-in Gait, page 21](#)
- [Full body modeling with Plug-in Gait, page 30](#)
- [Plug-in Gait labeling skeleton templates \(VSTs\) in Vicon Nexus, page 36](#)

If you are using Plug-in Gait for gait analysis, the precision of the marker placement is critical for obtaining accurate clinical results. Use the information and illustrations in the above topics to place markers on the patient.

## Plug-in Gait models and templates

### Lower body modeling with Plug-in Gait

This section describes lower body modeling with Plug-in Gait. It covers the following information:

- [Outputs from Plug-in Gait lower body model, page 6](#)
- [Marker sets for Plug-in Gait lower body model, page 7](#)
- [Marker placement for Plug-in Gait lower body model, page 9](#)
- [KAD marker sets for Plug-in Gait lower body model, page 16](#)
- [KAD marker placement for Plug-in Gait lower body model, page 17](#)

For details about the labeling skeleton templates to be used with Plug-in Gait lower body models, see [Plug-in Gait labeling skeleton templates \(VSTs\) in Vicon Nexus, page 36](#).

### Outputs from Plug-in Gait lower body model

Use a Plug-in Gait lower body model if you require the kinematic and kinetic calculation outputs listed in the following table. The output variables are prefixed by the appropriate context (L for left or R for right).

Joint angles, force, and moments are expressed in the three anatomical planes: sagittal, frontal, and coronal. Even if the joint powers are scalar, they can also be expressed in the anatomical planes in Vicon Polygon. Forces, moments and powers are normalized to the subject's height and body mass.

Output	Description
<b>Kinematics: Angles</b>	
AbsAnkleAngle	The angle between the AJC to KJC vector and the AJC to TOE vector.
AnkleAngles	Relative. The angles between shank and foot.
FootProgressAngles	Absolute. The angles between the foot and the global coordinate system.
HipAngles	Relative. The angles between pelvis and thigh.
KneeAngles	Relative. The angles between thigh and shank.
PelvisAngles	Absolute. The angles between the pelvis and the laboratory coordinate system.

## Plug-in Gait models and templates

Output	Description
<b>Kinetics: Forces</b>	
AnkleForce	The force between shank and foot.
GroundReactionForce	The force exchanged between the foot and the ground while walking.
HipForce	The force between pelvis and thigh.
KneeForce	The force between thigh and shank.
NormalizedGRF	The ground reaction force expressed as a percentage of the body weight.
WaistForce	The force between pelvis and thorax. <sup>a</sup>
<b>Kinetics: Moments</b>	
AnkleMoment	The moment between shank and foot.
HipMoment	The moment between pelvis and thigh.
KneeMoment	The moment between thigh and shank.
WaistMoment	The moment between pelvis and thorax. <sup>a</sup>
<b>Kinetics: Powers</b>	
AnklePower	The power between shank and foot.
HipPower	The power between pelvis and thigh.
KneePower	The power between thigh and shank.
WaistPower	The power between pelvis and thorax. <sup>a</sup>

<sup>a</sup> This output variable is calculated only if you use a Plug-in Gait model that contains the thorax.

### Marker sets for Plug-in Gait lower body model

All Plug-in Gait marker sets are designed for the Newington-Helen Hayes model on which Plug-in Gait is based. The marker set for Plug-in Gait lower body modeling includes markers for the pelvis and the lower limbs.


There are two variations of the standard marker set for the lower body model:

- A single sacral (SACR) marker for the pelvis
- Two posterior superior iliac spine (PSIS) markers for the pelvis

These markers provide the same function; if you use two PSIS markers, Plug-in Gait calculates the midpoint between them and uses that to perform the

## Plug-in Gait models and templates

calculations. If you use a single SACR marker, you identify that position to Plug-in Gait rather than having it calculated.

 **Note**

If you use a SACR marker, you must modify the supplied VST, which uses PSIS markers, or to obtain a ready-made SACR version of the Plug-in Gait VSTs, contact [Vicon Support](#)<sup>2</sup>.

Using the two PSIS markers has the benefit of providing redundancy, so if one of the pelvis markers is missing, it is possible to reconstruct a virtual marker based on the remaining three markers. You can do this using a Rigid Body Fill in Nexus.

---

<sup>2</sup> <mailto:support@vicon.com>



## Plug-in Gait models and templates

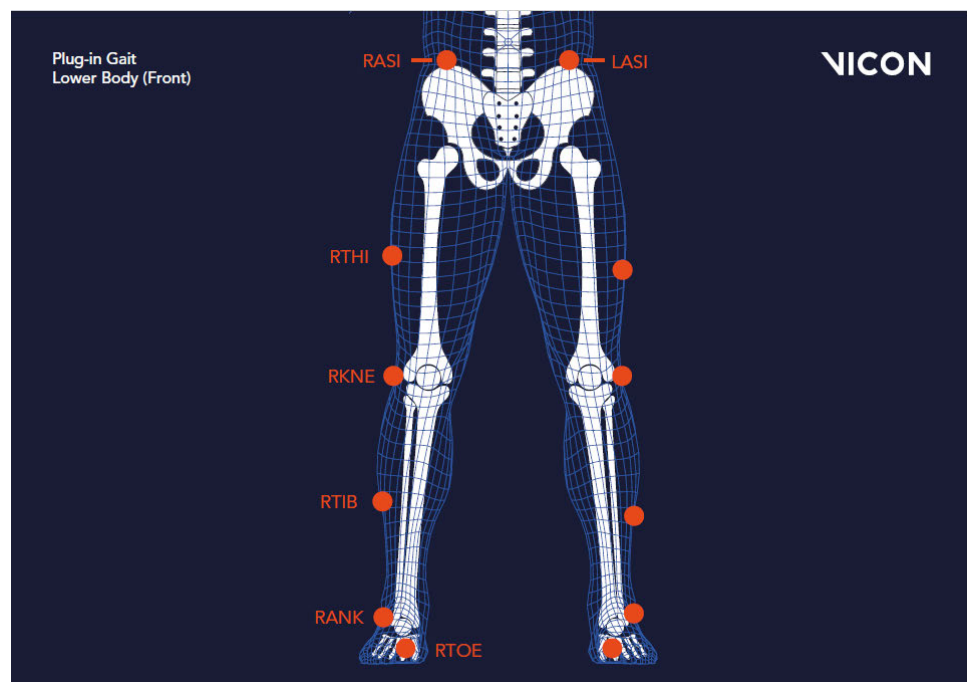
### Marker placement for Plug-in Gait lower body model

To demonstrate where to attach the standard lower body model markers to your patient, the following images show front, back, and side views. Some markers are shown from two views to help you better determine their position on your patient.

#### Important

As shown in the following images, some asymmetry is desirable as it helps the auto labeling routine distinguish right from left. In a lower body marker set, you can place the THI and/or TIB markers asymmetrically. Similarly, avoid symmetrical placement of marker clusters or groups of markers and also ensure markers are asymmetrical within each cluster/group.

The following image shows the front view. The left lower body markers are not labeled; place markers on the left side in a similar way to those on the right.



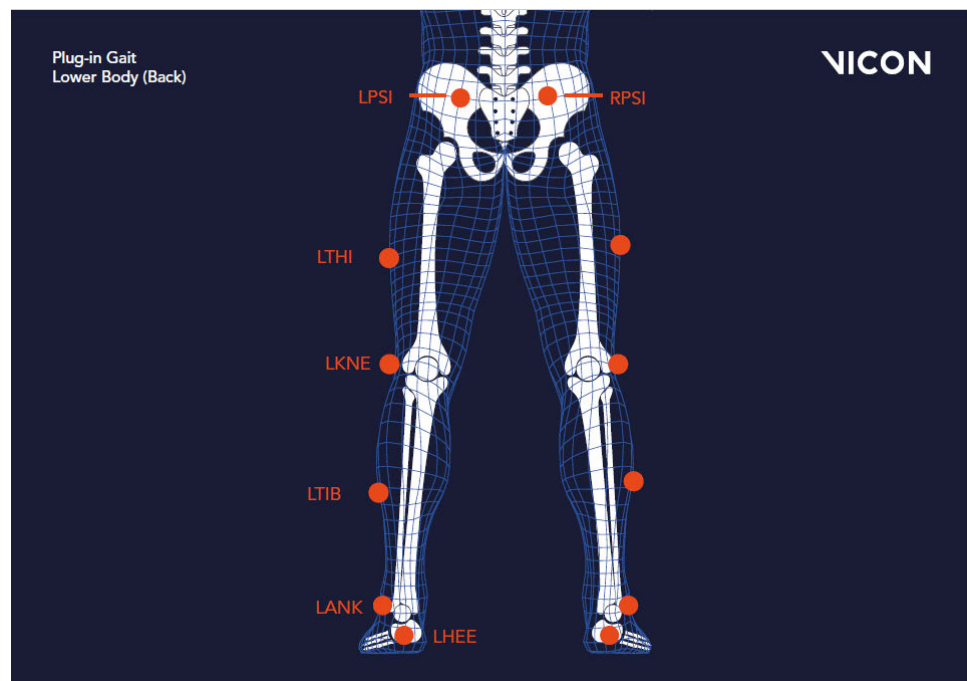
## Plug-in Gait models and templates



### Important

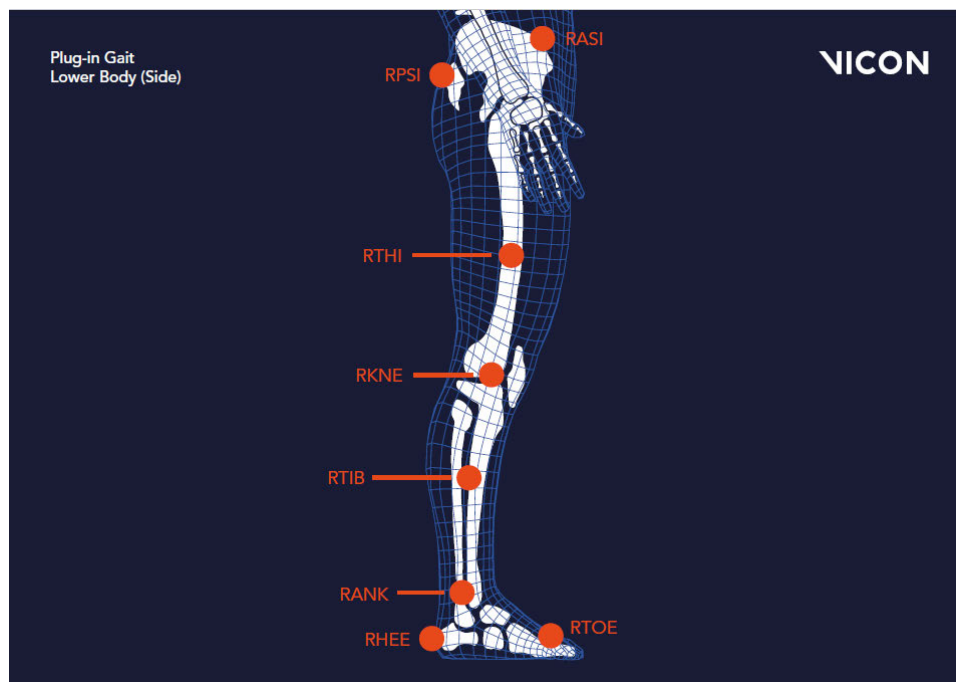
The THI and TIB markers anterior-posterior position is critical for identifying the orientation of the knee and ankle flexion axis.

The following image shows the back view. The right lower body markers are not labeled; attach markers on that side in a similar way to those on the left (with some asymmetry, as described above).



## Plug-in Gait models and templates

The following image shows the right side view. The left side view is not shown; attach markers on that side in a similar way to the right markers (with some asymmetry, as described above).



The following tables list the markers defined in Plug-in Gait templates for lower body modeling and describe where to place them on the patient:

- [Pelvis marker placement, page 12](#)
- [Lower limb marker placement, page 13](#)

## Plug-in Gait models and templates

### Pelvis marker placement

The following markers are positioned on the patient's pelvis:

Marker label	Definition	Position on patient
SACR	Sacral	On the skin mid-way between the posterior superior iliac spines (PSIS) and positioned to lie in the plane formed by the ASIS and PSIS points.
LASI	Left ASIS	Left anterior superior iliac spine
RASI	Right ASIS	Right anterior superior iliac spine
LPSI	Left PSIS	Left posterior superior iliac spine (immediately below the sacro-iliac joints, where the spine joins the pelvis) This marker is used with the RPSI marker as an alternative to the single SACR marker.
RPSI	Right PSIS	Right posterior superior iliac spine (immediately below the sacro-iliac joints, where the spine joins the pelvis) This marker is used with the LPSI marker as an alternative to the single SACR marker.

In some patients, especially obese individuals, the markers either can't be placed exactly on the ASIS, or are invisible in this position to cameras. In these cases, move each marker laterally by an equal amount along the ASIS-ASIS axis. The true inter-ASIS distance must then be manually measured and entered in the **Properties** pane at the bottom of the **Subjects** tab on the **Resources** pane. These markers, together with either the SACR marker or the LPSI and RPSI markers, define the pelvic coronal plane.

**⚠ Note**

If you use a SACR marker, you must modify the supplied VST, which uses PSIS markers, or to obtain a ready-made SACR version of the Plug-in Gait VSTs, contact [Vicon Support](#)<sup>3</sup>.

<sup>3</sup> <mailto:support@vicon.com>

## Plug-in Gait models and templates

### Lower limb marker placement

The following markers are positioned on each of the patient's lower limbs. For additional guidance, see the notes at the bottom of the table.

Marker label	Definition	Position on patient
<b>Left lower limb markers</b>		
LTHI	Left thigh	Over the lower lateral 1/3 surface of the left thigh
LKNE	Left knee	On the flexion-extension axis of the left knee
LTIB	Left tibia	Over the lower 1/3 surface of the left shank
LANK	Left ankle	On the lateral malleolus along an imaginary line that passes through the transmalleolar axis
LHEE	Left heel	On the calcaneus at the same height above the plantar surface of the foot as the toe marker
LTOE	Left toe	Over the second metatarsal head, on the mid-foot side of the equinus break between fore-foot and mid-foot
<b>Right lower limb markers</b>		
RTHI	Right thigh	Over the upper lateral 1/3 surface of the right thigh
RKNE	Right knee	On the flexion-extension axis of the right knee.
RTIB	Right tibia	Over the upper 1/3 surface of the right shank
RANK	Right ankle	On the lateral malleolus along an imaginary line that passes through the transmalleolar axis
RHEE	Right heel	On the calcaneus at the same height above the plantar surface of the foot as the toe marker
RTOE	Right toe	Over the second metatarsal head, on the mid-foot side of the equinus break between fore-foot and mid-foot

## Plug-in Gait models and templates

### Notes

**Knee markers** To locate the precise point for placing the knee markers (LKNE, RKNE), passively flex and extend the knee a little while watching the skin surface on the lateral aspect of the knee joint. Identify where knee joint axis passes through the lateral side of the knee by finding the lateral skin surface that comes closest to remaining fixed in the thigh. This landmark should also be the point about which the lower leg appears to rotate. Mark this point with a pen. With an adult patient standing, this pen mark should be about 1.5 cm above the joint line, mid-way between the front and back of the joint. Attach the marker at this point.

If you are using a knee alignment device (KAD), see also [KAD marker placement for Plug-in Gait lower body model, page 17](#).

**Thigh markers** The thigh markers (LTHI, RTHI) are used to calculate the knee flexion axis orientation. Place the LTHI marker over the lower lateral 1/3 surface and the RTHI marker over the upper lateral 1/3 surface of the thigh, just below the swing of the hand, although the height is not critical. The anterior-posterior placement of the marker is critical for correct alignment of the knee flexion axis. Try to keep the thigh marker off the belly of the muscle, but place the thigh marker at least two marker diameters proximal of the knee marker. Adjust the position of the marker so that it lies in the plane that contains the hip and knee joint centers and the knee flexion/extension axis.

If you are using a KAD, the precise placement of the thigh markers is not crucial.

**Tibia markers** The tibia markers (LTIB, RTIB) are used to determine the alignment of the ankle flexion axis. Similarly to the thigh markers, place the LTIB marker over the lower 1/3 surface of the shank and the RTIB marker over the upper 1/3 surface of the shank. The tibial marker should lie in the plane that contains the knee and ankle joint centers and the ankle flexion/extension axis. In a normal patient, the ankle joint axis between the medial and lateral malleoli is externally rotated by around 20 degrees with respect to the knee flexion axis. The placements of the shank markers should reflect this.

## Plug-in Gait models and templates

If you are using a KAD, the ankle dorsi-plantar flexion axis is assumed to be parallel to the knee flexion axis unless:

- The tibial torsion is manually measured and entered in the **Properties** pane at the bottom of the **Subjects Resources** pane.

or

- One marker on each medial malleolus is attached (RMED, LMED). During the static trial, Plug-in Gait automatically calculates the tibial torsion as the angle between the knee flexion and the ankle dorsi-plantar flexion axes.

**Toe and heel markers** If the toe markers (LTOE, RTOE) cannot be placed level with the heel markers (LHEE, RHEE), you must configure Plug-in Gait to compensate for this. For details of the relevant settings, see *Plug-in Gait Static pipeline* in the *Vicon Nexus User Guide*.

## Plug-in Gait models and templates

### KAD marker sets for Plug-in Gait lower body model

In addition to the standard lower body marker sets, an alternative marker set enables you to use a knee alignment device (KAD).

The KAD is a light-weight, spring-loaded G-clamp, whose adjustable jaws bridge the knee and whose stem is aligned with the knee flexion axis.

One standard-sized marker is fixed to the tip of the stem and two markers are mounted on the ends of two additional rods fixed to the device. The three markers are equidistant from the point where the stem meets the jaws of the clamp, enabling the 3D position of this point, known as the 'virtual knee marker', to be calculated.

Instead of the THI and TIB markers in the standard model, the KAD markers (left and right KAX, KD1, and KD2) are used to calculate the orientation of the medio-lateral axes of knee and ankle respectively.

The KAD is applied to the patient during a static trial to enable Plug-in Gait to calculate:

- The offset angle between the knee flexion axis orientation as calculated by using the KAD markers and knee flexion axis orientation as calculated by using the THI markers (Thigh Rotation Offset). When a KAD is present, the ankle dorsi-plantar flexion axis is assumed to be aligned with the knee flexion axis unless the tibial torsion measurement is entered.
- The angle between the ankle dorsi-plantar flexion axis orientation as calculated by using the KAD and the tibial torsion measurement and the ankle dorsi-plantar flexion axis orientation as calculated using the TIB markers (Shank Rotation Offset).

These calculations eliminate the reliance on the anterior posterior position of the THI and TIB markers.

A variation of the KAD marker set defines the additional LMED and RMED markers for the medial malleoli.

When you use a KAD, the tibial torsion measurement is critical for Plug-in Gait to identify the correct orientation of the ankle dorsi-plantar flexion axis. In fact, if the tibial torsion is left at 0 (zero), the ankle flex axis is assumed to be aligned with the knee flex axis. To enable Plug-in Gait to automatically calculate the tibial torsion measurement, attach the LMED and RMED markers on the medial malleoli of your patient.



## Plug-in Gait models and templates

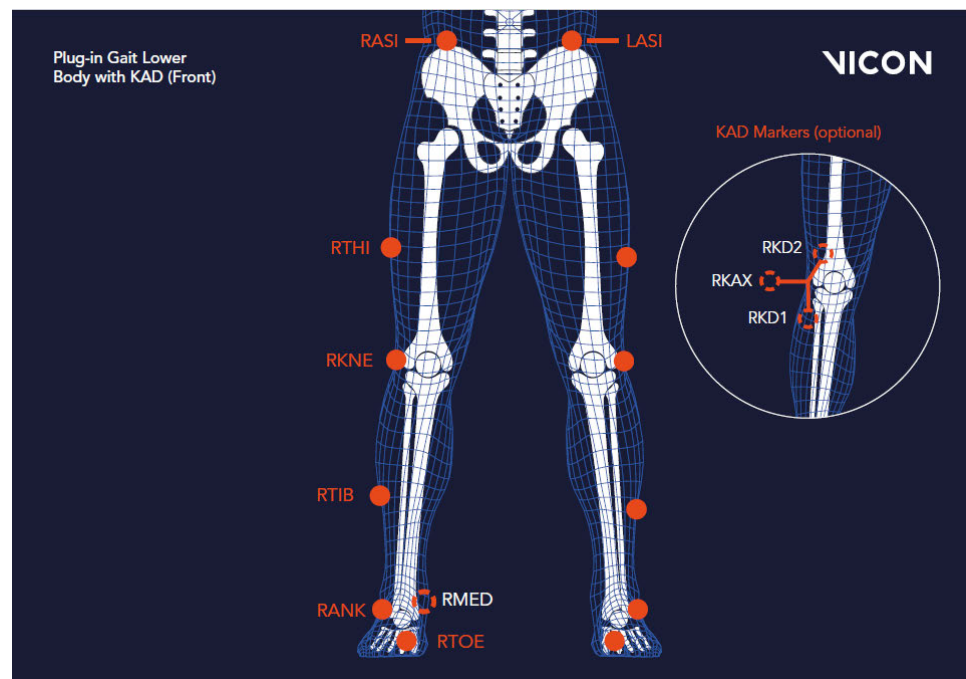
When the static trial has been processed, you can remove the KAD and the MED markers, and for dynamic trials, place the KNE marker exactly where the KAD pad used to be on the femoral epicondyle.

### KAD marker placement for Plug-in Gait lower body model

The following images show front, back, and side views to demonstrate where to attach the lower body model markers to your patient. You do this before capturing a static trial as described in the *Vicon Nexus User Guide*. Some markers are shown from two views to help you better determine their position on your patient.

The following image shows the front view. It includes the knee alignment device (KAD) marker variations, which are inset and shown with dashed lines to indicate they are optional.

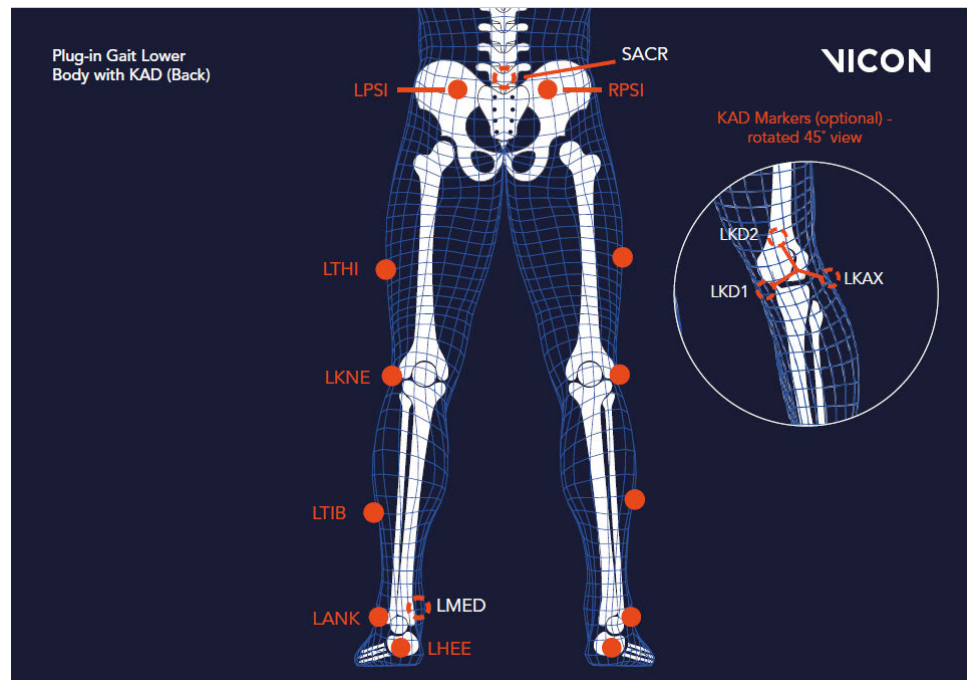
The left lower body markers are not labeled; attach markers on that side in a similar way to those on the right (with some asymmetry as described in [Marker placement for Plug-in Gait lower body model, page 9](#)).



## Plug-in Gait models and templates

The following image shows the back view. It includes the knee alignment device (KAD) marker variations, which are inset and shown with dashed lines to indicate they are optional.

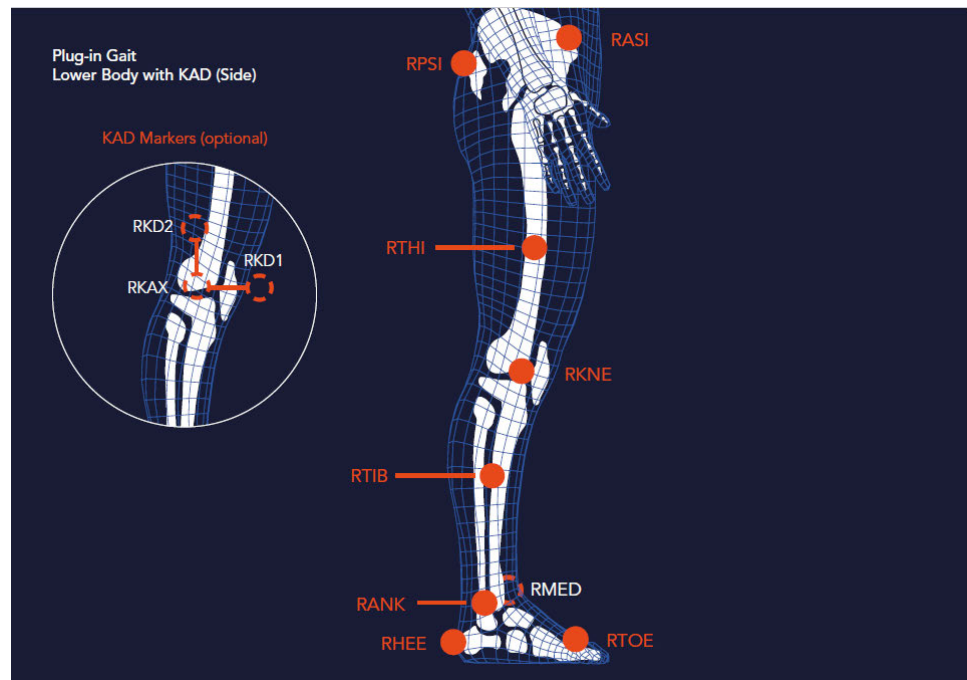
The right lower body markers are not labeled in this figure; attach markers on that side in a similar way to those on the left (with some asymmetry as described in [Marker placement for Plug-in Gait lower body model, page 9](#)).



## Plug-in Gait models and templates

The following image shows the right side view. It includes the knee alignment device (KAD) marker variations, which are inset and shown with dashed lines to indicate they are optional.

The left side view is not shown; attach markers on that side in a similar way to the right markers (with some asymmetry as described in [Marker placement for Plug-in Gait lower body model, page 9](#)).



If a knee alignment device (KAD) is used, it is attached instead of the LKNE and RKNE markers for the static trial only. Before dynamic capture and modeling, it must be removed and LKNE and RKNE markers attached instead.

The KAD markers are constructed in such a way as to enable the model to calculate a position for a virtual knee marker, which corresponds to the external pad. So, the external pad should be positioned as described for the knee marker.

## Plug-in Gait models and templates

The following table shows the KAD marker labels included for static trials.

Marker Label	Definition	Position
LKAX	Left knee	Left KAD axis For the left side, labeling goes counter clockwise from this LKAX marker
LKD1	Device 1	Left KAD marker 1
LKD2	Device 2	Left KAD marker2
RKAX	Right knee	Right KAD axis For the right side, labeling goes clockwise from the RKAX marker
RKD1	Device 1	Right KAD marker 1
RKD2	Device 2	Right KAD marker 2

For dynamic trials, the KAD must be removed, and the left or right KNE marker positioned at the same point as the external KAD pad.

## Plug-in Gait models and templates

### Upper body modeling with Plug-in Gait

This section describes Plug-in Gait upper body modeling, so you can determine if an upper body model will provide the data you require for your clinical analysis.

The following topics are covered:

- [Outputs from Plug-in Gait upper body model, page 21](#)
- [Marker sets for Plug-in Gait upper body modeling, page 23](#)
- [Marker placement for Plug-in Gait upper body model, page 23](#)

For details about the labeling skeleton templates to be used with Plug-in Gait upper body models, see [Plug-in Gait labeling skeleton templates \(VSTs\) in Vicon Nexus, page 36](#).

### Outputs from Plug-in Gait upper body model

Use a Plug-in Gait upper body model if you require the kinematic and kinetic calculation outputs listed in the following table. The output variables are prefixed by the appropriate context (L for left or R for right).

Output	Description
<b>Kinematics: Angles</b>	
ElbowAngles	Relative. The angles between the upper arm and forearm.
HeadAngles	Absolute. The angles between the head and the laboratory coordinate system.
NeckAngles	The angles between head relative to thorax.
ShoulderAngles	Relative. The angles between the upper arm and thorax.
SpineAngles	The angles between the thorax relative to the pelvis.
ThoraxAngles	Absolute. The angles between the thorax and the laboratory coordinate system.
WristAngles	Relative. The angles between the forearm and hand.

## Plug-in Gait models and templates

Output	Description
<b>Kinetics: Forces</b>	
ElbowForce	The force between the upper arm and forearm.
NeckForce	The force between the head relative to thorax.
ShoulderForce	The force between the upper arm and thorax.
WristForce	The force between the forearm and hand.
<b>Kinetics: Moments</b>	
ElbowMoment	The moment between the upper arm and forearm.
NeckMoment	The moment between the head relative to thorax.
ShoulderMoment	The moment between the upper arm and thorax.
WristMoment	The moment between the forearm and hand.
<b>Kinetics: Powers</b>	
ElbowPower	The power between the upper arm and forearm.
NeckPower	The power between the head relative to thorax.
ShoulderPower	The power between the upper arm and thorax.
WristPower	The power between the forearm and hand.

## Plug-in Gait models and templates

### Marker sets for Plug-in Gait upper body modeling

The marker set for Plug-in Gait upper body modeling includes markers for the head, torso, and upper limbs.

There are two variations of the standard marker set for the upper body model:

- Additional upper arm (UPA) and forearm (FRM) markers
- No UPA and FRM markers

The UPA and FRM markers are optional; however, using them improves marker tracking during dynamic trials.

### Marker placement for Plug-in Gait upper body model

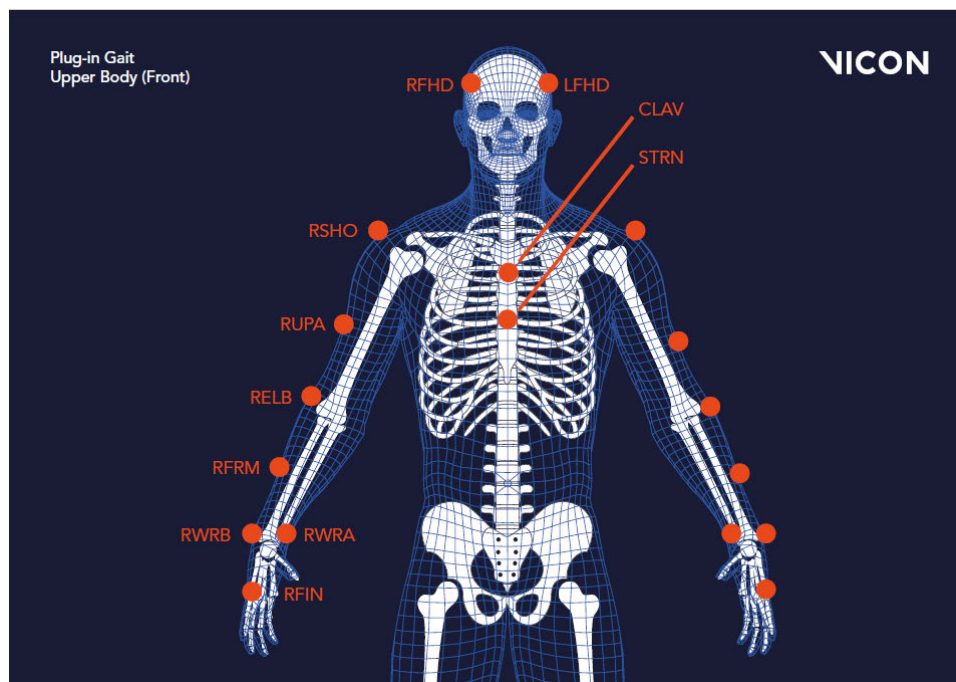
The following images show front, back, and side views to demonstrate where to attach the upper body markers to your patient. You do this before capturing a static trial as described in the *Vicon Nexus User Guide*. Some markers are shown from two views to help you better determine their position on your patient.

#### Important

As shown in the following images, some asymmetry is desirable as it helps the auto labeling routine distinguish right from left. For upper body modeling, you can place the UPA and FRM markers asymmetrically. Similarly, avoid symmetrical placement of marker clusters or groups of markers and also ensure markers are asymmetrical within each cluster/group.

## Plug-in Gait models and templates

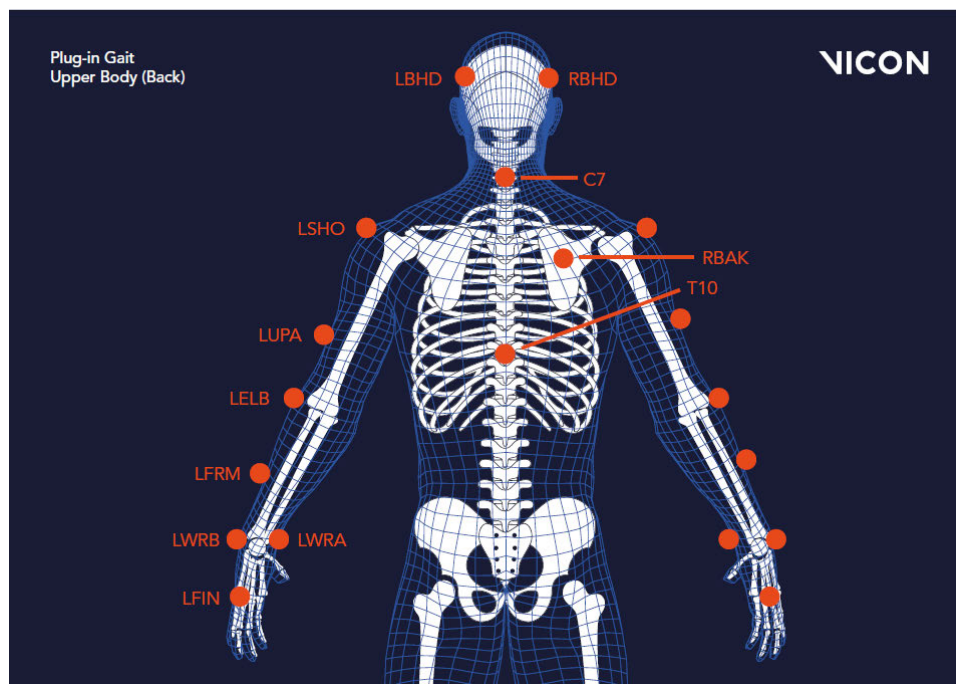
The following image shows the front view. The left upper body markers are not labeled; attach markers on that side in a similar way to those on the right (with some asymmetry as described above).





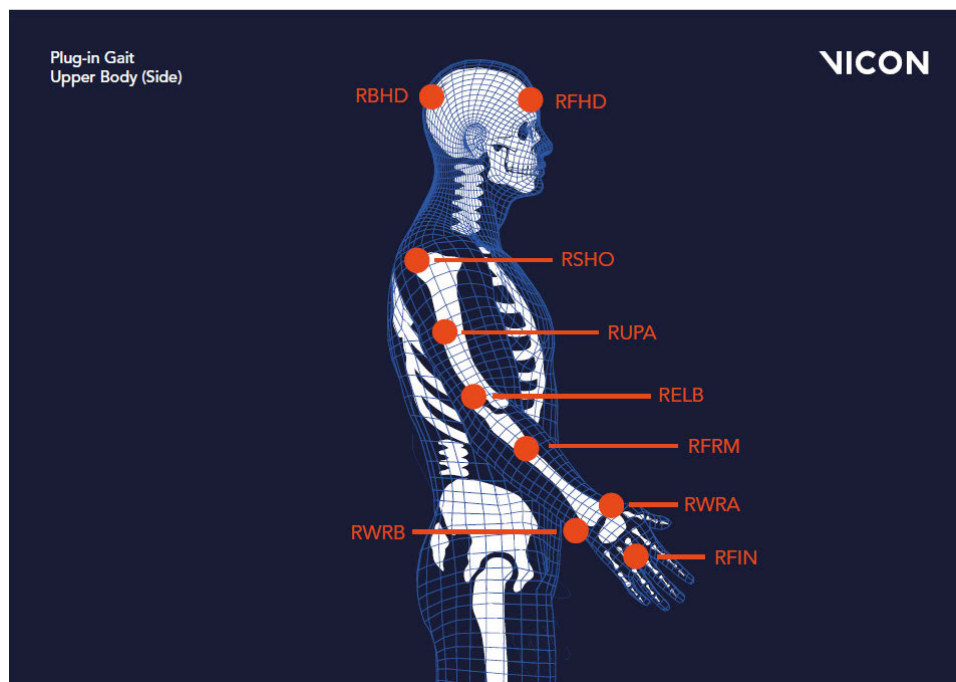
## Plug-in Gait models and templates

The following image shows the back view. The right upper body markers are not labeled; attach markers in a similar way to those on the left (with some asymmetry as described above).



## Plug-in Gait models and templates

The following image shows the right side view. The left side view is not shown; attach markers on that side in a similar way to those on the right (with some asymmetry as described above).



## Plug-in Gait models and templates

The following tables list the markers defined in Plug-in Gait templates for upper body modeling and describe where to place them on the patient.

### Head markers

The following table describes the markers positioned on the patient's head. To save time, many users buy a headband and permanently attach markers to it.

Marker label	Definition	Position on patient
LFHD	Left front head	Left temple
RFHD	Right front head	Right temple
LBHD	Left back head	Left back of head (defines the transverse plane of the head, together with the frontal markers)
RBHD	Right back head	Right back of head (defines the transverse plane of the head, together with the frontal markers)



#### Important

If the back markers cannot be placed level with the front markers, you must configure Plug-in Gait to compensate for this during the subject calibration process. To do this, in the **Properties** for the **Process Static Plugin Gait Model** pipeline operation, under **Assume Horizontal**, select **Head**.

## Plug-in Gait models and templates

### Torso markers

The following table describes the markers positioned on the patient's torso. The torso markers (C7, T10, CLAV, STRN) define the thorax sagittal plane; therefore, their lateral positioning is most important.

Marker label	Definition	Position on patient
C7	7th cervical vertebra	On the spinous process of the 7th cervical vertebra
T10	10th thoracic vertebra	On the spinous process of the 10th thoracic vertebra
CLAV	Clavicle	On the jugular notch where the clavicles meet the sternum
STRN	Sternum	On the xiphoid process of the sternum
RBAK	Right back	Anywhere over the right scapula (This marker has no equivalent marker on the left side. This asymmetry helps the autolabeling routine determine right from left on the subject. Placement is not critical as it is not included in the Plug-in Gait model calculations.)

## Plug-in Gait models and templates

### Upper limb markers

The following table describes the markers positioned on the patient's upper body.

Marker labels shown with an asterisk \* are optional; however, using them improves marker tracking during dynamic trials.

Marker label	Definition	Position on patient
<b>Left upper limb markers</b>		
LSHO	Left shoulder	On the acromio-clavicular joint
*LUPA	Left upper arm	On the upper lateral 1/3 surface of the left arm (Place asymmetrically with RUPA)
LELB	Left elbow	On the lateral epicondyle
*LFRM	Left forearm	On the lower lateral 1/3 surface of the left forearm (Place asymmetrically with RFRM)
LWRA	Left wrist marker A	At the thumb side of a bar attached to a wristband on the posterior of the left wrist, as close to the wrist joint center as possible. Loose markers can be used but for better tracking of the axial rotations, a bar is recommended.
LWRB	Left wrist marker B	At the little finger side of a bar attached to a wristband on the posterior of the left wrist, as close to the wrist joint center as possible. Loose markers can be used but for better tracking of the axial rotations, a bar is recommended.
LFIN	Left finger	Just proximal to the middle knuckle on the left hand
<b>Right upper limb markers</b>		
RSHO	Right shoulder	On the acromio-clavicular joint
*RUPA	Right upper arm	On the lower lateral 1/3 surface of the right arm (Place asymmetrically with LUPA)
RELB	Right elbow	On the lateral epicondyle approximating the elbow joint axis
*RFRM	Right forearm	On the lower lateral 1/3 surface of the right forearm (Place asymmetrically with LFRM)
RWRA	Right wrist marker A	At the thumb side of a bar attached symmetrically with a wristband on the posterior of the right wrist, as close to the wrist joint center as possible
RWRB	Right wrist marker B	At the little finger side of a bar attached symmetrically with a wristband on the posterior of the right wrist, as close to the wrist joint center as possible
RFIN	Right finger	Just below the middle knuckle on the right hand

## Plug-in Gait models and templates

# Full body modeling with Plug-in Gait

If you require Plug-in Gait full body modeling, use both a lower and an upper body model to provide the data you require for your clinical analysis.

This topic explains:

- [Outputs from Plug-in Gait full body model, page 30](#)
- [Marker sets for Plug-in Gait full body modeling, page 31](#)
- [Marker placement for Plug-in Gait full body model, page 32](#)

For a description of the labeling skeleton templates to be used with Plug-in Gait lower body, upper body, or full body models, see [Plug-in Gait labeling skeleton templates \(VSTs\) in Vicon Nexus, page 36](#).

## Outputs from Plug-in Gait full body model

Use a Plug-in Gait lower body and upper body model if you require the kinematic and kinetic calculation outputs listed in [Outputs from Plug-in Gait lower body model, page 6](#) and Outputs from Plug-in Gait upper body model. The output variables are prefixed by the appropriate context (L for left or R for right).

## Plug-in Gait models and templates

### Marker sets for Plug-in Gait full body modeling

There are two variations of the standard lower body model:

- A single sacral (SACR) marker
- Two posterior superior iliac spine (PSIS) markers for the pelvis.

These markers provide the same function; if you use two PSIS markers, Plug-in Gait calculates the midpoint between them and uses that to perform the calculations. If you use a single SACR marker, you identify that position to Plug-in Gait rather than having it calculated.

#### Note

If you use a SACR marker, you must modify the supplied VST, which uses PSIS markers, or to obtain a ready-made SACR version of the Plug-in Gait VSTs, contact [Vicon Support](#)<sup>4</sup>.

In addition to the standard lower body marker sets, an additional marker set enables you to use a knee alignment device (KAD). The KAD markers (left and right KAX, KD1, and KD2) are used instead of the THI and TIB markers in the standard model to calculate the orientation of the medio-lateral axes of knee and ankle respectively.

A variation of the KAD marker set defines the additional LMED and RMED markers for the medial malleoli. The MED markers enable Plug-in Gait to automatically calculate the tibial torsion measurement. For further information on the KAD and MED markers, see [KAD marker sets for Plug-in Gait lower body model, page 16](#).

When you use KAD+MED markers, in order to verify the ankle axis, the Plug-in Gait Static pipeline displays the torsioned tibia instead of the untorsioned tibia. If joint angles are required, you must also run the Plug-in Gait Dynamic pipeline.

<sup>4</sup> <mailto:support@vicon.com>

## Plug-in Gait models and templates

### Marker placement for Plug-in Gait full body model

The following images show front, back, and side views to demonstrate where to attach the full body model markers to your patient. You do this when you are capturing a static trial as described in the *Vicon Nexus User Guide*.

Some markers are shown from two views to help you better determine their position on your patient.

The following image shows the front view. This view includes the knee alignment device (KAD) marker variations, which are shown inset, with dashed lines to indicate that they are optional. If you have chosen to use a Plug-in Gait marker set that includes KAD markers, attach the KAD pad to the patient instead of the THI and TIB markers. For details on the KAD, see [KAD marker placement for Plug-in Gait lower body model, page 17](#).

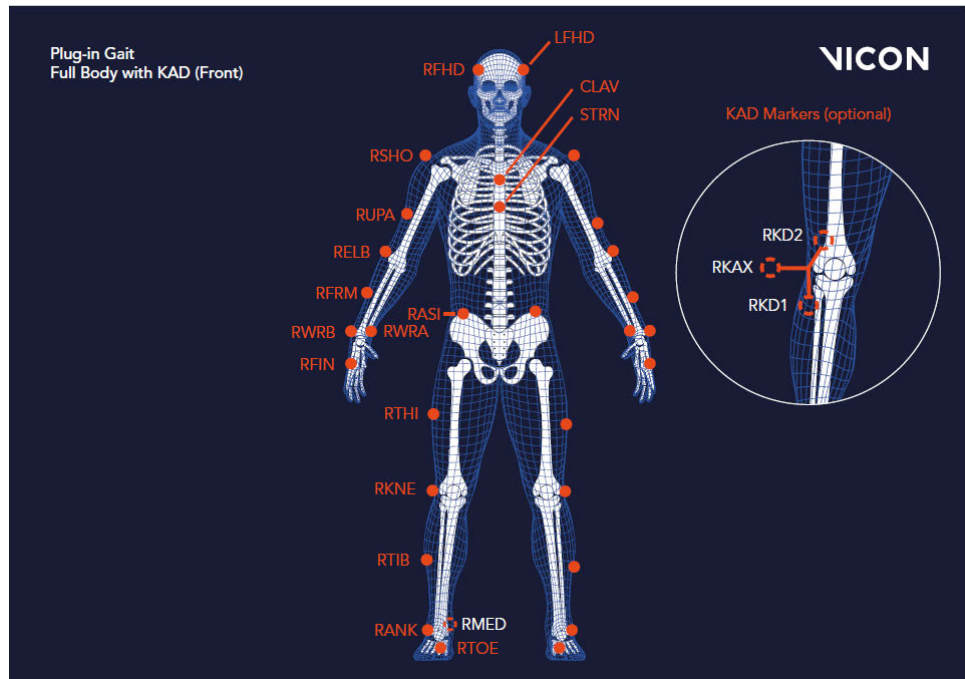
#### Important

As shown in the following images, some asymmetry is desirable as it helps the auto labeling routine distinguish right from left. For a full body set, you can place the THI, TIB, UPA and FRM markers asymmetrically. Similarly, avoid symmetrical placement of marker clusters or groups of markers and also ensure markers are asymmetrical within each cluster/group.



## Plug-in Gait models and templates

The left body markers are not labeled in this figure; attach markers on that side in a similar way (with some asymmetry) to those on the right.



 **Tip**

To assist with labeling, place the UPA, FRM, THI, and TIB markers at slightly different heights on the left and right sides:

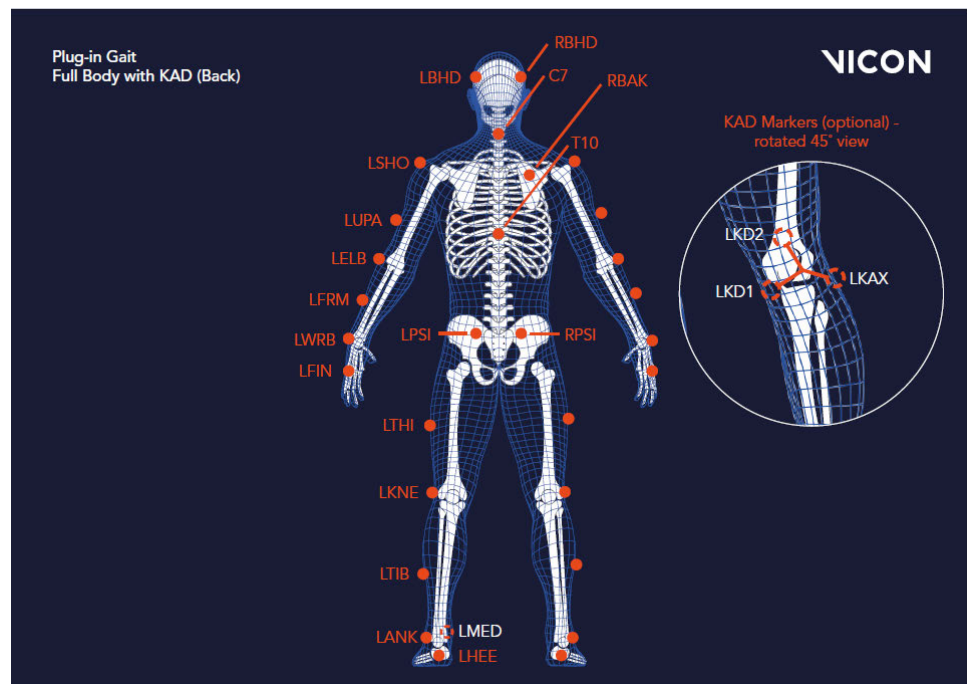
Upper 1/3: RUPA, RFRM, RTHI, RTIB

Lower 1/3: LUPA, LFRM, LTHI, LTIB

## Plug-in Gait models and templates

The following image shows the back view. This view includes the sacral (SACR) and knee alignment device (KAD) marker variations, which are shown inset, with dashed lines to indicate that they are optional. For details on the SACR marker, see [Marker sets for Plug-in Gait lower body model, page 7](#). If you have chosen to use a Plug-in Gait marker set that includes KAD markers, attach the KAD pad to the patient instead of the THI and TIB markers. For details on the KAD, see KAD marker sets for Plugin Gait lower body model.

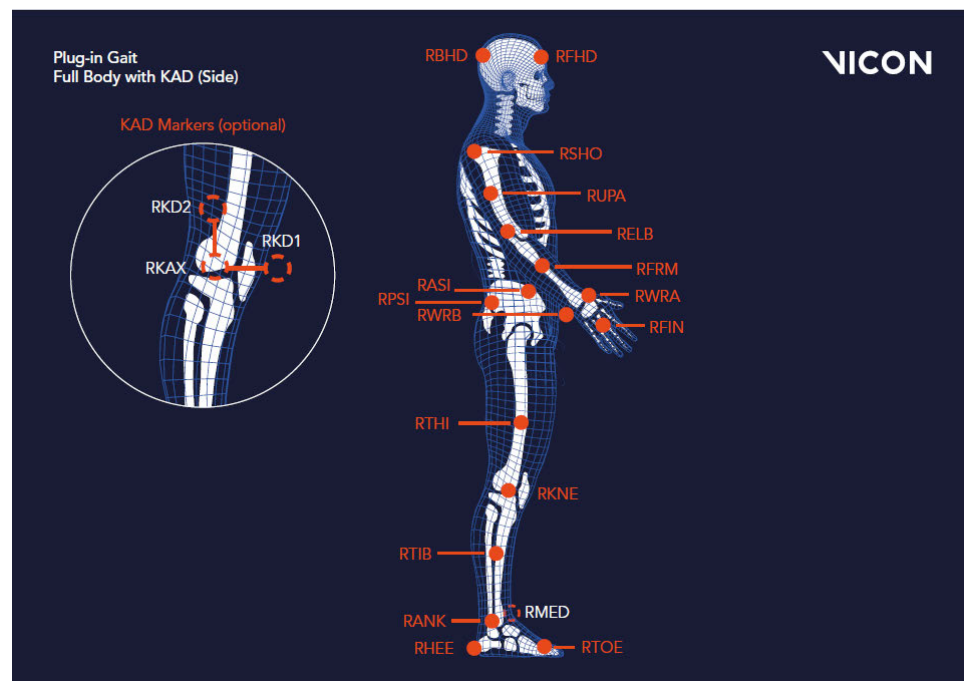
The right body markers are not labeled in this figure; attach markers on that side in a similar way to those on the left (with some asymmetry as described above). The RBAK marker has no equivalent marker on the left side; this asymmetry helps the autolabeling routine determine right from left on the subject.



## Plug-in Gait models and templates

The following image shows the right side view. This view includes the knee alignment device (KAD) marker variations, which are shown inset, with dashed lines to indicate that they are optional. If you have chosen to use a Plug-in Gait marker set that includes KAD markers, attach the KAD pad to the patient instead of the THI and TIB markers. For details on the KAD, see [KAD marker sets for Plug-in Gait lower body model, page 16](#).

The left side view is not shown; attach markers on that side in a similar way to the right markers (with some asymmetry as described above).



For detailed guidance on placing markers on a patient for full body modeling, the following sections:

- [Marker placement for Plug-in Gait lower body model, page 9](#)
- [KAD marker placement for Plug-in Gait lower body model, page 17](#)
- [Marker placement for Plug-in Gait upper body model, page 23](#)

## Plug-in Gait models and templates

# Plug-in Gait labeling skeleton templates (VSTs) in Vicon Nexus

The Plug-in Gait biomechanical model calculates joint kinematics and kinetics from the XYZ marker positions and specific subject anthropometric measurements. As with all motion capture and analysis in Vicon Nexus, the information about the marker set as well as the generic relationship between the physical markers attached to a subject is contained in a labeling skeleton template (.vst) file. This template defines a generic model of the chosen marker set.

You create a subject in Nexus based on a specific template file and then you calibrate the generic marker set model defined in the template to your particular subject. The calibration process creates a labeling skeleton (.vsk) file which is strictly specific to your subject. Nexus then uses this subject-specific .vsk file to automatically label dynamic motion capture trials for that patient both in real time and in post-processing.

### Important

The labeling skeleton templates included in the supplied .vst files are used only to define the marker set and to enable Nexus to perform automatic labeling. They are not biomechanical models that will output valid joint angles or other kinematic/kinetic variables. To derive valid kinematics or kinetics, use Plug-in Gait or create your own biomechanical model using Vicon BodyBuilder, Python or MATLAB.

## Plug-in Gait models and templates

The following table lists the predefined Plug-in Gait labeling skeleton templates (.vst files) supplied with Nexus, identifying the portion of the body it applies to for gait analysis.

Plug-in Gait template file	Description	Lower body modeling	Upper body modeling
PlugInGait FullBody Ai.vst	Full body model defining two markers on the posterior superior iliac spine (PSIS)	y	y
PlugInGait LowerBody Ai.vst	Lower body model defining two markers on the posterior superior iliac spine (PSIS)	y	n

An extended version of Plug-in Gait that defines additional markers for foot modeling is available. For information about the Oxford Foot Model plug-in, contact [Vicon Support](mailto:support@vicon.com)<sup>5</sup>.

These Plug-in Gait template files are installed under the Nexus ModelTemplates folder (by default, C:\Program Files\Vicon\Nexus2.#\ModelTemplates). If you create a template of your own, store it in this location, so that it will be immediately available for selection from the drop-down list when you create a subject node based on a predefined template file. (If you choose not to store it in this location, you can instead browse to the relevant location.)

<sup>5</sup> <mailto:support@vicon.com>

## Plug-in Gait bones

# Plug-in Gait bones

For information on Plug-in Gait bones, see the following topics:

- [Complete list of Plug-in Gait bones, page 39](#)
- [Plug-in Gait virtual markers, page 42](#)
- [Plug-in Gait joint centers, page 43](#)

## Plug-in Gait bones

### Complete list of Plug-in Gait bones

Lower body:		Upper body:	
Name	Description	Name	Description
PELO	Pelvis Origin	HEDO	Head Origin
PELP	Pelvis Proximal	HEDP	Head Proximal
PELA	Pelvis Anterior	HEDA	Head Anterior
PELL	Pelvis Lateral	HEDL	Head Lateral
RFEO	Right Femur Origin	TRXO	Thorax Origin
RFEP	Right Femur Proximal	TRXP	Thorax Proximal
RFEA	Right Femur Anterior	TRXA	Thorax Anterior
RFEL	Right Femur Lateral	TRXL	Thorax Lateral
LFEO	Left Femur Origin	CSPO	C Spine Origin
LFEP	Left Femur Proximal	CSPP	C Spine Proximal
LFEA	Left Femur Anterior	CSPA	C Spine Anterior
LFEL	Left Femur Lateral	CSPL	C Spine Lateral
RTIO	Right Tibia Origin	SACO	Sacrum Origin
RTIP	Right Tibia Proximal	SACP	Sacrum Proximal
RTIA	Right Tibia Anterior	SACA	Sacrum Anterior
RTIL	Right Tibia Lateral	SACL	Sacrum Lateral
LTIO	Left Tibia Origin	RCLO	Right Clavicle Origin
LTIP	Left Tibia Proximal	RCLP	Right Clavicle Proximal
LTIA	Left Tibia Anterior	RCLA	Right Clavicle Anterior
LTIL	Left Tibia Lateral	RCLL	Right Clavicle Lateral
RFOO	Right Foot Origin	LCLO	Left Clavicle Origin
RFOP	Right Foot Proximal	LCLP	Left Clavicle Proximal
RFOA	Right Foot Anterior	LCLA	Left Clavicle Anterior
RFOL	Right Foot Lateral	LCLL	Left Clavicle Lateral
LFOO	Left Foot Origin	RHUO	Right Humerus Origin
LFOP	Left Foot Proximal	RHUP	Right Humerus Proximal
LFOA	Left Foot Anterior	RHUA	Right Humerus Anterior

## Plug-in Gait bones

Lower body:		Upper body:	
Name	Description	Name	Description
LFOL	Left Foot Lateral	RHUL	Right Humerus Lateral
RTOO	Right Toe Origin	LHUO	Left Humerus Origin
RTOP	Right Toe Proximal	LHUP	Left Humerus Proximal
RTOA	Right Toe Anterior	LHUA	Left Humerus Anterior
RTOL	Right Toe Lateral	LHUL	Left Humerus Lateral
LTOO	Left Toe Origin	RRAO	Right Radius Origin
LTOP	Left Toe Proximal	RRAP	Right Radius Proximal
LTOA	Left Toe Anterior	RRAA	Right Radius Anterior
LTOL	Left Toe Lateral	RRAL	Right Radius Lateral
		LRAO	Left Radius Origin
		LRAP	Left Radius Proximal
		LRAA	Left Radius Anterior
		LRAL	Left Radius Lateral
		RHNO	Right Hand Origin
		RHNP	Right Hand Proximal
		RHNA	Right Hand Anterior
		RHNL	Right Hand Lateral
		LHNO	Left Hand Origin
		LHNP	Left Hand Proximal
		LHNA	Left Hand Anterior
		LHNL	Left Hand Lateral
		RFIO	Right Finger Origin
		RFIP	Right Finger Proximal
		RFIA	Right Finger Anterior
		RFIL	Right Finger Lateral
		LFIO	Left Finger Origin
		LFIP	Left Finger Proximal
		LFIA	Left Finger Anterior
		LFIL	Left Finger Lateral
		RTBO	Right Thumb Origin
		RTBP	Right Thumb Proximal



## Plug-in Gait bones

Lower body:		Upper body:	
Name	Description	Name	Description
		RTBA	Right Thumb Anterior
		RTBL	Right Thumb Lateral
		LTBO	Left Thumb Origin
		LTBP	Left Thumb Proximal
		LTBA	Left Thumb Anterior
		LTBL	Left Thumb Lateral

## Plug-in Gait bones

### Plug-in Gait virtual markers

Plug-in Gait creates virtual markers that lie on the axes of a segment's coordinate systems: at the origin, anterior axis, lateral axis, and proximal (vertical) axis. These virtual markers are not necessary for the basic use of Plug-in Gait. Advanced users may use them for exporting the rotational and translational motion of the segments for analysis.

The following table lists the virtual markers created for each segment.

Virtual marker	Segment coordinate system
segmentNameO	segment Origin
segmentNameA	Anterior axis
segmentNameP	Proximal axis
segmentNameL	Lateral axis

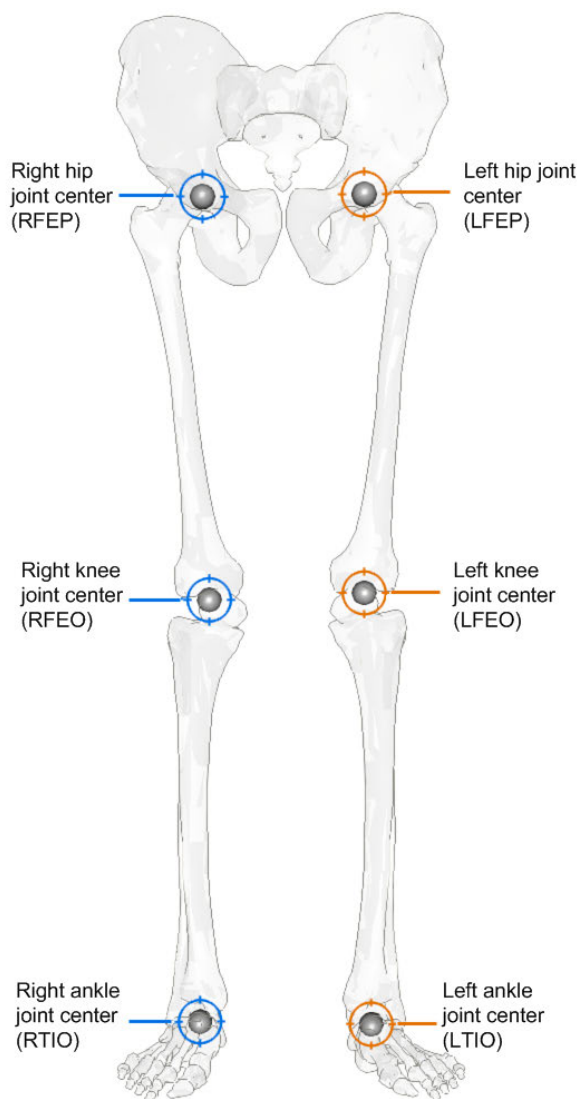
For example, Plug-in Gait would create the following virtual markers for the pelvis segment:

- PELO: pelvis Origin
- PELA: pelvis Anterior axis
- PELP: pelvis Proximal axis
- PELL: pelvis Lateral axis

## Plug-in Gait bones

### Plug-in Gait joint centers

The following image shows Plug-in Gait joint centers:



## Plug-in Gait lower body forces and moments

# Plug-in Gait lower body forces and moments

The forces calculated by Plug-in Gait and displayed by Vicon Polygon are in the local co-ordinate frame of the distal segment in the hierarchical kinetic chain.

This means that the Ankle joint forces are recorded in the Foot segment axis system. Therefore:

- Ground Reaction force Z will look similar to Ankle Force X
- Ground Reaction Force Y will look similar to Ankle Force Z
- Ground Reaction Force X will look similar to Ankle Force Y

For the tibia this changes, as the axis orientation now changes:

- Z force is therefore compression or tension at the joint
- Y force is mediolateral forces at the joint
- X force is anteroposterior forces at the joint

The positive force acts in the positive direction of the axis in the distal segment on which it acts. A negative force acts in the negative direction along the axis.

In Plug-in Gait, we use an external moment and force description. That means that:

- For the Z axis, a negative force is compression and a positive force, tension
- For the Y axis, a positive force for the right side is medial and negative lateral
- For the X axis, a positive force is anterior and negative posterior

## Plug-in Gait lower body forces and moments

The following table lists all the lower body forces and moments with their positive and negative descriptors.

Description	Segment axes	Force or moment component	+ve descriptor	-ve descriptor
Ankle Force X	Foot	Compression/ Tension	Tension	Compression
RAnkle Force Y	Right Foot	Medial/Lateral	Medial	Lateral
Ankle Force Z	Foot	Anterior/ Posterior	Anterior	Posterior
Knee Force X	Tibia	Anterior/ Posterior	Anterior	Posterior
RKnee Force Y	Right Tibia	Medial/Lateral	Medial	Lateral
LKnee Force Y	Left Tibia	Medial/Lateral	Lateral	Medial
Knee Force Z	Tibia	Tension/ Compression	Tension	Compression
Hip Force X	Thigh	Anterior/ Posterior	Anterior	Posterior
RHip Force Y	Right Thigh	Medial/Lateral	Medial	Lateral
LHip Force Y	Left Thigh	Medial/Lateral	Lateral	Medial
Hip Force Z	Thigh	Tension/ Compression	Tension	Compression
Ankle Moment X	Foot	Dorsi/Plantar flexion	Dorsiflexion	Plantar flexion
Ankle Moment Y	Foot	Abduction/ Adduction	Adduction	Abduction
Ankle Moment Z	Foot	Rotation	Internal	External
Knee Moment X	Tibia	Flexion/ Extension	Flexion	Extension
Knee Moment Y	Tibia	Varus/Valgus	Varus	Valgus
Knee Moment Z	Tibia	Rotation	Internal	External
Hip Moment X	Thigh	Flexion/ Extension	Flexion	Extension
Hip Moment Y	Thigh	Abduction/ Adduction	Adduction	Abduction
Hip Moment Z	Thigh	Rotation	Internal	External

## Plug-in Gait kinematic and kinetic calculations

# Plug-in Gait kinematic and kinetic calculations

The following topics describe the way in which Plug-in Gait performs calculations to measure the kinematics and kinetics of subjects. They provide an in-depth understanding of marker placement, and will help you to interpret the results. They describe the geometrical relationships between markers, and segments, and gives fixed values applied to the kinetic segments. Given the same inputs, you should be able to replicate the results.

- [Lower body kinematics, page 53](#)
- [Upper body kinematics, page 69](#)
- [Angle outputs, page 75](#)
- [Kinetic modeling, page 76](#)

The internal structure and the specific algorithms used are not covered.

## Plug-in Gait kinematic and kinetic calculations

### About Plug-in Gait processes

The Plug-in Gait Dynamic pipeline consists of the following components: all individual pipeline operations:

- A quintic spline filter based on code written by Herman Woltring. This filter is intended to be applied to the real marker trajectory data before the modeling stage. No further explicit filtering of the data occurs during the modeling stage.
- Operations that automatically detect and autocorrelate gait cycle events.
- The modeling stage, which takes the real marker trajectories, and generates 'virtual' marker trajectories that represent kinematic and kinetic quantities (angles, moments etc.) and representations of the modeled segments.
- An export operation, to enable you to save your processed trial data to a C3D file.

This guide covers only the modeling stage of the process. You can perform modeling on the real marker data independently from the filtering and event detection processes by selecting the appropriate check box in the pipeline.

## Plug-in Gait kinematic and kinetic calculations

### Segment meshes

Plug-in Gait outputs virtual markers that are used for several purposes:

- To calculate variables
- For visualization purposes, such as to define the positions of meshes (representing bones), which can be displayed in the Polygon application. These mesh outputs are rigidly linked to the calculated rigid body segments but are not necessarily the same. The origins and axes for the meshes are dependent on the meshes contained in the Polygon mesh file.



## Plug-in Gait kinematic and kinetic calculations

### Plug-in Gait internal models

Internally, the modeling stage consists of four interdependent models:

- A kinematic lower body
- A kinematic upper body
- A kinetic lower body
- A kinetic upper body

The kinematic models are responsible for the definitions of the rigid body segments, and the calculations of joint angles between these segments.

The kinetic models then apply masses and moments of inertia to the segments, and enable the "reactions" that occur on the segments to be calculated.

## Plug-in Gait kinematic and kinetic calculations

### Overview of the Plug-in Gait modeling process

To run the models, you must supply the required subject measurements. When you have done this, the stages of the Plug-in Gait modeling process are:

- The initial stage checks that the required components are present. This includes checks for required markers present in the trial, and subject parameter values. Modeling only continues if these requirements are met. The pelvis markers are the minimum required for the lower body model, and the thorax markers are required for the upper body model.
- Various static values that can be calculated as being fixed for the whole trial, and are needed for the definitions of the segments, are calculated.
- The positions of the rigid segments are defined on a frame-by-frame basis. Each segment is defined by an origin in global (laboratory) coordinates, and three orthogonal axis directions.

In general, the three axis directions are defined using two directions derived from the marker data.

- One of these directions is taken as a dominant or principal direction, and used to directly define one of the axes in the segment.
- The second direction is subordinate to the first, and is used with the first direction to define a plane.
- The third axis of the segment is taken to be perpendicular to this plane.
- Then the second axis can be found that is perpendicular to both the first and third axes. All segment axis systems are right-handed systems.

The outputs that are required from the modeling are then calculated, based on the frame-by-frame positions of the segments.

## Plug-in Gait kinematic and kinetic calculations

### Static vs. dynamic models

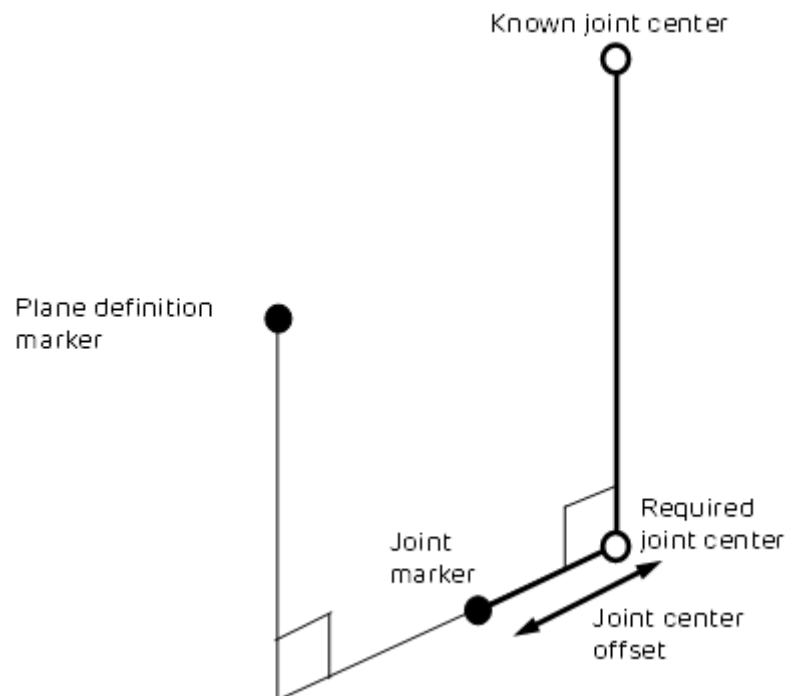
The kinematic models are run slightly differently for the static trials, to calculate certain static 'calibration' angles that are required for the dynamic modeling. These differences are noted in the descriptions of the models, otherwise it should be assumed that the model is calculated in the same way for both trial types.

When the static modeling is being performed, calculated subject measurements are output to the subject measurements file. This is not done for the dynamic trial, even if new values are calculated internally to enable the model to be run.

## Plug-in Gait kinematic and kinetic calculations

### The chord function

To define joint centers, the chord function is used extensively in the Plug-in Gait models. Three points are used to define a plane. One of these points is assumed to be a previously calculated joint center, and a second is assumed to be a real marker, at some known, perpendicular distance (the joint center offset) from the required joint center.



(It's called a chord because by definition, the three points (two joint centers and the joint marker) lie on the periphery of a circle.)

A modified version of the function calculates the required joint center position when the plane definition marker is rotated out of this plane by a known angle round the proposed joint center axis. For an illustration of this, see [Dynamic knee joint center calculation, page 59](#).

## Plug-in Gait kinematic and kinetic calculations

### Lower body kinematics

- [Lower body fixed values, page 53](#)
- [Pelvis, page 55](#)
- [Knee Alignment Device \(KAD\), page 56](#)
- [Knee joint center, page 57](#)
- [Femur, page 60](#)
- [Ankle joint center, page 60](#)
- [Tibia, page 64](#)
- [Foot, page 65](#)

### Lower body fixed values

The Newington-Gage model is used to define the positions of the hip joint centers in the pelvis segment.

If the InterAsis distance has not been entered in the subject measurements, this is calculated as the mean distance between the LASI and RASI markers, for each frame in the trial for which there is a valid position for each marker.

If the Asis to Trochanter distances have not been entered, they are calculated from the left and right leg lengths using the formula:

$$\text{AsisTrocDist} = 0.1288 * \text{LegLength} - 48.56$$

This is done independently for each leg.

The value C is then calculated from the mean leg length:

$$C = \text{MeanLegLength} * 0.115 - 15.3, \text{ aa is half the InterAsis distance, and mm the marker radius.}$$

These are used to then calculate the offset vectors for the two hip joint centers (LHJC and RHJC) as follows:

$$X = C * \cos(\text{theta}) * \sin(\text{beta}) - (\text{AsisTrocDist} + \text{mm}) * \cos(\text{beta})$$

$$Y = -(C * \sin(\text{theta}) - \text{aa})$$

$$Z = -C * \cos(\text{theta}) * \cos(\text{beta}) - (\text{AsisTrocDist} + \text{mm}) * \sin(\text{beta})$$

## Plug-in Gait kinematic and kinetic calculations

where theta is taken as 0.5 radians, and beta as 0.314 radians.

For the right joint center, the Y offset is negated (since Y is in the lateral direction for the pelvis embedded coordinate system).

The position of the top of the lumbar vertebra 5 (the reference point for [Dempster data, page 110](#)) is then estimated as

$$(LHJC + RHJC)/2 + (0.0, 0.0, 0.828) * \text{Length}(LHJC - RHJC)$$

where the value 0.828 is a ratio of the distance from the hip joint center level to the top of the lumbar 5 compared to distance between the hip joint centers on the pelvis mesh.

Knee and ankle offsets are then calculated by adding half the measured joint width and marker diameter to give the distance from the center point of the marker to the joint center.

The general direction of the subject walking in the global coordinate system is then found by looking at the first and last valid position of the LASI marker. The X displacement is compared to the Y displacement. If the X displacement is bigger, the subject is deemed to have been walking along the X axis either positively or negatively, depending on the sign of the X offset. Otherwise, the Y axis is chosen. These directions are used to define a coordinate system matrix (similar to a segment definition) denoted the ProgressionFrame. Note that it's assumed that the Z axis is always vertical, and that the subject is walking along one of these axes, and not diagonally, for example.

If the distance between the first and last frame of the LASI marker is less than a threshold of 800mm however, the progression frame is calculated using the direction the pelvis is facing during the middle of the trial. This direction is calculated as a mean over 10% of the frames of the complete trial. Within these frames, only those which have data for all the pelvis markers are used. For each such frame, the rear pelvis position is calculated from either the SACR marker directly, or the center point of the LPSI and RPSI markers. The front of the pelvis is calculated as the center point between the LASI and RASI markers. The pelvis direction is calculated as the direction vector from the rear position to the front. This direction is then used in place of the LASI displacement, as described above, and compared to the laboratory X and Y axes to choose the Progression Frame.

## Plug-in Gait kinematic and kinetic calculations

### Pelvis

First the pelvis segment coordinate system is defined from the waist markers. The origin is taken as the midpoint of the two asis markers. The dominant axis, taken as the Y axis, is the direction from the right asis marker to the left asis marker. The secondary direction is taken as the direction from the sacrum marker to the right asis marker. If there is no sacrum marker trajectory, the posterior markers are used. If both are visible, the mean is used. If just one is visible, then that one is used. The Z direction is generally upwards, perpendicular to this plane, and the X axis generally forwards.

The position and scale of the pelvis is thus determined by the two asis markers, since they determine the origin of the coronal orientation of the pelvis. The posterior sacral markers (or psis markers) determine only the anterior tilt of the pelvis. Their actual distance behind the asis markers and lateral position is immaterial, allowing a sacral wand marker to be used, for example.

If the asis markers are also used to calculate the inter asis distance, they are therefore also used to determine the lateral positions of the hip joint centers within the pelvis segment. It is important for these to be as accurate as possible, since they affect the determination of the femur segments, and thus influence both the hip angles, and also the knee joint angles.

## Plug-in Gait kinematic and kinetic calculations

### Knee Alignment Device (KAD)

For the model to determine the knee and ankle joint centers, the markers must be very carefully positioned, and it is the responsibility of clinical staff to use their anatomical knowledge to position markers such that the model is able to make as good an approximation to the joint centers as possible.

The dynamic model uses the Thigh and Shank wand markers to define the plane of containing the joint centers, and one method of marker placement is to carefully position these markers to align with your judgment of where the joint centers are.

Alternatively, the Knee Alignment Device (KAD) may be used. This must be placed on the patient during the static trial to indicate the plane of the knee joint center. Then the model calculates the relative angle of the Thigh wand marker, and this angle is used in the dynamic trial to determine the joint center without the KAD. This technique relies on the accurate placement of the KAD, rather than the accurate placement of the wand marker.



## Plug-in Gait kinematic and kinetic calculations

### Knee joint center

- [Static knee joint center calculation, page 57](#)
- [Dynamic knee joint center calculation, page 59](#)

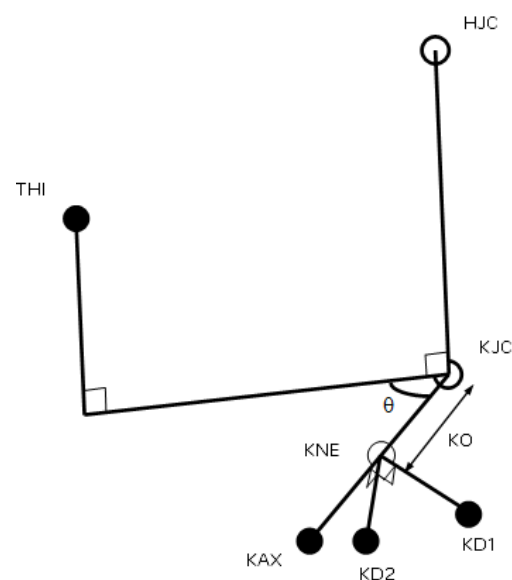
### Static knee joint center calculation

If a KAD is being used in the static model, firstly a virtual KNE marker is determined by finding the point that is equidistant from the three KAD markers, such that the directions from the point to the three markers are mutually perpendicular.

For the right knee, the markers RKAX, RKD1, RKD2 must be labeled in a clockwise direction, and for the left knee, the markers LKAX, LKD1, LKD2 must be labeled anti-clockwise. That is, if the two KD markers are positioned anteriorly, the upper marker should be KD1.

The joint center KJC is then determined using the chord function with the HJC, KNE and KAX. The HJC-KJC and KJC-KNE lines will be perpendicular, and the KJC-KNE line has a length equal to the knee offset (KO).

The thigh marker rotation offset ( $\theta$ ) is then calculated by projecting its position on to a plane perpendicular to the HJC-KJC line.



## Plug-in Gait kinematic and kinetic calculations

If a KAD is not being used in a static trial, then processing proceeds exactly as for a dynamic trial.

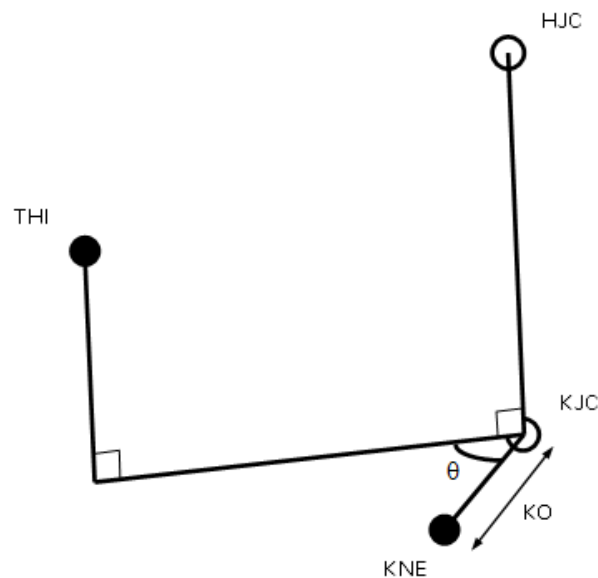
Note that for static trials without a KAD, the anterior-posterior position of the KJC is determined by the position of the THI wand marker, and the value of wand offset value that is entered (if you do not enter a value, a value of zero is assumed). Correct determination of the KJC (and the AJC) is very important, especially for the kinetic calculations. In the clinic, you have to assess which method of marker positioning gives the best estimate of the KJC: using a KAD or using the THI marker.

## Plug-in Gait kinematic and kinetic calculations

### Dynamic knee joint center calculation

In the dynamic model, the KJC is determined using the modified chord function, from the global position of the HJC, the thigh wand marker (THI), and the knee marker (KNE), together with the knee offset (KO), and thigh wand angle offset ( $\theta$ ) from the subject measurements.

KJC is found such that the KNE marker is at a distance of KO from the KJC, in a direction perpendicular to the line from the HJC to KJC. It is also found such that the angle between the KJC-KNE line and the KJC-THI line, projected onto a plane perpendicular to the HJC-KJC line, is the same as the thigh wand offset angle.



There is only one position for the KJC that satisfies these two conditions.

## Plug-in Gait kinematic and kinetic calculations

### Femur

The femur origin is taken as the knee joint center. The primary Z axis is taken from the knee joint center (KJC) to the hip joint center (HJC). The secondary axis is taken parallel to the line from the knee joint center to the knee marker (or virtual knee marker, for static KAD trials). This in fact directly gives the direction of the Y axis. For both the left and the right femur, the Y axis is directed towards the left of the subject. The X axis for both femura is hence directed forwards from the knee.

Note that in a static trial although a KAD determines the plane in which the knee joint center lies, it does not directly determine the lateral orientation of the "knee axis" which is implicitly defined as the Y axis of the femur segment. The lateral orientation is defined by the vertical orientation of the Z axis (the line joining the hip and knee joint centers). The Y axis may pass either above or below the KNE marker.

### Ankle joint center

The ankle joint center is determined in a similar manner to the knee joint center (see [Knee joint center, page 57](#)).

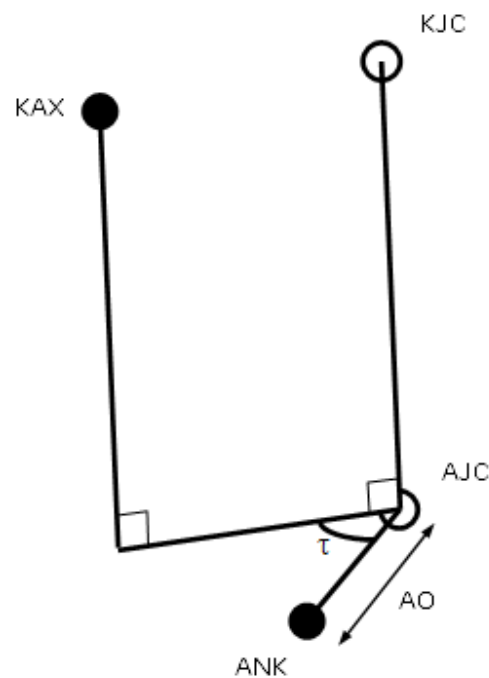
- [Static ankle joint center calculation, page 61](#)
- [Dynamic ankle joint center calculation, page 63](#)

## Plug-in Gait kinematic and kinetic calculations

### Static ankle joint center calculation

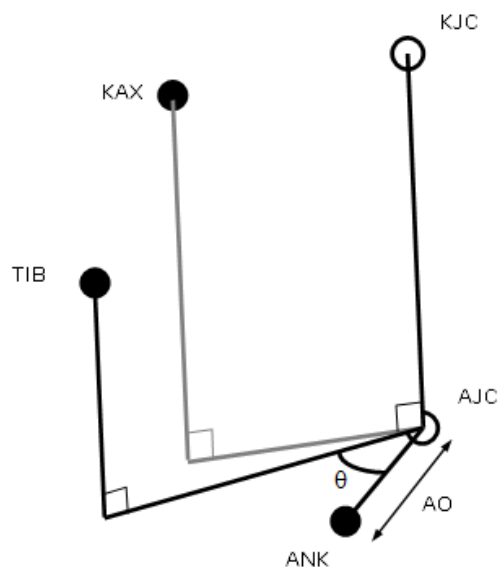
In static trials with a KAD, the KAX marker is used to define the plane of the knee axis, and the plane of the ankle axis is assumed to be parallel to this. A value for Tibial Torsion can be entered, and the plane of the in which the Ankle joint center lies will be rotated by this amount relative to the plane containing the KAX marker.

Thus the AJC is found using the modified chord function, such that it has a distance equal to the ankle offset from the ANK marker (AO), and such that the ANK-AJC line forms an angle equal to the Tibial Torsion with the projection of the KAX-AJC line into the plane perpendicular to the KJC-AJC line. Note that Tibial Torsion is thus considered as an external rotation of the ankle axis relative to the knee axis.



## Plug-in Gait kinematic and kinetic calculations

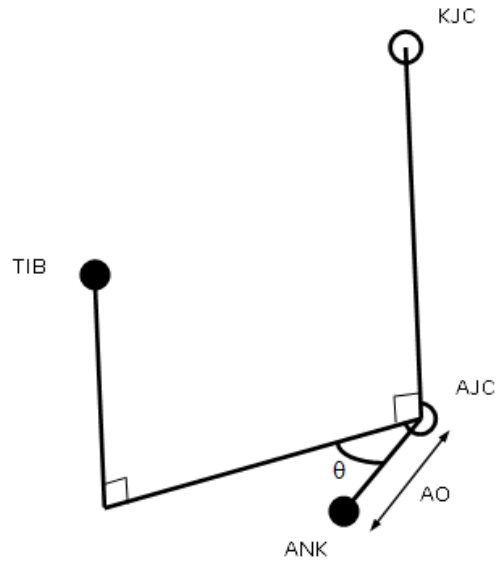
The shank marker rotation offset is then calculated by projecting its position onto the same plane. Note that this value takes into account the value of the tibial torsion, and in general, you would expect it to be slightly less than the value for Tibial Torsion, if the TIB wand marker is conventionally placed.



## Plug-in Gait kinematic and kinetic calculations

### Dynamic ankle joint center calculation

In the dynamic trial, and static trials without a KAD, the ankle joint center is calculated from the knee joint center, shank wand marker and ankle marker with the ankle offset and shank rotation offset using the modified chord function. Thus the ankle joint center is at a distance of ankle offset from the ankle marker, and the angle between the KJC-AJC-ANK plane and the KJC-AJC-TIB plane is equal to the tibia rotation offset.



## Plug-in Gait kinematic and kinetic calculations

### Tibia

[Tortioned tibia, page 64](#)

[Untortioned tibia, page 64](#)

### Tortioned tibia

The tibial rotation offset as determined by the static trial already takes into account the tibial torsion. Thus a Tortioned Tibia is defined with an origin at the AJC, the Z Axis in the direction from the AJC to the KJC, the Y axis leftwards along the line between the AJC and ANK marker, and the X axis generally forwards. This is representative of the distal end of the tibia.

### Untortioned tibia

A second tibia is also generated representing the tibia before tibial torsion is applied, by rotating the X and Y axes of the Tortioned Tibia round the Z axis by the negative of the tibial torsion (i.e. externally for +ve values). This represents the proximal end, and is used to calculate the knee joint angles.



## Plug-in Gait kinematic and kinetic calculations

### Foot

[Static foot, page 66](#)

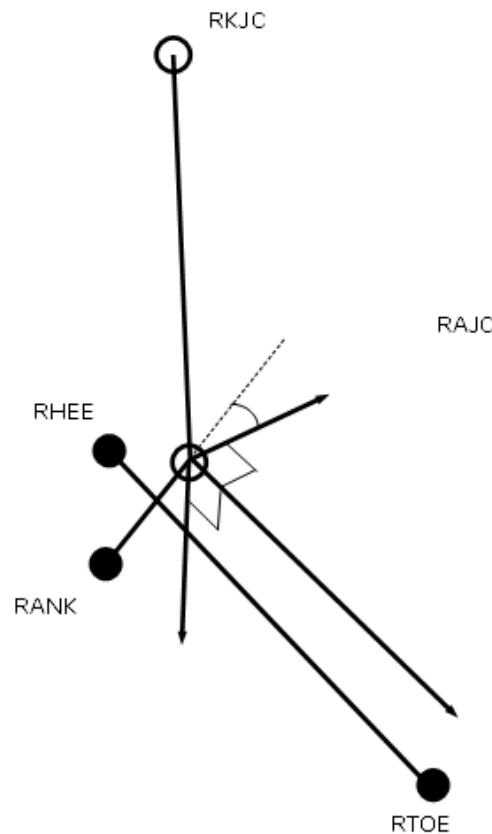
[Dynamic foot, page 68](#)

## Plug-in Gait kinematic and kinetic calculations

### Static foot calculation

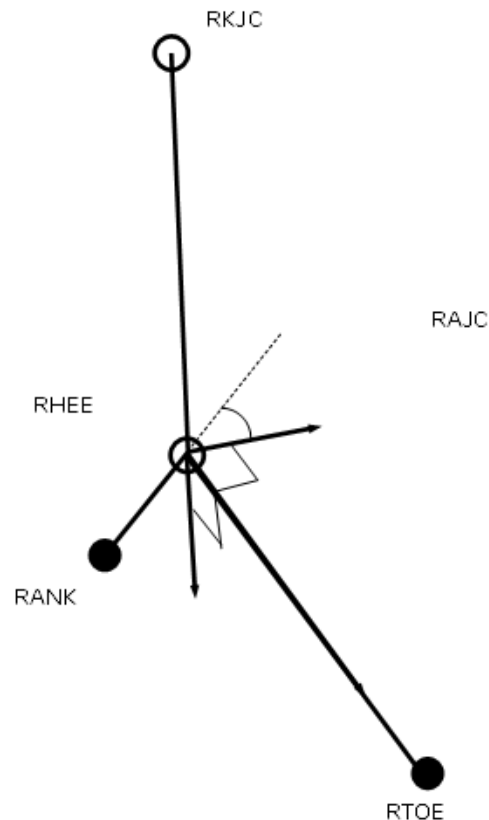
The heel marker is used in the static trial, and the model effectively makes two segments. For both segments, the AJC is used as the origin.

The main foot segment is constructed using the TOE-HEE line as the primary axis. If the settings for the model have the foot flat check box selected (ie you have selected Left Foot and/or Right Foot in the Assume Horizontal properties for the Process Static Plug-in Gait Model pipeline operation), then HEE is moved vertically (along the global Z axis) to be at the same height as TOE. This line is taken as the Z axis, running forwards along the length of the foot. The direction of the Y axis from the untortioned tibia is used to define the secondary Y axis. The X axis thus points down, and the Y axis to the left.



## Plug-in Gait kinematic and kinetic calculations

A second foot segment is constructed, using the TOE-AJC as the primary axis, and again the Y axis of the untorted tibia to define the perpendicular X axis and the foot Y axis (the 'uncorrected' foot).

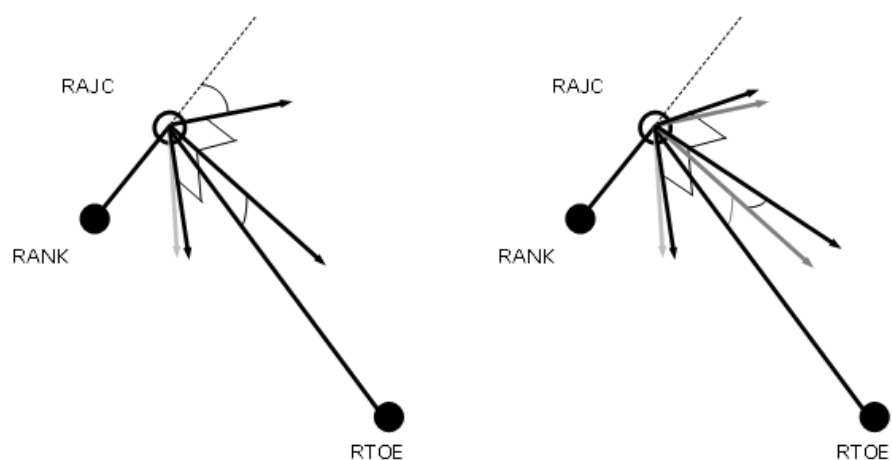


The Static offset angles (Plantar Flexion offset and Rotation offset) are then calculated from the 'XYZ' Cardan Angles between the two segments (rotating from the 'uncorrected' segment to the heel marker based foot segment). This calculation is performed for each frame in the static trial, and the mean angles calculated. The static plantar-flexion offset is taken from the rotation round the Y axis, and the rotation offset is the angle round the X axis. The angle round the Z axis is ignored.

## Plug-in Gait kinematic and kinetic calculations

### Dynamic foot calculation

In the dynamic trial, the foot is calculated in the same way as for the 'uncorrected' foot. The resulting segment is then rotated first round the Y axis by the Plantar Flexion offset. Then the resulting segment is rotated around its X axis by the rotation offset.



## Plug-in Gait kinematic and kinetic calculations

### Upper body kinematics

- [Upper body fixed values, page 69](#)
- [Head, page 70](#)
- [Thorax, page 70](#)
- [Shoulder joint center, page 71](#)
- [Clavicle, page 71](#)
- [Elbow joint center, page 72](#)
- [Wrist joint center, page 73](#)
- [Humerus, page 73](#)
- [Radius, page 73](#)
- [Hand, page 74](#)

### Upper body fixed values

A shoulder offset value is calculated from the Subject measurement value entered, plus half the marker diameter. Elbow, wrist and hand offset values are also calculated from the sum of the respective thickness with the marker diameter divided by two.

A progression frame is independently calculated in just the same way as for the lower body. C7 is tested first to determine if the subject moved a distance greater than the threshold. If not, the other thorax markers T10 CLAV and STRN are used to determine the general direction the thorax was facing in from a mean of 10% of the frames in the middle of the trial.

Note that in principle it could be possible to arrive at different reference frames for the upper and lower body, though the circumstances would be extreme.

## Plug-in Gait kinematic and kinetic calculations

### Head

The head origin is initially defined as the midpoint between the LFHD and RFHD markers (also denoted 'Front').

The midpoint between the LBHD and RBHD markers ('Back') is also calculated, along with the 'Left' and 'Right' sides of the head from the LFHD and LBHD midpoint, and the RFHD and RBHD midpoint respectively.

The predominant head axis, the X axis, is defined as the forward facing direction (Front - Back). The secondary Y axis is the lateral axis from Right to Left (which is orthogonalized as usual).

For the static processing, the YXZ Euler angles representing the rotation from the head segment to the lab axes are calculated. The Y rotation is taken as the head Offset angle, and the mean of this taken across the trial.

For the dynamic trial processing, the head Offset angle is applied around the Y axis of the defined head segment.

After the head XYZ axes are defined and the static head offset angle is applied, a (-0.84, 0, -0.3) mesh origin offset multiplied by a headscale value ( $2 * \text{distance between temples}$ ) is applied.

### Thorax

The orientation of the thorax is defined before the origin. The Z axis, pointing upwards, is the predominant axis. This is defined as the direction from the midpoint of the STRN and T10 to the midpoint of CLAV and C7. A secondary direction pointing forwards is the midpoint of C7 and T10 to the midpoint of CLAV and STRN. The resulting X axis points forwards, and the Y axis points leftwards.

The thorax origin is then calculated from the CLAV marker, with an offset of half a marker diameter backwards along the X axis.

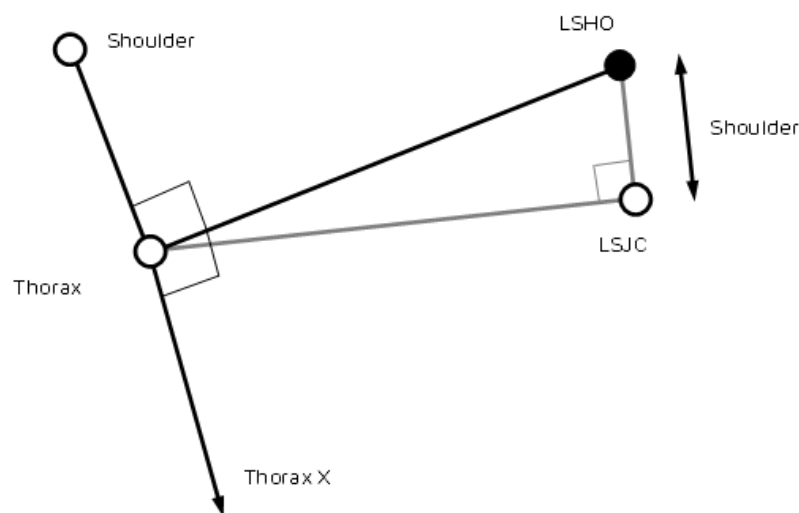
## Plug-in Gait kinematic and kinetic calculations

### Shoulder joint center

The clavicles are considered to lie between the thorax origin, and the shoulder joint centers. The shoulder joint centers are defined as the origins for each clavicle. Note that the posterior part of the shoulder complex is considered too flexible to be modeled with this marker set.

Initially a direction is defined, which is perpendicular to the line from the thorax origin to the SHO marker, and the thorax X axis. This is used to define a virtual shoulder 'wand' marker.

The chord function is then used to define the shoulder joint center (SJC) from the Shoulder offset, thorax Origin, SHO marker and shoulder 'wand'.



### Clavicle

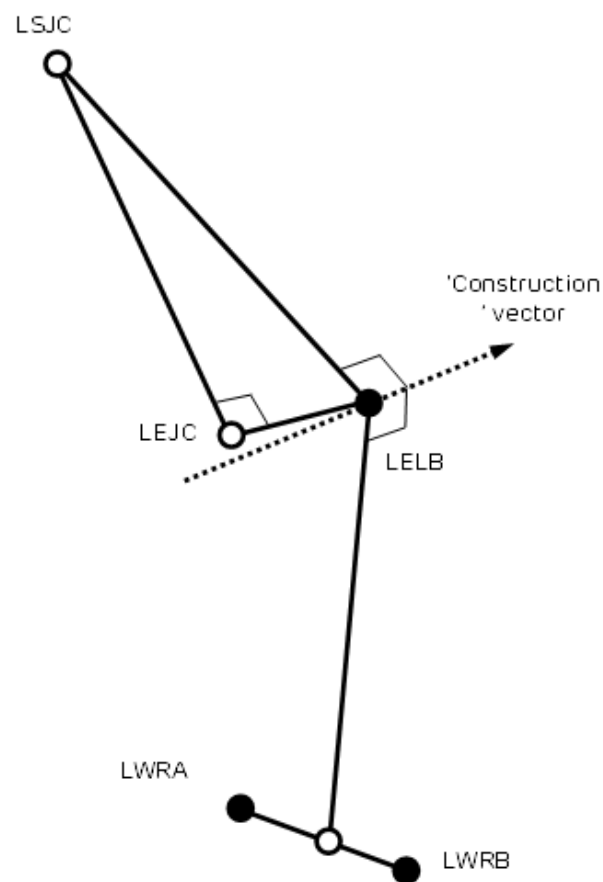
The clavicle segment is defined from the direction from the joint center to the thorax origin as the Z axis, and the shoulder wand direction as the secondary axis. The X axis for each clavicle points generally forwards, and the Y axis for the left points upwards, and the right clavicle Y axis points downwards.

## Plug-in Gait kinematic and kinetic calculations

### Elbow joint center

A construction vector direction is defined, being perpendicular to the plane defined by the shoulder joint center, the elbow marker (LELB) and the midpoint of the two wrist markers (LWRA, LWRB).

The elbow joint center is defined using the chord function, in the plane defined by the shoulder joint center, the elbow marker and the previously defined construction vector.

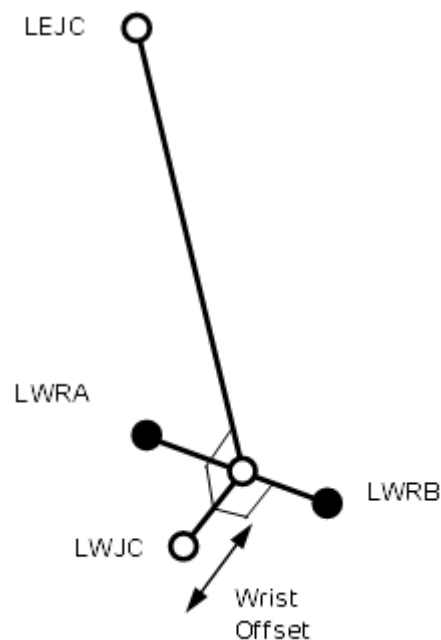




## Plug-in Gait kinematic and kinetic calculations

### Wrist joint center

After the elbow joint center is calculated, the wrist joint center (WJC) is calculated. In this case the chord function is not used. The wrist joint center is simply offset from the midpoint of the wrist bar markers along a line perpendicular to the line along the wrist bar, and the line joining the wrist bar midpoint to the elbow joint center.



### Humerus

After the wrist joint center is defined, the Humerus is calculated with its origin at the EJC, a principal Z axis from EJC to SJC, and a secondary line approximating to the X axis between the EJC and the WJC.

### Radius

The radius origin is set at the wrist joint center. The principal axis is the Z axis, from the WJC to the EJC. The secondary line approximating to the Y axis is taken as the Y axis of the Humerus segment.

## Plug-in Gait kinematic and kinetic calculations

### Hand

The hand is defined by first defining its origin. The chord function is used again for this, with the WJC, FIN marker and Hand Offset. The midpoint of the wrist bar markers is used to define the plane of calculation.

The principal Z axis is then taken as the line from the hand origin to the WJC, and a secondary line approximating the Y axis is defined by direction of the line joining the wrist bar markers.

## Plug-in Gait kinematic and kinetic calculations

### Angle outputs

The output angles for all joints are calculated from the YXZ Cardan angles derived by comparing the relative orientations of the two segments.

The knee angles are calculated from the femur and the Untortioned tibia segments, whilst the ankle joint angles are calculated from the Tortioned tibia and the foot segment.

In the case of the feet, since they are defined in a different orientation to the tibia segments, an offset of 90 degrees is added to the flexion angle. This does not affect the Cardan angle calculation of the other angles since the flexion angle is the first in the rotation sequence.

The progression angles of the feet, pelvis, thorax and head are the YXZ Cardan calculated from the rotation transformation of the subject's Progression Frame for the trial onto each segment orientation.

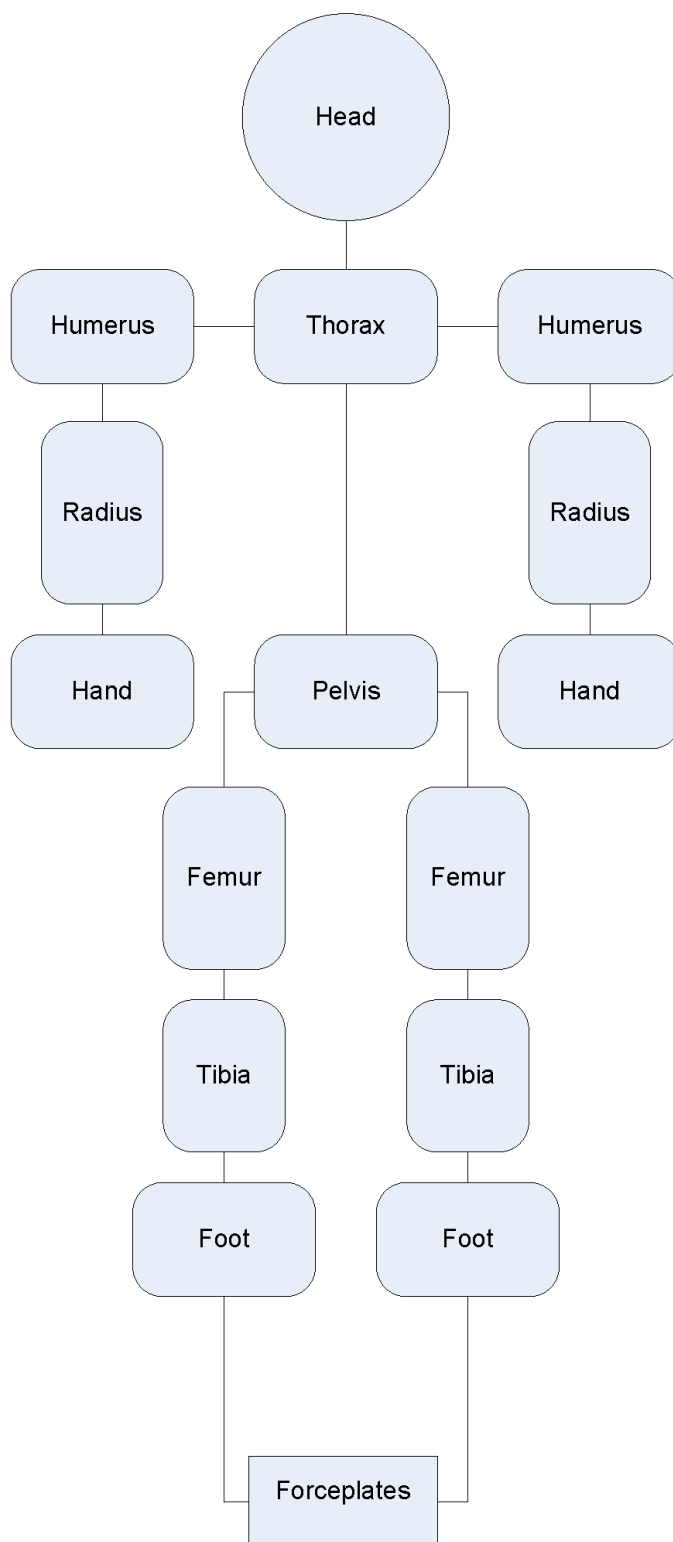
## Plug-in Gait kinematic and kinetic calculations

### Kinetic modeling

The kinetic modeling parts of the model simply assign masses and radii of gyration to the segments defined in the kinematic model. An estimate of the position of the center of mass is required in the segment. This is defined as a point at a given proportion along a line from the distal joint center (normally the origin of the segment) towards the proximal joint center of a "typical" segment. The masses of each segment are calculated as a proportion of the total body mass. The principal axes moments of inertia are calculated from (mass) normalized radii of gyration from these tables too. In general the moment is considered to be zero around the longitudinal axis of most segments. Since experimental data were not available, estimates have been made for the radii of gyration of the pelvis and thorax. You can change these values in the **Properties** pane of the **Process Dynamic Plug-in Gait Model** pipeline operation.

The following diagram shows the kinetic hierarchy.

## Plug-in Gait kinematic and kinetic calculations



## Plug-in Gait kinematic and kinetic calculations

Note that the clavicles are not considered to have mass in themselves, so reactions for the humerus segments are considered to act directly on the thorax.

The feet are only 'connected' to the forceplates where forceplate measurements and marker data indicate a match. Only one segment is chosen to be in contact with a given forceplate for each frame.

Note also that the "untortioned" tibiae are used for the kinetic modeling. This means that where the KAD and a tibial torsion have been used, and the proximal frame is chosen to reference the ankle moments, the flexion and abduction moments will not correspond to the axes used to calculate the ankle angles. Having said that, the axes are calculated with a "floating axis" definition, so even for corresponding segments the axes will not be coincident.

Even though the "untortioned" tibiae are used for the reference frames, a difference in moments will be observed if the trial is processed with a different tibial torsion. When the tibial torsion is applied in the static trial, the ankle joint center is moved backwards, then the "untortioned" tibia is calculated by rotating the tortioned tibia round the Z axis, keeping the ankle joint center in position. Thus, for a given trial, as tibial torsion is increased, and the joint center is rotated backwards around the ankle marker, the ankle flexion moment will generally become more positive.

## Plug-in Gait kinematic and kinetic calculations

Segment	CoM	Mass	Radius of gyration
Pelvis <sup>a</sup>	0.895	0.142	0.31
Femur	0.567	0.1	0.540
Tibia	0.567	0.0465	0.528
Foot	0.5	0.0145	0.690
Humerus	0.564	0.028	0.542
Radius	0.57	0.016	0.526
Hand <sup>b</sup>	0.6205	0.006	0.440
Thorax <sup>c</sup>	0.63	0.355	0.31
Head <sup>d</sup>	see below	0.081	1.116

a) Pelvis: The center of mass is defined along a line from the midpoint of the hip joint centers, to the center of the top surface of the Lumbar 5 vertebra. For simplified scaling, this distance is defined as 0.925 times the distance between the hip joint centers, and the Lumbar5 is defined as lying directly on the Z axis (derived by inspection from the bone mesh used in Polygon). The radius of gyration for the pelvis is an estimate, and is applied round all three axes. It is the default user value in the Dynamic Plug-in Gait operation.

b) Hand: The length of the hand in this model is defined as the distance from the wrist joint center to the finger tip. An estimate of 0.75 is taken as the proportion of this length to the "Knuckle II" reference point referred to in the [Dempster data, page 110](#).

c) Thorax: The thorax length is taken as the distance between an approximation to the C7 vertebra and the L5 vertebra in the Thorax reference frame. C7 is estimated from the C7 marker, and offset by half a marker diameter in the direction of the X axis. L5 is estimated from the L5 provided from the pelvis segment, but localized to the thorax, rather than the pelvis. The positions are calculated for all frames in the trial, and averaged to give the mean length. The Center of mass is deemed to lie at a proportion of 0.63 along this line. The radius of gyration for the thorax is the default user value in the Dynamic Plug-in Gait operation.

d) Head: If you're calculating the Head CoM yourself, note that the Head Origin is shifted from the midpoint between the front markers using a (-0.84, 0, -0.3) mesh offset multiplied by a headscale value (2 \* distance between temples). An optional static head rotation offset is also factored in. The center of mass of the head is defined as being 0.52 \* the distance from the front to the back of the head along the X axis from the head origin (the midpoint of the front head

## Plug-in Gait kinematic and kinetic calculations

markers). The length of the head used for the inertial normalization is the distance from this point to the C7 vertebra (the mean position localized to the head segment). The inertia value for the head is applied around all three axes.



## Plug-in Gait kinematic and kinetic calculations

### Whole body center of mass

The center of mass is calculated whenever the head or thorax segment is present. A weighted sum of all the centers of mass of all the segments is made, where segments are defined by markers. The sum is still made if segments, such as the hands, for example, do not have markers. The center of mass is the center of mass of all the modeled segments.

#### Caution

Note that this center of mass algorithm has not been clinically tested, and may be misleading in some clinical situations. In particular, the thorax segment is modeled kinetically as a rigid body which includes the mass of the abdomen (which is not independently modeled). The markers which define the thorax are at the top of the thorax, and the center of mass is assumed to be on a line directed towards the L5 vertebra. Any bending of the trunk in the upper lumbar region will cause this assumption to fail, which may cause a significant error in the position of the center of mass for the whole body.

The projection of the center of mass onto the floor is made simply by setting the Z value to zero.

## Plug-in Gait output angles

# Plug-in Gait output angles

The output angles for all joints are calculated from the YXZ Cardan angles derived by comparing the relative orientations of the segments proximal (parent) and distal (child) to the joint.

The knee angles are calculated from the femur and the Untorsioned tibia segments, while the ankle joint angles are calculated from the Torsioned tibia and the foot segment.

In the case of the feet, because they are defined in a different orientation to the tibia segments, an offset of 90 degrees is added to the flexion angle. This does not affect the Cardan angle calculation of the other angles because the flexion angle is the first in the rotation sequence.

The progression angles of the feet, pelvis, thorax and head are the YXZ Cardan calculated from the rotation transformation of the subject's progression frame for the trial onto each segment orientation.

The following topics provide further details.

- [Angle definitions, page 83](#)
- [Plug-in Gait kinematic variables, page 86](#)
- [Upper body angles as output from Plug-in Gait, page 95](#)
- [Lower body angles as output from Plug-in Gait, page 98](#)

## Plug-in Gait output angles

### Angle definitions

Plug-in Gait uses Cardan angles, modified in the case of the ankle angles, to represent both:

- Absolute rotations of the pelvis and foot segments and
- Relative rotations at the hip, knee, and ankle joints

These angles can be described either as a set of rotations carried out one after the other (ordered).

For more information about the use of Cardan angles to calculate joint kinematics, refer to Kadaba, Ramakrishnan and Wooten (1990) and Davis, Öunpuu, Tyburski and Gage (1991) (see Plug-in Gait references).

The rotations are measured about anatomical axes in order to simplify their interpretation.

For more information on joint angle descriptions, including the issues of gimbal lock and Codman's Paradox, see:

- [Ordered rotations, page 83](#)
- [Angle goniometric description, page 84](#)

### Ordered rotations

To describe an angle using ordered rotations, the following are true:

- One element is 'fixed'. For absolute rotations the laboratory axes are fixed. The proximal segment axes are fixed for relative rotations.
- The second element 'moves'. This means the segment axes move for absolute rotations and distal segment moves for relative rotations.

A joint angle is then defined using the following ordered rotations:

- The first rotation (flexion) is made about the common flexion axis. The other two axes, abduction and rotation, are afterwards no longer aligned in the two elements.
- The second rotation (abduction) is made about the abduction axis of the moving element. The third rotation (rotation) is made about the rotation axis of the moving element.

## Plug-in Gait output angles

### Angle goniometric description

In addition to using ordered rotations, joint angles can also be described using goniometric information. Using goniometric definitions, a joint angle is described by the following:

- Flexion is about the flexion axis of the proximal (or absolute) element.
- Rotation is about the rotation axis of the distal element.
- Abduction axis 'floats' so as always to be at right angles to the other two.

Cardan angles work well unless a rotation approaching 90 degrees brings two axes into line. When this happens, one of the possible rotations is lost and becomes unmeasurable. Fortunately, this does not frequently occur in the joints of the lower limbs during normal or pathological gait. However this may occur in the upper limb and particularly at the shoulder. For more information, see [Gimbal lock, page 84](#) and also [Codman's Paradox, page 84](#) below.

### Gimbal lock

Gimbal lock occurs when using Cardan (Euler) angles and any of the rotation angles becomes close to 90 degrees, for example, lifting the arm to point directly sideways or in front (shoulder abduction about an anterior axis or shoulder flexion about a lateral axis respectively). In either of these positions the other two axes of rotation become aligned with one another, making it impossible to distinguish them from one another, a singularity occurs and the solution to the calculation of angles becomes unobtainable.

For example, assume that the humerus is being rotated in relation to the thorax in the order Y,X,Z and that the rotation about the X-axis is 90 degrees.

In such a situation, rotation in the Y-axis is performed first and correctly. The X-axis rotation also occurs correctly BUT rotates the Z axis onto the Y axis. Thus, any rotation in the Y-axis can also be interpreted as a rotation about the Z-axis.

True gimbal lock is rare, arising only when two axes are close to perfectly aligned.

### Codman's Paradox

The second issue however, is that in each non-singular case there are two possible angular solutions, giving rise to the phenomenon of "Codman's Paradox" in anatomy (Codman, E.A. (1934). *The Shoulder. Rupture of the Supraspinatus Tendon and other Lesions in or about the Subacromial Bursa*).

## Plug-in Gait output angles

Boston: Thomas Todd Company), where different combinations of numerical values of the three angles produce similar physical orientations of the segment. This is not actually a paradox, but a consequence of the non-commutative nature of three-dimensional rotations and can be mathematically explained through the properties of rotation matrices (Politti, J.C., Goroso, G., Valentinuzzi, M.E., & Bravo, O. (1998). *Codman's Paradox of the Arm Rotations is Not a Paradox: Mathematical Validation*. *Medical Engineering & Physics*, 20, 257-260).

Codman proposed that the completely elevated humerus could be shown to be in either extreme external rotation or in extreme internal rotation by lowering it either in the coronal or sagittal plane respectively, without allowing any rotation about the humeral longitudinal axis.

To demonstrate Codman's Paradox, complete the following steps:

1. Place the arm at the side, elbow flexed to 90 degrees and the forearm internally rotated across the stomach.
2. Elevate the arm 180 degrees in the sagittal plane.
3. Lower the arm 180 degrees to the side in the coronal plane.  
Observe that the forearm now points 180 degrees externally rotated from its original position with no rotation about the humeral longitudinal axis actually having occurred.
4. Note the difficulty in describing whether the fully elevated humerus was internally or externally rotated.

This ambiguity can cause switching between one solution and the other, resulting in sudden discontinuities. A combination of gimbal lock and Codman's Paradox can lead to unexpected results when joint modeling is carried out. In practice, the shoulder is the only joint commonly analyzed that has a sufficient range of motion about all rotation axes for these to be an issue. Generally, if you are aware of the reasons for the inconsistent data, you can manipulate any erroneous results by adding 180 or 360 degrees.

As Plug-in Gait uses Cardan (Euler) angles in all cases to calculate joint angles, they are subject to both Gimbal Lock in certain poses, and the inconsistencies that occur as a result of Codman's Paradox.

Plug-in Gait includes some steps to minimize the above effects by trying to keep the shoulder angles in consistent and understandable quadrants. This is not a complete solution however, as the above issues are inherent when using Cardan (Euler) angles and clinical descriptions of motion.

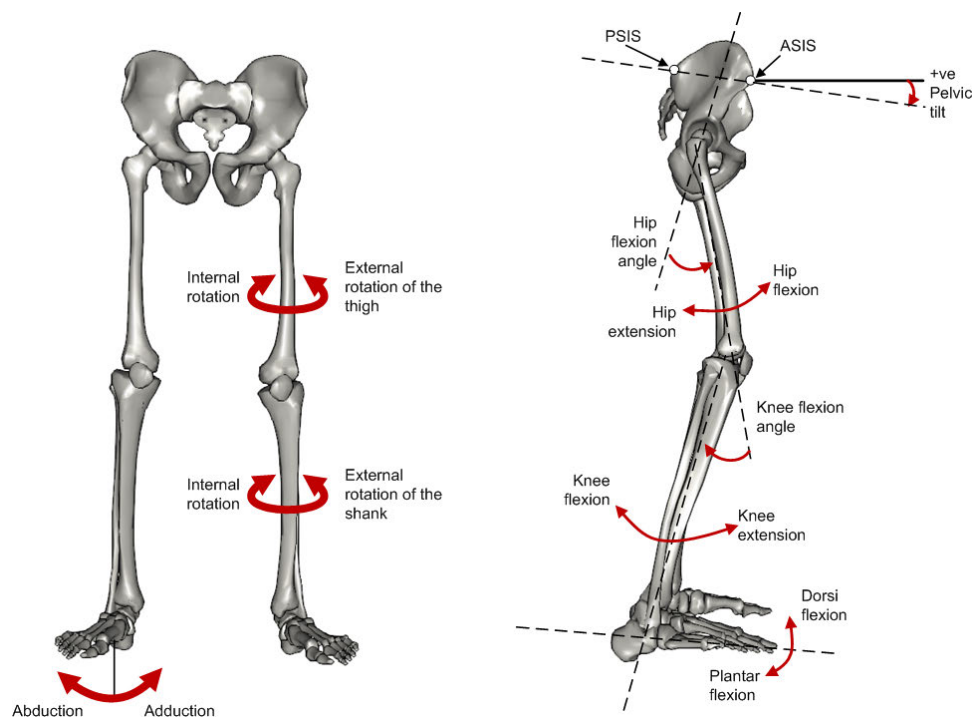
## Plug-in Gait output angles

## Plug-in Gait kinematic variables

When gait cycle events have been defined, derived kinematic quantities are calculated and written to file.

Note that throughout this section, axes are described as follows:

- Transverse axes are those axes which pass from one side of the body to the other;
- Sagittal axes pass from the back of the body to the front; and
- Frontal axes pass in a direction from the center of the body through the top of the head.



## Plug-in Gait output angles

### List of kinematic variables calculated by Plug-in Gait

The following table lists all the kinematic variables calculated by Plug-in Gait. It includes information describing each variable in terms of ordered rotations or goniometric definitions.

For example, knee rotation is a relative angle measured between the thigh as the proximal segment and the shank as the distal segment. Its 'goniometric' axis is fixed to the shank as the distal segment. Incidentally, this angle, although always calculated, is often omitted from reports because it is so difficult to measure with precision.

Foot rotation and foot progression, also known as foot alignment, are not expressed in terms of goniometric axes, since the ankle angles are not calculated as strict Cardan angles. Both rotations measure the alignment of the foot. The first is relative to the shank, and the second is measured as an absolute angle in the laboratory's transverse plane.

Absolute angles are measured relative to laboratory axes with the sagittal and transverse axes automatically selected according to the direction of walking. In Plug-in Gait, the laboratory axis closest to the subject's direction of progression is labeled the laboratory sagittal axis.

Each variable is listed in the following table.

## Plug-in Gait output angles

Angle rotation	Goniometric	Description
Pelvic tilt	Absolute	<p>Pelvic tilt is normally calculated about the laboratory's transverse axis. If the subject's direction of forward progression is closer to the laboratory's sagittal axis, however, then pelvic tilt is measured about this axis.</p> <p>The sagittal pelvic axis, which lies in the pelvis transverse plane, is normally projected into the laboratory sagittal plane. Pelvic tilt is measured as the angle in this plane between the projected sagittal pelvic axis and the sagittal laboratory axis. A positive value (up) corresponds to the normal situation in which the PSIS is higher than the ASIS.</p>
Pelvic obliquity	Absolute	<p>Pelvic obliquity is measured about an axis of rotation that is perpendicular to the axes of the other two rotations. This axis does not necessarily correspond with any of the laboratory or pelvic axes. Pelvic obliquity is measured in the plane of the laboratory transverse axis and the pelvic frontal axis. The angle is measured between the projection into the plane of the transverse pelvic axis and projection into the plane of the laboratory transverse axis (the horizontal axis perpendicular to the subject's axis of progression). A positive pelvic obliquity value (up) relates to the situation in which the same side of the pelvis is higher.</p>
Pelvic rotation	Absolute	<p>Pelvic rotation is calculated about the frontal axis of the pelvic co-ordinate system. It is the angle measured between the sagittal axis of the pelvis and the sagittal laboratory axis (axis closest to subject's direction of progression) projected into the pelvis transverse plane. A negative (external) pelvic rotation value means the opposite side is in front.</p>
Hip flexion/extension	Relative	<p>Hip flexion is calculated about an axis parallel to the pelvic transverse axis which passes through the hip joint center. The sagittal thigh axis is projected onto the plane perpendicular to the hip flexion axis. Hip flexion is then the angle between the projected sagittal thigh axis and the sagittal pelvic axis. A positive (Flexion) angle value corresponds to the situation in which the knee is in front of the body.</p>
Hip ab/adduction	Relative	<p>Hip adduction is measured in the plane of the hip flexion axis and the knee joint center. The angle is calculated between the long axis of the thigh and the frontal axis of the pelvis projected into this plane. A positive number corresponds to an adducted (inwardly moved) leg.</p>



## Plug-in Gait output angles

Angle rotation	Goniometric	Description
Hip rotation	Relative	Hip rotation is measured about the long axis of the thigh segment and is calculated between the sagittal axis of the thigh and the sagittal axis of the pelvis projected into the plane perpendicular to the long axis of the thigh. The sign is such that a positive hip rotation corresponds to an internally rotated thigh.
Knee flexion/extension	Relative	The sagittal shank axis is projected into the plane perpendicular to the knee flexion axis. Knee flexion is the angle in that plane between this projection and the sagittal thigh axis. The sign is such that a positive angle corresponds to a flexed knee.
Knee ab/adduction (Knee varus/valgus)	Relative	This is measured in the plane of the knee flexion axis and the ankle center, and is the angle between the long axis of the shank and the long axis of the thigh projected into this plane. A positive number corresponds to varus (outward bend of the knee).
Knee rotation	Relative	Knee rotation is measured about the long axis of the shank. It is measured as the angle between the sagittal axis of the shank and the sagittal axis of the thigh, projected into a plane perpendicular to the long axis of the shank. The sign is such that a positive angle corresponds to internal rotation. If a tibial torsion value is present in the Session form, it is subtracted from the calculated knee rotation value. A positive tibial torsion value therefore has the effect of providing a constant external offset to knee rotation.
Ankle dorsi/plantar flexion	Relative	The foot vector is projected into the foot sagittal plane. The angle between the foot vector and the sagittal axis of the shank is the foot dorsi/plantar flexion. A positive number corresponds to dorsiflexion.
Foot rotation	Relative	This is measured about an axis perpendicular to the foot vector and the ankle flexion axis. It is the angle between the foot vector and the sagittal axis of the shank, projected into the foot transverse plane. A positive number corresponds to an internal rotation.
Foot-based dorsi/plantar flexion		This optional angle is defined similarly to ankle dorsi/plantar flexion, but it is measured in a plane containing the knee and ankle centers and the toe marker.

## Plug-in Gait output angles

Angle rotation	Goniometric	Description
Foot progression	Absolute	This is the angle between the foot vector (projected into the laboratory's transverse plane) and the sagittal laboratory axis. A positive number corresponds to an internally rotated foot.
Head tilt	Absolute	Head tilt is normally calculated about the laboratory's transverse axis. If the subject's direction of forward progression is closer to the laboratory's sagittal axis, however, then head tilt is measured about this axis. The sagittal head axis is normally projected into the laboratory sagittal plane. Head tilt is measured as the angle in this plane between the projected sagittal head axis and the sagittal laboratory axis. A positive value (up) corresponds to <b>backward</b> head tilt.
Head obliquity	Absolute	Head lateral tilt is measured about an axis of rotation perpendicular to the axes of the other two rotations. This axis does not necessarily correspond with any of the laboratory or head axes. Head lateral tilt is measured in the plane of the laboratory transverse axis and the head frontal axis. The angle is measured between the projection into the plane of the transverse head axis and projection into the plane of the laboratory transverse axis (the horizontal axis perpendicular to the subject's axis of progression). A <b>positive</b> head obliquity value (up) relates to the situation in which the same side of the head is higher.
Head rotation	Absolute	Head rotation is calculated about the frontal axis of the head co-ordinate system. It is the angle measured between the sagittal axis of the head and the sagittal laboratory axis (axis closest to subject's direction of progression) projected into the head transverse plane. A negative (external) head rotation value means the opposite side is in front.
Thorax tilt	Absolute	Thorax tilt is normally calculated about the laboratory's transverse axis. If the subject's direction of forward progression is closer to the laboratory's sagittal axis, however, then thorax tilt is measured about this axis. The sagittal thorax axis is normally projected into the laboratory sagittal plane. Thorax tilt is measured as the angle in this plane between the projected sagittal thorax axis and the sagittal laboratory axis. A positive value (up) corresponds to forward thorax tilt.

## Plug-in Gait output angles

Angle rotation	Goniometric	Description
Thorax obliquity	Absolute	Thorax obliquity is measured about an axis of rotation perpendicular to the axes of the other two rotations. This axis does not necessarily correspond with any of the laboratory or thorax axes. Thorax obliquity is measured in the plane of the laboratory transverse axis and the Thorax frontal axis. The angle is measured between the projection into the plane of the transverse thorax axis and projection into the plane of the laboratory transverse axis (the horizontal axis perpendicular to the subject's axis of progression). As the thorax segment is defined with the frontal Z axis point downward a positive (up) thorax obliquity angle relates to the situation in which the opposite side of the thorax is lower.
Thorax rotation	Absolute	Thorax rotation is calculated about the frontal axis of the thorax co-ordinate system. It is the angle measured between the sagittal axis of the thorax and the sagittal laboratory axis (axis closest to subject's direction of progression) projected into the thorax transverse plane. As the thorax segment is defined with the frontal Z axis point downward a positive (internal) thorax rotation value means the opposite side is <b>behind</b> .
Neck flexion/extension	Relative	The sagittal head axis is projected onto the plane perpendicular to the thorax sagittal axis. Neck flexion is then the angle between the projected sagittal head axis and the sagittal thorax axis around the fixed transverse axis of the thorax. A positive (flexion) angle value corresponds to the situation in which the head is tilted forward.
Neck lateral flexion	Relative	The angle between the long axis of the head and the long axis of the thorax around a floating transverse axis.
Neck rotation	Relative	Neck rotation is measured about the long axis of the head. It is measured as the angle between the sagittal axis of the head and the sagittal axis of the thorax, around a floating frontal axis. As the thorax frontal axis points downward while the head frontal axis points upward, a positive angle therefore refers to rotation of the head toward the opposite side.
Spine flexion/extension	Relative	Spine flexion is the angle between the sagittal thorax axis and the sagittal pelvis axis around the fixed transverse axis of the pelvis. A positive (flexion) angle value corresponds to the situation in which the thorax is tilted forward.

## Plug-in Gait output angles

Angle rotation	Goniometric	Description
Spine lateral flexion	Relative	The angle between the long axis of the thorax and the long axis of the pelvis, around a floating transverse axis.
Spine rotation	Relative	It is measured as the angle between the sagittal axis of the thorax and the sagittal axis of the pelvis, around a floating frontal axis. As the thorax frontal axis points downward while the pelvis frontal axis points upward, a positive angle therefore refers to rotation of the thorax toward the opposite side.
Shoulder flexion/extension	Relative	Shoulder flexion is calculated about an axis parallel to the thorax transverse axis. Shoulder flexion is the angle between the projected sagittal-humerus axis and the sagittal-thorax axis around the fixed transverse axis. of the thorax. A positive (flexion) angle value corresponds to the situation in which the arm is in front of the body.
Shoulder ab/adduction	Relative	The angle is calculated between the transverse axis of the humerus and the transverse axis of the thorax around a floating sagittal axis. A negative number corresponds to an abducted (outwardly moved) arm.
Shoulder rotation	Relative	Shoulder rotation is measured about the long axis of the humerus segment and is calculated between the sagittal axis of the humerus and the sagittal axis of the thorax around a floating frontal axis. The sign is such that a positive shoulder rotation corresponds to an internally rotated humerus.
Elbow flexion/extension	Relative	Elbow flexion is the only kinematic parameter calculated at the elbow as the segment definitions of the Humerus and radius result in two of the axes being shared. Elbow flexion is calculated between the sagittal radius axis and the sagittal humerus axis around the fixed transverse axis of the humerus. A positive number indicates a flexion angle.
Wrist flexion/extension	Relative	Wrist flexion is the angle between the sagittal hand axis and the sagittal radius axis around the fixed transverse axis of the radius. A positive (flexion) angle value corresponds to the situation in which the wrist bends toward the palm.
Wrist ab/adduction	Relative	The angle is calculated between the transverse axis of the hand and the transverse axis of the radius around a floating sagittal axis. A positive number corresponds to the hand abducting toward the thumb.

## Plug-in Gait output angles

Angle rotation	Goniometric	Description
Wrist rotation	Relative	Wrist rotation is measured about the long axis of the hand segment and is calculated between the sagittal axis of the hand and the sagittal axis of the radius around a floating frontal axis. The sign is such that a positive wrist rotation corresponds to the hand rotating in the direction of the thumb.

For more information, see also:

- [Complete pelvis position description, page 93](#)
- [Complete hip position description, page 93](#)
- [Complete knee position description, page 94](#)

### Complete pelvis position description

A pelvis in which the three markers all lay in the horizontal plane and the line joining the ASIS markers was parallel to a laboratory axis, would have zero tilt, obliquity and rotation.

To visualize the pelvic angles, start with a pelvis in this neutral position, tilt it about the transverse axis by the amount of pelvic tilt, rotate it about its (tilted) sagittal axis by the amount of pelvic obliquity and rotate it about its (tilted and oblique) frontal axis by the amount of pelvic rotation. The pelvis is now in the attitude described by those degrees of tilt, obliquity and rotation.

The transverse and frontal plane kinematics of all joints are influenced by the mathematics involved with embedded axes. The following is an example which demonstrates the effect of using embedded axes to calculate "pelvic obliquity" in a static trial: If a calibration device, designed with 15 degrees of pelvic tilt and level ASIS markers, is statically rotated 20 degrees from a lab's axis of progression, a report generated by Plug-in Gait will show 10 degrees of pelvic obliquity. For more clarification about the effect of embedded axes on joint kinematics, refer to Kadaba, Ramakrishnan and Wooten (1990).

### Complete hip position description

A thigh whose long axis was parallel to the frontal pelvic axis, and in which the knee flexion axis was parallel to the pelvic transverse axis, would be in the neutral position (described by zeroes in all three angles). To move from this neutral position to the actual thigh position described by the three angles, first flex the

## Plug-in Gait output angles

hip by the amount of the hip flexion, then adduct by the amount of hip adduction, then rotate the thigh about the (flexed and adducted) long axis of the thigh, and it is in the position described by those three angles.

### Complete knee position description

A neutral shank is positioned such that the shank is in line with the thigh and the ankle flexion axis is parallel to the knee flexion axis. From this position, flex the knee by the amount of knee flexion, bend inward by the amount of valgus/varus, and rotate by the amount of knee rotation, to produce the actual position described by those three angles.

## Plug-in Gait output angles

### Upper body angles as output from Plug-in Gait

The following tables display the upper body segment angles from Plug-in Gait.

All upper body angles are calculated in rotation order YXZ.

As Euler angles are calculated, each rotation causes the axis for the subsequent rotation to be shifted. X' indicates an axis which has been acted upon and shifted by one previous rotation, X'' indicates a rotation axis which has been acted upon and shifted by two previous rotations.

## Plug-in Gait output angles

### Left upper body angles

Angles		Positive rotation	Axis	Direction
LHeadAngles	1	Backward Tilt	Prg.Fm. Y	Clockwise
	2	Right Tilt	Prg.Fm. X'	Anti-clockwise
	3	Right Rotation	Prg.Fm. Z''	Clockwise
LThoraxAngles	1	Forward Tilt	Prg.Fm. Y	Clockwise
	2	Right Tilt	Prg.Fm. X'	Anti-clockwise
	3	Right Rotation	Prg.Fm. Z''	Clockwise
LNeckAngles	1	Forward Tilt	Thorax Y	Clockwise
	2	Left Tilt	Thorax X'	Clockwise
	3	Left Rotation	Thorax Z''	Clockwise
LSpineAngles	1	Forward Thorax Tilt	Pelvis Y	Anti-Clockwise
	2	Left Thorax Tilt	Pelvis X'	Clockwise
	3	Left Thorax Rotation	Pelvis Z''	Anti-Clockwise
LShoulderAngles	1	Flexion	Thorax Y	Anti-clockwise
	2	Abduction	Thorax X'	Anti-clockwise
	3	Internal Rotation	Thorax Z''	Anti-clockwise
LElbowAngles	1	Flexion	Humeral Y	Anti-clockwise
	2	-	Humeral X'	-
	3	-	Humeral Z''	-
LWristAngles	1	Ulnar Deviation	Radius X	Clockwise
	2	Extension	Radius Y'	Clockwise
	3	Internal Rotation	Radius Z''	Clockwise



## Plug-in Gait output angles

### Right upper body angles

Angles		Positive rotation	Axis	Direction
RHeadAngles	1	Backward Tilt	Prg.Fm. Y	Clockwise
	2	Left Tilt	Prg.Fm. X'	Clockwise
	3	Left Rotation	Prg.Fm. Z''	Anti-clockwise
RThoraxAngles	1	Forward Tilt	Prg.Fm. Y	Clockwise
	2	Left Tilt	Prg.Fm. X'	Clockwise
	3	Left Rotation	Prg.Fm. Z''	Anti-clockwise
RNeckAngles	1	Forward Tilt	Thorax Y	Clockwise
	2	Right Tilt	Thorax X'	Anti-clockwise
	3	Right Rotation	Thorax Z''	Anti-clockwise
RSpineAngles	1	Forward Thorax Tilt	Pelvis Y	Anti-Clockwise
	2	Right Thorax Tilt	Pelvis X'	Anti-clockwise
	3	Right Thorax Rotation	Pelvis Z''	Clockwise
RShoulderAngles	1	Flexion	Thorax Y	Anti-clockwise
	2	Abduction	Thorax X'	Clockwise
	3	Internal Rotation	Thorax Z''	Clockwise
RElbowAngles	1	Flexion	Humeral Y	Clockwise
	2	-	Humeral X'	-
	3	-	Humeral Z''	-
RWristAngles	1	Ulnar Deviation	Radius X	Anti-clockwise
	2	Extension	Radius Y'	Clockwise
	3	Internal Rotation	Radius Z''	Anti-clockwise

## Plug-in Gait output angles

### Lower body angles as output from Plug-in Gait

The following tables display the lower body segment angles from Plug-in Gait.

All lower body angles are calculated in rotation order YXZ except for ankle angles, which are calculated in order YZX.

As Euler angles are calculated, each rotation causes the axis for the subsequent rotation to be shifted.  $X'$  indicates an axis which has been acted upon and shifted by one previous rotation,  $X''$  indicates a rotation axis which has been acted upon and shifted by two previous rotations.

## Plug-in Gait output angles

### Left lower body angles

Angles	Positive rotation	Axis	Direction
LPelvisAngles	1 Anterior Tilt	Prg.Fm. Y	Anti-clockwise
	2 Upward Obliquity	Prg.Fm. X'	Anti-clockwise
	3 Internal Rotation	Prg.Fm. Z''	Clockwise
LFootProgressAngles	1 -	Prg.Fm. Y	-
	2 -	Prg.Fm. X'	-
	3 Internal Rotation	Prg.Fm. Z''	Clockwise
LHipAngles	1 Flexion	Pelvis Y	Clockwise
	2 Adduction	Pelvis X'	Clockwise
	3 Internal Rotation	Pelvis Z''	Clockwise
LKneeAngles	1 Flexion	Thigh Y	Anti-clockwise
	2 Varus/Adduction	Thigh X'	Clockwise
	3 Internal Rotation	Thigh Z''	Clockwise
LAnkleAngles	1 Dorsiflexion	Tibia Y	Clockwise
	2 Inversion/ Adduction	Tibia X''	Clockwise
	3 Internal Rotation	Tibia Z'	Clockwise

## Plug-in Gait output angles

### Right lower body angles

Angles		Positive rotation	Axis	Direction
RPelvisAngles	1	Anterior Tilt	Prg.Fm. Y	Anti-clockwise
	2	Upward Obliquity	Prg.Fm. X'	Clockwise
	3	Internal Rotation	Prg.Fm. Z''	Anti-clockwise
RFootProgressAngles	1	-	Prg.Fm. Y	-
	2	-	Prg.Fm. X'	-
	3	Internal Rotation	Prg.Fm. Z''	Anti-clockwise
RHipAngles	1	Flexion	Pelvis Y	Clockwise
	2	Adduction	Pelvis X'	Anti-clockwise
	3	Internal Rotation	Pelvis Z''	Anti-clockwise
RKneeAngles	1	Flexion	Thigh Y	Anti-clockwise
	2	Varus/Adduction	Thigh X'	Anti-clockwise
	3	Internal Rotation	Thigh Z''	Anti-clockwise
RAnkleAngles	1	Dorsiflexion	Tibia Y	Clockwise
	2	Inversion/ Adduction	Tibia X''	Anti-clockwise
	3	Internal Rotation	Tibia Z'	Anti-clockwise

## Plug-in Gait output specification

The following topics provide definitions to enable you to reliably reconstruct the segment co-ordinate systems using Plug-in Gait outputs in third-party modeling software.

- [Global \(laboratory\) co-ordinate system, page 102](#)
- [Pelvis, page 103](#)
- [Femur, page 104](#)
- [Tibia, page 105](#)
- [Foot, page 106](#)
- [Joint kinematic definitions, page 107](#)
- [Joint kinetics, page 109](#)

The Plug-in Gait model consists of seven segments (including the left and right side):

- Pelvis
- Femur (left and right)
- Tibia (left and right)
- Feet (left and right)

When **Plug-in Gait Static** calculations are performed, a scaling length for each of the 7 segments is written to the subject's *.mp* file.

The **Plug-in Gait Dynamic** process outputs joint kinematics and kinetics to a *.c3d* file, which also defines them in terms of their order and sign conventions.

For information about the definition of the Plug-in Gait model itself and the algorithms used to locate the segment co-ordinate systems and calculate the segment lengths from skin fixed marker data, see [Plug-in Gait kinematic and kinetic calculations, page 46](#).

The marker names used here are from the standard Plug-in Gait marker definitions. For precise definitions of their location, see [Plug-in Gait models and templates, page 5](#).

## Plug-in Gait output specification

### Global (laboratory) co-ordinate system

The laboratory co-ordinate system is required here as a reference for the pelvis kinematics. The lab system is also used later in the definition of the foot co-ordinate frame.

The global Z axis defines the vertical, i.e. perpendicular to the lab floor.

The global X and Y axes are in the plane of the lab floor, with X often defining the direction of normal walking along the laboratory walkway.

## Plug-in Gait output specification

### Pelvis

The origin of the pelvis co-ordinate system in Plug-In Gait is the midpoint of the vector connecting the two asis landmarks (LASI and RASI). The co-ordinate system of the pelvis is reconstructed from the surface markers on the ASIS and PSIS landmarks, but should be considered to be related to the bony geometry of the pelvis as follows.

The Y axis is lateral (to the left) and is directed from the right hip joint center (RHJC) to the left hip joint center (LHJC), where the HJC are defined as the center of the spherical part of the femoral head:

$$\bar{Y}_{PELVIS} = \frac{\overline{LHJC} - \overline{RHJC}}{|\overline{LHJC} - \overline{RHJC}|}$$

The Z axis is then perpendicular to Y and the vector between the sacrum (SACR) and the midpoint of the asis landmarks:

$$\bar{Z}_{PELVIS} = \frac{\overline{MASI} - \overline{SACR}}{|\overline{MASI} - \overline{SACR}|} \wedge \bar{Y}_{PELVIS}$$

where:

$$\overline{MASI} = \frac{\overline{LASI} + \overline{RASI}}{2}$$

(The sacral marker is not always used, and this landmark can be calculated as being at the midpoint of the vector connecting the LPSI and RPSI markers).

The X axis is naturally the cross product of the Y and Z pelvis axes:

$$\bar{X}_{PELVIS} = \bar{Y}_{PELVIS} \wedge \bar{Z}_{PELVIS}$$

In the Plug-in Gait model, the pelvis Y axis is assumed to be parallel to the vector between the LASI and RASI markers, but the definition above is more suitable when constructing a co-ordinate system from known hip joint centers.

The length of the pelvis segment calculated by the Plug-in Gait model is equal to the inter-hip distance:

$$\bar{L}_{PELVIS} = |\overline{LHJC} - \overline{RHJC}|$$

Plug-in Gait also outputs the inter-asis distance, which can also be used to assist in reconstruction of the morphology of the pelvis.

## Plug-in Gait output specification

### Femur

The accuracy/validity of the femoral coordinate system is affected by the estimation of the knee joint center location as well as the knee flexion extension axis. These two estimations are reliant upon your providing accurate marker placement and subject measurements.

The co-ordinate axes are aligned with the long axis of the femurs and the knee flexion axes as follows.

The Z axis of the femur is directed from the knee joint center to the hip joint center:

$$\bar{Z}_{\text{FEMUR}} = \frac{\overline{\text{HJC}} - \overline{\text{KJC}}}{|\overline{\text{HJC}} - \overline{\text{KJC}}|}$$

The X axis is anterior and is perpendicular to the knee flexion axis,  $\bar{K}_F$  :

$$\bar{X}_{\text{FEMUR}} = \bar{K}_F \wedge \bar{Z}_{\text{FEMUR}}$$

Finally, the Y axis is lateral (to the left for both legs) and is given by:

$$\bar{Y}_{\text{FEMUR}} = \bar{Z}_{\text{FEMUR}} \wedge \bar{X}_{\text{FEMUR}}$$

The scaling length of the femur is simply the distance from the knee joint center to the hip joint center:

$$\bar{L}_{\text{FEMUR}} = |\overline{\text{HJC}} - \overline{\text{KJC}}|$$



## Plug-in Gait output specification

### Tibia

The Tibia effectively has two co-ordinate systems: a proximal one for calculating knee joint angles and a distal one for calculating ankle joint angles.

Both segments have their origins at the ankle joint center (AJC) and are defined in a manner similar to the femoral segments. Again, the location of the ankle joint center and ankle flexion axis calculated by Plug-in Gait are reliant upon your providing accurate marker placement and subject measurements.

Firstly, the proximal system uses the knee joint center, ankle joint center and the

knee flexion axis,  $\bar{K}_F$  :

$$\bar{Z}_{TIBIA} = \frac{\bar{K}JC - \bar{A}JC}{|\bar{K}JC - \bar{A}JC|}$$

$$\bar{X}_{TIBIA,P} = \bar{K}_F \wedge \bar{Z}_{TIBIA}$$

$$\bar{Y}_{TIBIA,P} = \bar{Z}_{TIBIA} \wedge \bar{X}_{TIBIA,P}$$

The distal coordinate system is then rotated about the long axis of the tibia (Z)

such that it is aligned with the ankle flexion axis,  $\bar{A}_F$  :

$$\bar{X}_{TIBIA,D} = \bar{A}_F \wedge \bar{Z}_{TIBIA}$$

$$\bar{Y}_{TIBIA,D} = \bar{Z}_{TIBIA} \wedge \bar{X}_{TIBIA,D}$$

The scaling length of the tibia is the distance from the ankle joint center to the knee joint center:

$$\bar{L}_{TIBIA} = |\bar{K}JC - \bar{A}JC|$$

## Plug-in Gait output specification

### Foot

The origin of the foot segments of the Plug-in Gait model is located at the ankle joint centers. The foot co-ordinate system is defined in a rather more complex manner within the Plug-in Gait model than is necessary to recreate the motion of the bones from the Plug-in Gait kinematics output.

Firstly, the system Z axis is equal to the vector from the toe to heel markers (HEE and TOE), projected into the plane of the laboratory floor (X-Y plane):

$$\bar{Z}_{\text{FOOT}} = (\bar{Z}_{\text{GLOBAL}} \wedge \bar{V}_{\text{FOOT}}) \wedge \bar{Z}_{\text{GLOBAL}}$$

Where:

$$\bar{V}_{\text{FOOT}} = \frac{\overline{\text{HEE}} - \overline{\text{TOE}}}{|\overline{\text{HEE}} - \overline{\text{TOE}}|}$$

The X axis is then perpendicular to this and the ankle flexion axis and is directed vertically:

$$\bar{X}_{\text{FOOT}} = \bar{A}_F \wedge \bar{Z}_{\text{FOOT}}$$

And finally, the Y axis is naturally the cross product of these two axes:

$$\bar{Y}_{\text{FOOT}} = \bar{Z}_{\text{FOOT}} \wedge \bar{X}_{\text{FOOT}}$$

The scaling length of the foot is the distance from the ankle joint center to the toe marker:

$$\bar{L}_{\text{FOOT}} = |\overline{\text{TOE}} - \bar{A}_{\text{JC}}|$$

## Plug-in Gait output specification

### Joint kinematic definitions

The following table specifies how the rotations within each of the joints of the model are ordered as trajectories in the *.c3d* file.

**Note**

Angles are always given in the *.c3d* file as degrees.

For all of the joints, the joint co-ordinate system method of reporting kinematics has been used to specify flexion, abduction, and rotation. It is difficult to give a consistent definition of these angles for all of the joints due to the differing meaning of flexion etc.

Instead, the axis in the proximal segment embedded co-ordinate system about which each of the rotations takes place (together with the order these rotations should be applied) is given in the following table showing Euler angle specification.

## Plug-in Gait output specification

Joint	1st Component	2nd Component	3rd Component	Order
Global → Pelvis	Tilt (Y)	Obliquity (X)	Rotation (-Z)	1,2,3
Left Hip	Flexion (-Y)	Adduction (-X)	Rotation (-Z)	1,2,3
Left Knee	Flexion (Y)	Adduction (-X)	Rotation (-Z)	1,2,3
Left Ankle	Flexion (-Y) <sup>1</sup>	Inversion (Z)	Rotation (X)	1,3,2
Right Hip	Flexion (-Y)	Adduction (X)	Rotation (Z)	1,2,3
Right Knee	Flexion (Y)	Adduction (X)	Rotation (Z)	1,2,3
Right Ankle	Flexion (-Y) <sup>1</sup>	Inversion (-Z)	Rotation (-X)	1,3,2

1. The feet segments are peculiar to the rest of the model, not only because of the different rotation order, but also because the orientation of the foot at zero degrees flexion is straight upwards, that is, the toe will point towards the knee. An offset of +90 degrees should be applied in order to point the foot forwards.

## Plug-in Gait output specification

### Joint kinetics

The output from Plug-in Gait also contains forces, moments and powers for each of the segments.

**i** Note

Nexus displays the Plug-in Gait units as:

- Forces - N/kg
- Moments - N.mm/kg
- Power - W/kg

Plug-in Gait outputs generated by Nexus are normalized to the subject's body mass, and their values are stored in the `.c3d` file as such. Therefore, the units in the `.c3d` file metadata should be divided by kg for these outputs (i.e. N/kg, N.mm/kg, W/kg).

For both forces and moments, the reaction frame can be specified within Plug-in Gait to be proximal, distal, or in the global frame.

For each of the forces, the components in the `.c3d` file match the co-ordinate directions described in this document. For the moments, however, the order they are stored in the `.c3d` file matches the rotation order shown in the table in [Joint kinematic definitions, page 107](#), and therefore do not correspond to any of the segment embedded co-ordinate systems.

## Plug-in Gait output specification

The following table lists the components of the moments in terms of the axes about which they act.

Joint	1st Component	2nd Component	3rd Component
Left hip	-Y	X	Z
Left knee	Y	X	Z
Left ankle (prox.) <sup>1</sup>	Y	X	Z
Left ankle (dist.) <sup>1</sup>	Y	Z	-X
Right hip	-Y	-X	-Z
Right knee	Y	-X	-Z
Right ankle (prox.) <sup>1</sup>	Y	-X	-Z
Right ankle (dist.) <sup>1</sup>	Y	-Z	X

1. Due to the differing alignment of the foot and tibia segment co-ordinate systems, the components of the ankle moment differ depending on whether they are represented in the proximal, distal or global co-ordinate systems.

## References

Dempster, WT. (1955) *Space requirements of the seated operator*. WADC Technical Report 55-159, Wright-Patterson Air Force Base, OH.