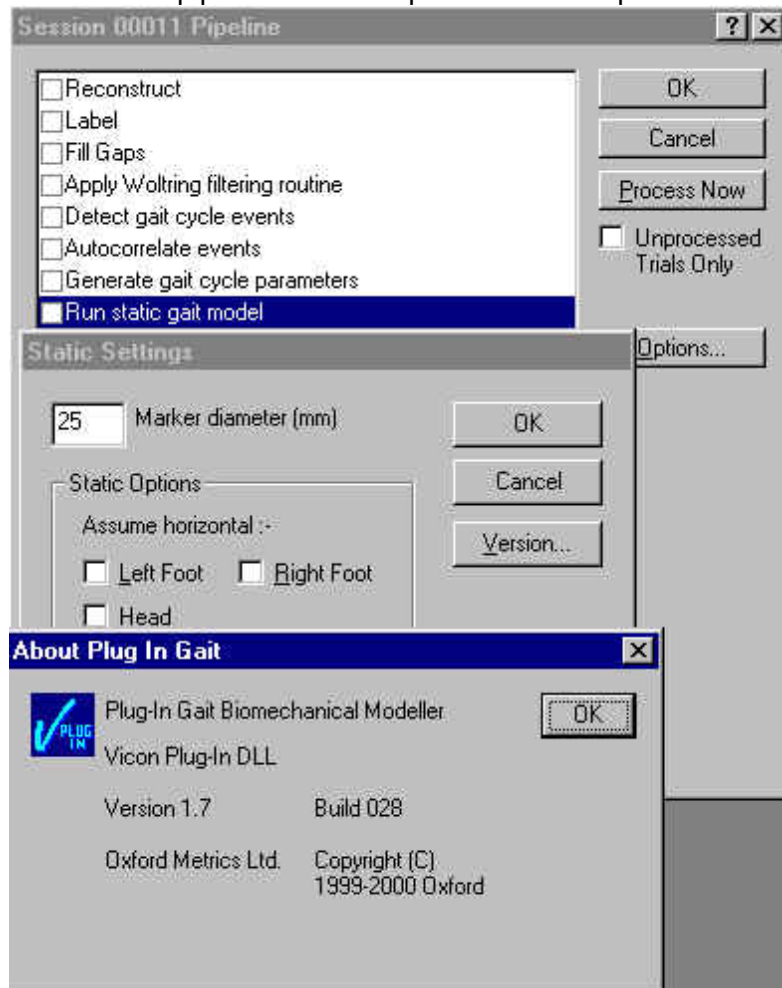# Plug-In Gait

How to use Plug In Gait

How to Use Plug In Gait
This chapter will guide you through the steps required to process your data using the Plug in Gait package. These guidelines should be used with Plug in Gait version 1.7 onwards.

To check which version you are running, highlight either the static model or the dynamic model in the pipeline. Select options and then press the version tab.

Plug in Gait is the next generation of the Vicon Clinical Manager software package. It employs the same model as referenced in Vicon Clinical Manager with some additional features. One such feature is the addition of an upper body model. With the addition of the upper body model, there is now the option to process lower body, upper body, or full body data. This guide will teach you how to process each model. All model processing occurs in Workstation, thereby allowing a smooth pipeline into Polygon, Vicon's multimedia reporting tool.

The Plug in Gait Checklist

This checklist is provided to give the user a step by step guideline on how to process data using the Plug in Gait software package.

This guideline will not cover marker placement. This topic will be covered in another section.

In order to properly process the model, a static and dynamic trial are required. The static trial **MUST** have a heel marker. Plug In Gait allows you the option to keep the heel marker in a dynamic trial in order to treat the foot as a segment. The model is designed to automatically detect the presence of this marker and make its calculations appropriately. The model will also automatically detect the presence of a Knee Alignment Device (KAD) provided that the markers are labeled properly. With these details out of the way, lets begin.

1.   In Workstation, open the static c3d file. If one is not already created, open the tvd file, reconstruct and label.
2.   Next go to the subject measurements window located under the "Trial" pull down menu. (Trial|Subject Measurements).
3.   You can see from this view that there are some fields that have yellow hue. These fields are the mandatory fields and need to be filled in on order for the model to run.
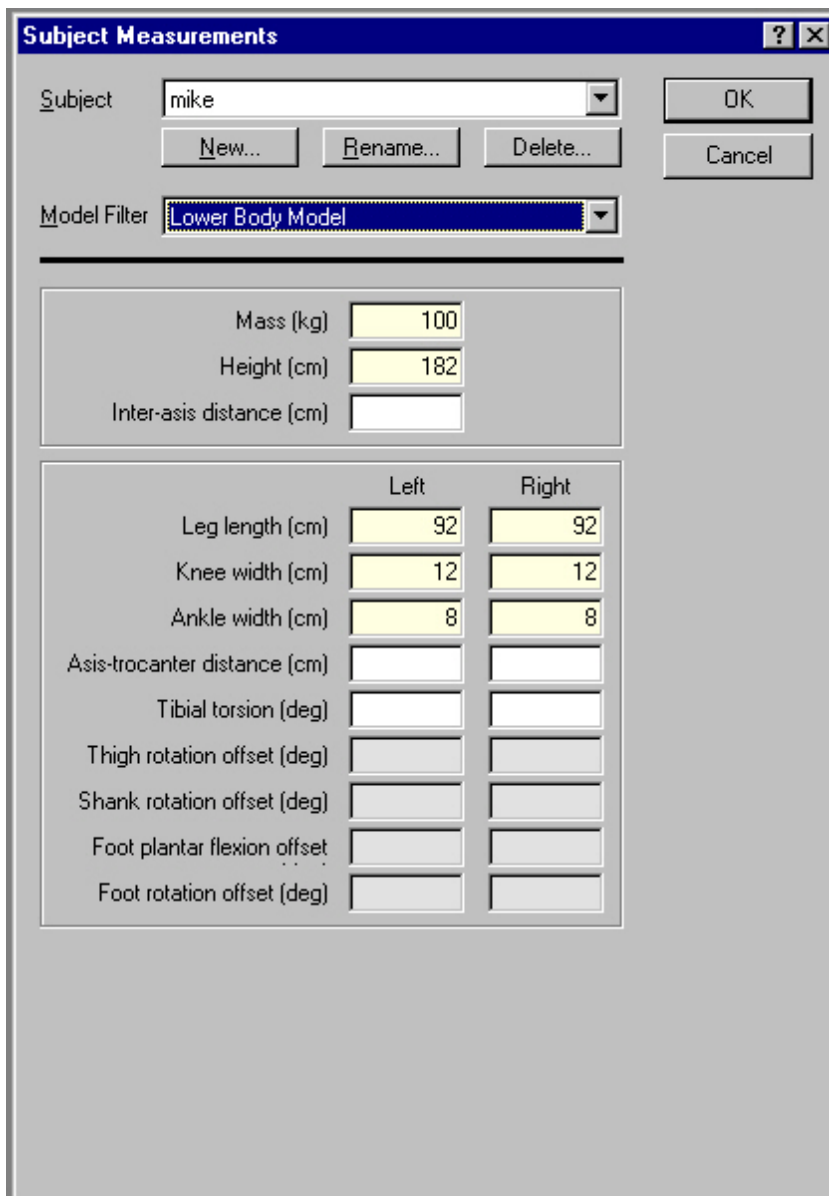
Inter-Asis distance, Asis-trochanter distance, and Tibial Torsion are all optional parameters. The rest of the parameters will be calculated by the model.

4.   Open the pipeline and click the box for "Run Static Gait Model" selection.
5.   While the selection is highlighted, select the options tab and check "Assume Horizontal," if appropriate.
6.   Once this is done, select process now in the pipeline. You should see some blinking as the model performs it calculations. The first indicator that you model has run successfully will be the appearance of "pants" on your subject (if you are using the Plug In Gait.mkr set).
7.   The second indicator that you model has run successfully will be the presence of calculations located in the subject measurements box. If you are not using a KAD, you should expect to see zeroes for thigh rotation offset and shank rotation offset. The model assumes that you have placed the thigh and shank markers in the correct plane and should therefore be zero.
8.   Save and close the trial.
9.   Open (or process as above) your dynamic trial.
10.   Open pipeline and select these options, Fill gaps, Woltring filter, Detect etc ?????
11.   Also highlight and check "Run Dynamic Gait Model." Ensure that the "Run Static Gait Model" box is unchecked.
12.   Now click on the process now button.
13.   You should now see some "pants" appear on the subject of your dynamic trial.
14.   At this point, visually verify that the events determined using the automated detection routines are correct.
15.   Manually change or enter the events if the autodetection is incorrect.
16.   Save the trial
17.   Start Polygon report and import data.

<u>Subjects and Subject Measurements</u>

When processing the model, certain measurements are required. These measurements are a combination of entered and calculated values. In order to associate these values with collected data, it is necessary to create a subject. If you have used the autolabel feature in Workstation, then there will already be a subject ready for you to use. You can verify this by resting your mouse pointer on a marker. You notice that a bubble appears with the dialog "marker name : subject name," i.e. Lasi:Michael.

First, let's begin by opening a static trial. If you do not have a static trial that has already been processed, then you must reconstruct and autolabel. Next, open the <u>subject measurements window</u> under the trial menu.
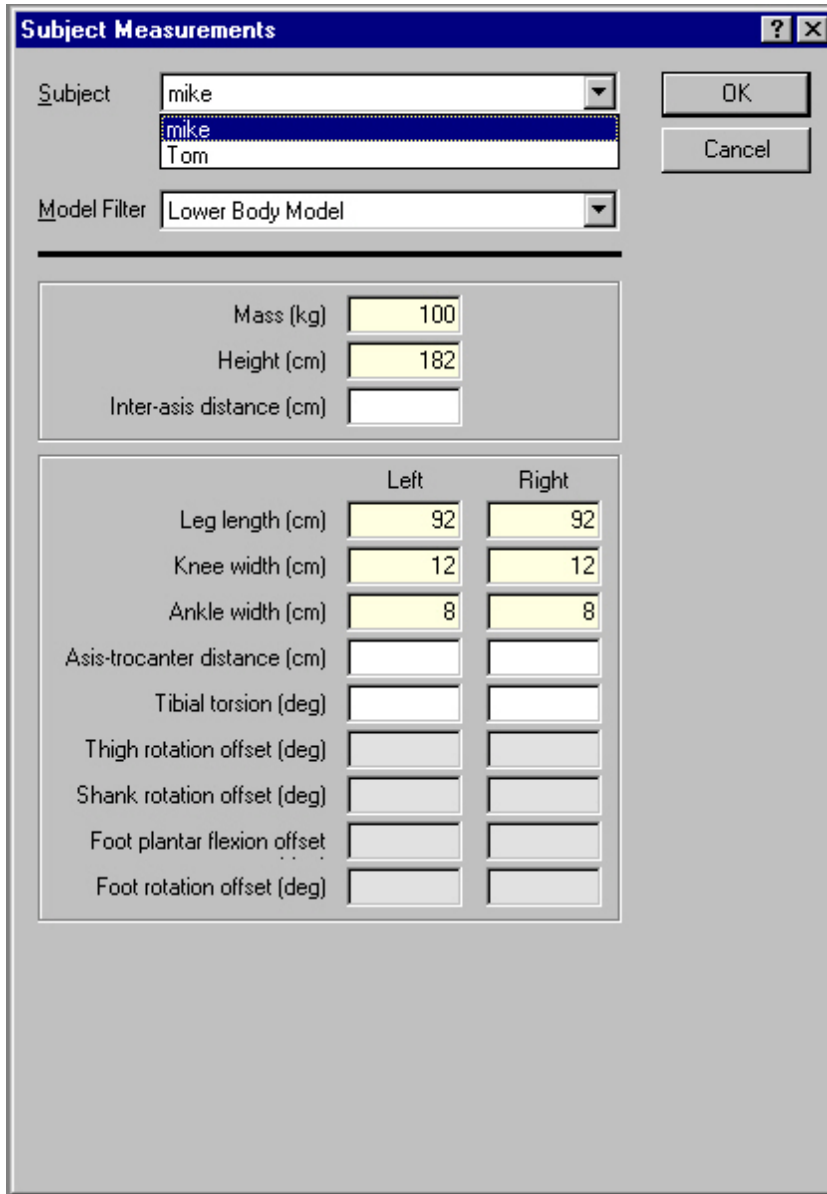
Subject Measurements			? X

Subject	mike	▼	OK
	New...	Rename...	Delete...	Cancel

Model Filter	Lower Body Model	▼

Mass (kg)	100
Height (cm)	182
Inter-asis distance (cm)	

	Left	Right
Leg length (cm)	92	92
Knee width (cm)	12	12
Ankle width (cm)	8	8
Asis-trocanter distance (cm)		
Tibial torsion (deg)		
Thigh rotation offset (deg)		
Shank rotation offset (deg)		
Foot plantar flexion offset		
Foot rotation offset (deg)		

You can have multiple subjects in a session and if that is the case, then you need to process the model for each subject using their subject measurements. You can specify which subject measurements should be used by selecting the correct subject from the subject pulldown menu.

The next part of the subject measurements window is the model filter. This is where you can select which model you would to process. You will notice that when you select each respective model, the measurements that are required and displayed change.

Subject Measurements dialog box

Subject: mike

| New... | Rename... | Delete... |

OK | Cancel

Model Filter: All models
- Lower Body Model
- Upper Body Model
- All models

Mass (kg): 100
Height (cm): 182
Inter-asis distance (cm):
Head angle (deg):

	Left	Right
Leg length (cm)	92	92
Knee width (cm)	12	12
Ankle width (cm)	8	8
Asis-trocanter distance (cm)		
Tibial torsion (deg)		
Thigh rotation offset (deg)		
Shank rotation offset (deg)		
Foot plantar flexion offset		
Foot rotation offset (deg)		
Shoulder offset (cm)	4	4
Elbow width (cm)	4	4
Wrist width (cm)	3	3
Hand thickness (cm)	2	2

or the purposes of this tutorial, we will use the model filter, U.all models The measurements that are required are mass, height, leg length, knee width, ankle width, shoulder offset, elbow width, wrist width, and hand thickness. Please note that these measurements should all be entered in kilograms and centimeters.

The measurements for Inter-ASIS distance, ASIS-trochanter distance, and tibial torsion are all optional entries. If these measurements are not entered then the model will calculate them. For more information on these measurements, please refer to the Plug in Gait Model report, the Vicon Clinical Manager manual or click here for an abridged version.

Subject Measurements

Mass (required): This is the mass of the subject in kilograms. (1 lb=2.2 kg)

Height (required): This is the height of the subject in centimeters. (1 inch=2.54 cm)

Inter-ASIS distance (optional): If this is not entered the model will calculate this distance based on the position of the LASI and RASI markers (recommended). If you are collecting data on an obese patient and can not properly place the ASIS markers, place those markers laterally and preserve the level of the ASIS. Palpate the LASI and RASI points and manually measure this distance. This measurement should be entered here for this scenario.

Head Angle (Calculated): This is the absolute angle of the head with the global coordinate system.

Leg Length (required): This is the true leg length measurement. It is measured from the ASIS to the medial malleolus. In the case of a patient who can straighten their legs, the measurement should be taken in two pieces??. The leg length will be the sum of the length from the ASIS to the Knee and from the knee to the medial malleolus.

Knee Width (required): This is the measurement of the knee width, about the flexion axis, in centimeters.

Ankle Width (required): This is the measurement of the ankle width, about the medial and lateral malleoli, in centimeters.

ASIS-Trochanter Distance (optional): This is the perpendicular distance from the trochanter to the ASIS point. If this value is not entered, then a regression formula is used to calculate the hip joint centre. This value will be calculated as part of this process. If this value is entered, it will be factored into an equation which represents the hip joint centre. For more details on this, please refer to the paper by Davis, et. al in the reference section. It is recommended that this value not be entered when processing the model.

Tibial Torsion (optional): Tibial torsion is the angle between the ankle flexion axis and the knee flexion axis. The sign convention is that if a negative value of tibial torsion is entered, the ankle flexion axis is rotated externally with respect to the knee flexion axis. If tibial torsion is entered while using a KAD, the ankle flexion/extension axis will be adjusted from the KAD's defined position to a position dictated by the tibial torsion value.

Thigh Rotation Offset (calculated): When a KAD is used, this value is calculated to account for the position of the thigh wand (marker). By using the KAD, placement of the thigh wand in the plane of the hip joint centre and the knee joint centre is not crucial. Please note that if you do not use a KAD, this value will be reported as zero because the model is assuming that the thigh wand has been placed exactly in the plane of the hip joint centre and the knee joint centre.

Shank Rotation Offset (calculated): The shank rotation offset is similar to the thigh rotation offset. This value is calculated if a KAD is present and removes the importance of placing the shank wand in the exact plane of the knee joint centre and the ankle joint centre. As above, if you do not use a KAD, then these values will be zero.

A note about the foot: VCM previously treated the foot as a vector, using only two markers during dynamic trials. Plug in Gait will process the foot as a vector if the heel marker is missing during dynamic trials. If all three markers are present then Plug in Gait will treat the foot as a three dimensional segment and NOT as a vector. The following parameters are used only if the foot is treated as a vector.

Foot Plantar Flexion Offset (calculated):   Calculated as a rotation about the ankle flexion axis. This angle is measured between the line joining the heel and toe markers and the line joining the heel marker and the toe marker. This is one of the rotations performed in establishing the foot vector.

Foot Rotation Offset (calculated): This is a rotation about the foot rotation axis, which is perpendicular to the foot vector (after applying the foot plantar flexion offset) and the ankle flexion axis. This angle is measured between the line joining the heel and the toe markers and the line joining the ankle joint centre and the toe marker. This is the final rotation performed in establishing the orientation of the foot vector.

Shoulder Offset (required): This is the vertical distance from the centre of the glenohumeral joint to the marker on the acromion calivicular joint. Some researchers have used the (anterior/posterior girth)/2 to establish a guideline for the parameter.

Elbow Width (required): This is the distance between the medial and lateral epicondyles of the humerus.

Wrist Width (required): This is the distance between the ulnar and radial styloids.

Hand Thickness (required): This is the distance between the dorsal and palmar surfaces of the hand.

On a normal monitor the required, optional, and calculated fields will all have different colored backgrounds. Some laptops may not display these color differences.

Required fields will have a yellow hue background, optional fields will be white, and fields that are calculated by the model will be gray.

Filtering and Filling Gaps

The data that we intend to process will have imperfections in it that are inherent in all 3-D motion capture data. Considerations such as filling gaps and filtering are extremely important. Vicon Clinical Manager had it's own set of gap filling and filtering routines which were carried out without user intervention. With Plug in Gait, there are some options available because it resides in Workstation. When processing data, all calculations should be performed on continuous (within reason) and smooth data.

The first option is to fill gaps. The fill gaps routine is a cubic spline. Its first step before filling is to defragment all of the trajectories. If you click on the options tab when fill gaps is highlighted, you can manipulate the size of the gaps you wish to fill (as illustrated to the right). What size gap is appropriate to fill can only be determined by the discretion of the researcher. A good guideline to use when trying to decide how big of a gap to fill, is to calculate how much data will be filled with respect to time. For example, data
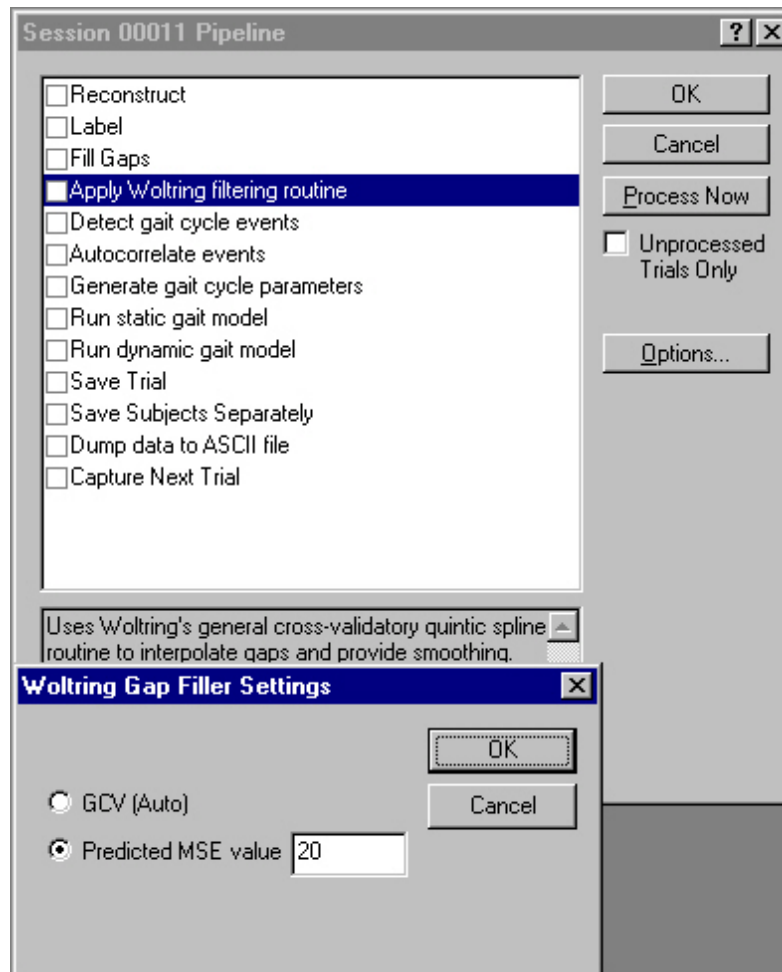
captured at 1200 Hz using the restriction to the right, will fill gaps that are 1/12 of a second or less (10 samples / 120 samples/s).
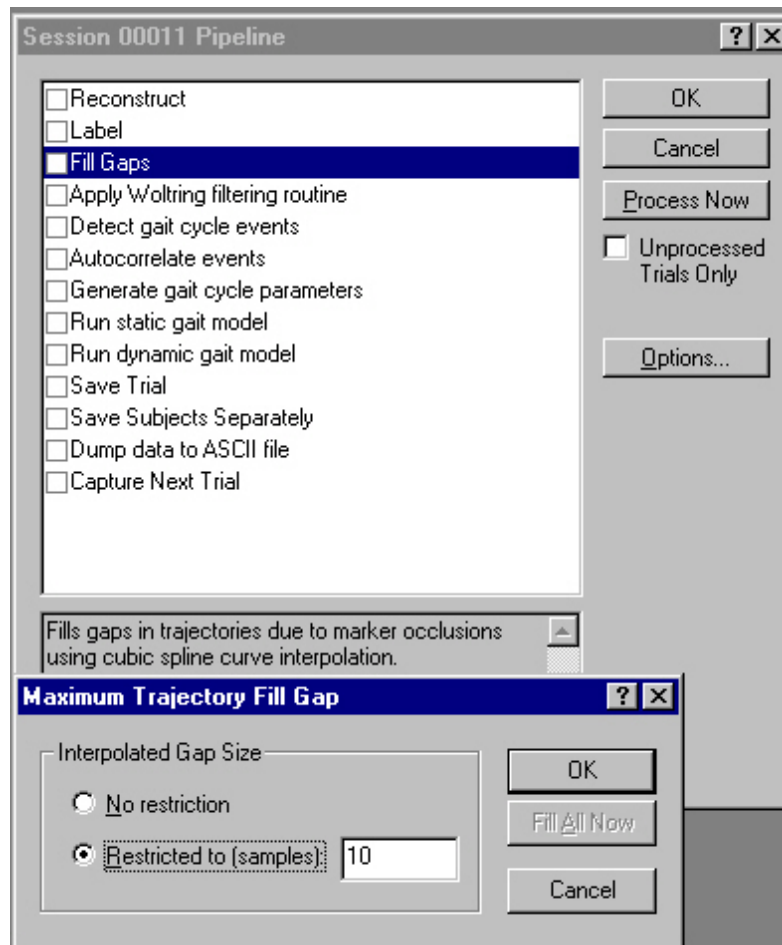
Filtering is an important process. Non filtered data can appear very noisy and perhaps not as meaningful. We provide the Woltring Filter for our users. The Woltring filter is a quintic spline routine. This filter will fill gaps as part of its process but it is recommended that the fill gaps routine (cubic spline) be used because small flares can be interpolated incorrectly.

There are two options available for the Woltring Filter. The General Cross Validation (GCV) and the predicted MSE (Mean Square Error) value. The GCV option will filter your data using cross validation, which basically means that it will filter the data more where it thinks it needs more filtering and filter it less where it doesn't need as much.

The MSE option, will filter the entire data range with a constant value, treating all parts of the data range the same. To closely emulate the type of filtering that was performed in VCM, we recommend filtering at an MSE of 20.

Session 00011 Pipeline

☐ Reconstruct
☐ Label
☐ Fill Gaps
■ Apply Woltring filtering routine
☐ Detect gait cycle events
☐ Autocorrelate events
☐ Generate gait cycle parameters
☐ Run static gait model
☐ Run dynamic gait model
☐ Save Trial
☐ Save Subjects Separately
☐ Dump data to ASCII file
☐ Capture Next Trial

OK
Cancel
Process Now
☐ Unprocessed Trials Only
Options...

Uses Woltring's general cross-validatory quintic spline routine to interpolate gaps and provide smoothing.

Woltring Gap Filler Settings

OK
Cancel

○ GCV (Auto)
● Predicted MSE value 20

Gait Cycle Events and Parameters

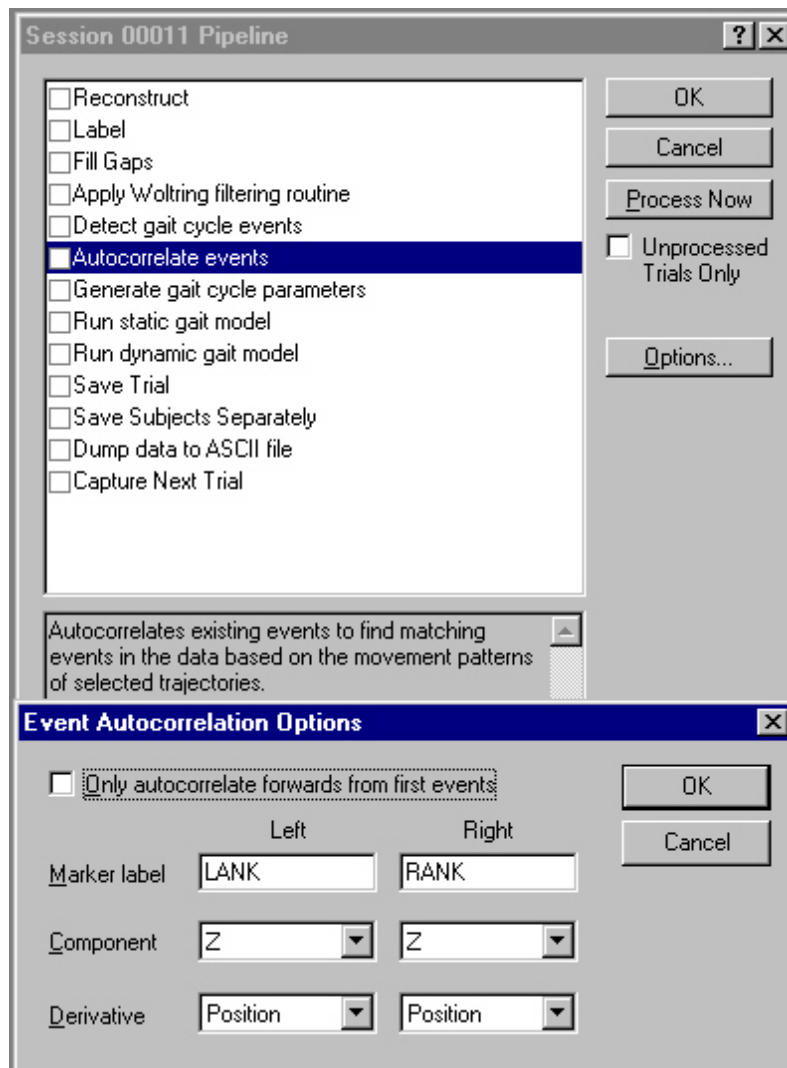Detect gait cycle events is an option that will detect when gait cycle events occur if there is a force plate present. The options for this item in the pipeline generally do not need to be modified.

Session 00011 Pipeline

☐ Reconstruct
☐ Label
☐ Fill Gaps
☐ Apply Woltring filtering routine
■ **Detect gait cycle events**
☐ Autocorrelate events
☐ Generate gait cycle parameters
☐ Run static gait model
☐ Run dynamic gait model
☐ Save Trial
☐ Save Subjects Separately
☐ Dump data to ASCII file
☐ Capture Next Trial

OK
Cancel
Process Now
☐ Unprocessed Trials Only
Options...

Generates foot strike and foot off events based on force plate data, if present. Options allow the foot marker labels to be chosen for correct identification of left and right events and for detecting clean force plate strikes.

Gait Cycle Event Detection Options

Force Plate Detection

Force Threshold (N) [20]

	Left	Right
Posterior marker label	LANK	RANK
Anterior marker label	LTOE	RTOE

OK
Cancel

Autocorrelate events allows you to use pattern recognition to mark gait cycle events that occur before and after a force plate strike

Session 00011 Pipeline

[ ] Reconstruct
[ ] Label
[ ] Fill Gaps
[ ] Apply Woltring filtering routine
[ ] Detect gait cycle events
[■] Autocorrelate events
[ ] Generate gait cycle parameters
[ ] Run static gait model
[ ] Run dynamic gait model
[ ] Save Trial
[ ] Save Subjects Separately
[ ] Dump data to ASCII file
[ ] Capture Next Trial

OK
Cancel
Process Now
[ ] Unprocessed Trials Only
Options...

Autocorrelates existing events to find matching events in the data based on the movement patterns of selected trajectories.

Event Autocorrelation Options

[ ] Only autocorrelate forwards from first events

OK
Cancel

|	Left	Right
Marker label	LANK	RANK
Component	Z	Z
Derivative	Position	Position

Generate gait cycle parameters determine the temporal-spatial parameters of gait. Through the options window you can select the units that you wish to output with the model.
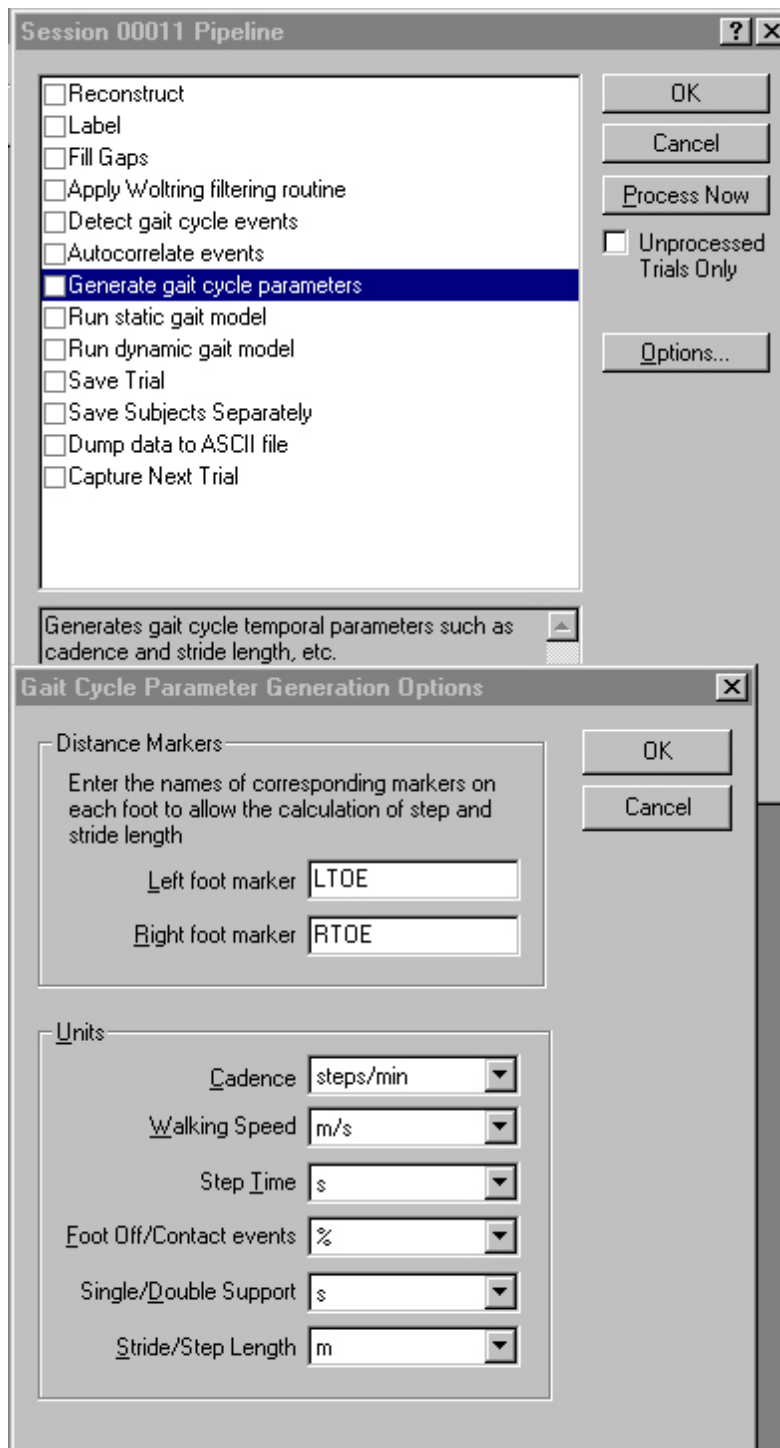
Running the Static Model

Before you run all of your gap filling, filtering, and gait cycle event options, you need to process the static model. With a static trial open, select this option in the pipeline. In the options tab for this phase of the model, you can select your marker diameter and check if the patient is foot flat or in equinus. This step is very critical because if you erroneously process the data, i.e. check assume horizontal when the patient is in

equinus, then you will have bad data. Therefore care must be taken in checking the foot flat options,
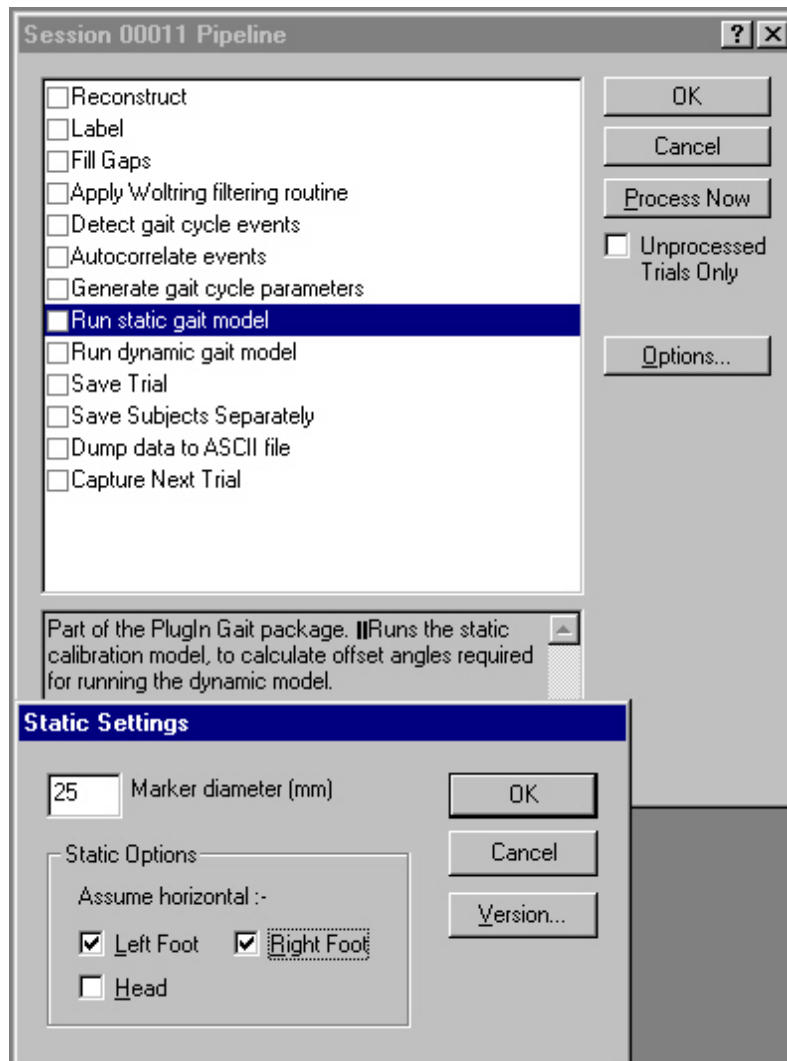

You can verify your model ran, at this point, three ways. The first way is to check the processing log under the view menu. This will tell you exactly what was performed as part of the pipeline.
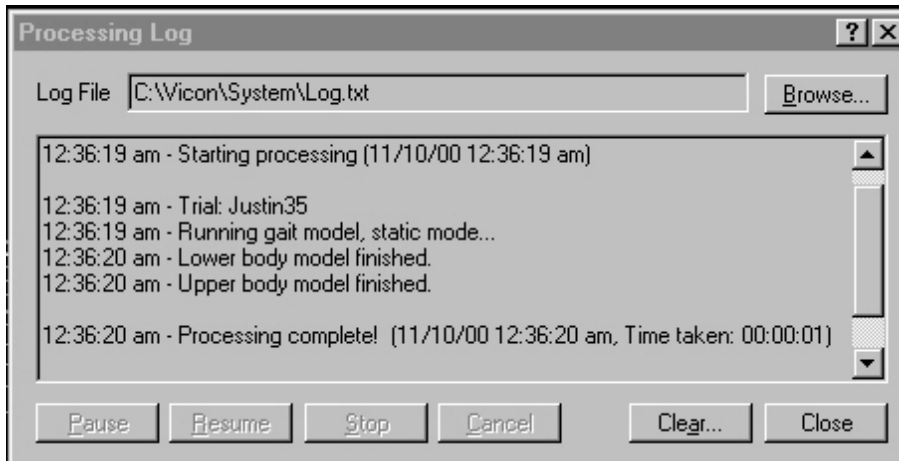
The second method of verification is to check the subject measurements. All of the calculated parameters should now have values. This method of verification only works for the static trial.

The third and easiest method of verification is to observe the subject in the workspace. If the Plug in Gait marker set is used, the subject should now appear to be wearing a pair of pants.
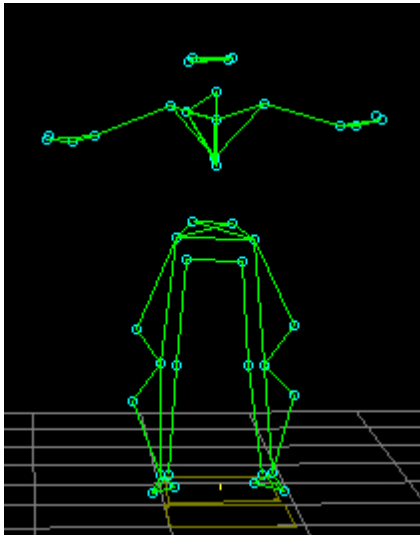

Running the Dynamic Model

Once you have run the static model, you are now ready to run the dynamic model. To save time, you could process the remainder of the dynamic trials with the batch processing feature of the pipeline.

For the purposes of this tutorial, we will concentrate on just one trial. Open the dynamic trial and the pipeline window. At this point, you can select options such as fill gaps, Woltring Filter, detect gait cycle events, autocorrelate events, and generate temporal parameters. The most important feature here is to select run dynamic gait model.U

Generally, you shouldn't need to adjust the options on this window apart from the marker diameter.
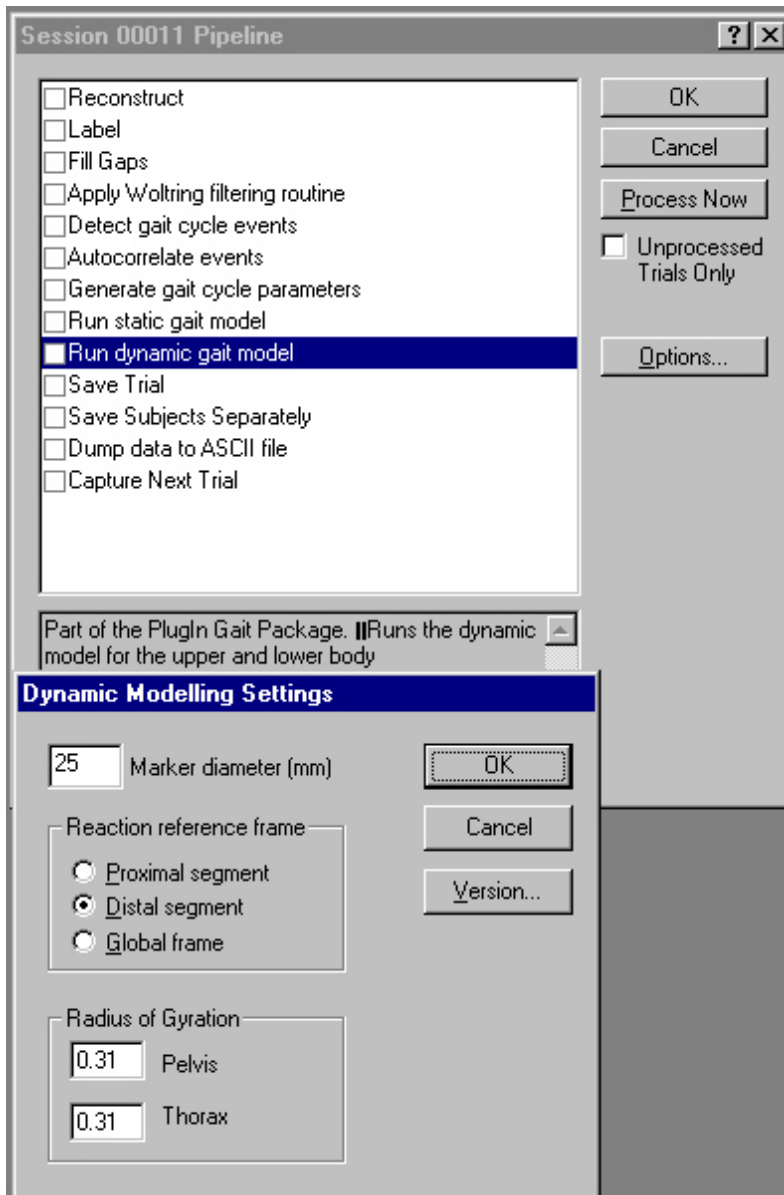
Once you hit process, you should see the Workspace 'flash' for a second and then your patient will appear walking through the space with the "pants" on.

If you see the pants, you next step would be to verify that all of the gait cycle events are correct. If they are not present or some are missing you can use the add events tools at the bottom of the Workstation screen. Once you have visually verified the integrity of the data and you are happy with the gait cycle events, save your c3d file and head to Polygon because your processing is finished!

Detailed Marker Placement and Subject Measurements

This chapter will detail where markers should be placed on a subject so that the model in PIG will work according to its assumptions.

PIG requires certain information for data processing. Before a patient is prepared for analysis, the following measurements need to be recorded. It is recommended that personal information is recorded during the preliminary examination.

Subject Measurements

Physical examination The physical measurements needed to process data in PIG include the following: height, weight, right leg length, left leg length, right knee width, left knee width, right ankle width and left ankle width. These measurements should be recorded using the units specified in your Preference section in the File menu. The measurements for tibial torsion or ASIS-greater trochanter distance may be required depending on the PIG model to be used for data analysis. The inter-ASIS distance may be required if the ASIS markers cannot be placed accurately. Please refer to the Joint Measurement section in this chapter for more details.

Note   Calipers are easier to use than tape measures to measure the knee and ankle widths.

Note   Joint mobility measurements may be recorded for personal records, but are not required for PIG.

Mass
The mass of the subject in kilograms as measured on a weighing scale. The mass is a necessary measurement in determining the kinetics.

Height
The height of the subject from top of the head to the floor with the subject standing flat on both feet. This measurement is not used by the PIG model.

Inter-ASIS distance
ASIS-ASIS distance is the distance between the left ASIS and right ASIS. This measurement is only needed when markers cannot be placed directly on the ASIS, for example, in obese patients.

Leg Length
True leg length is measured between the ASIS and the medial malleolus, via the knee joint. If, for example, the subject is standing in crouch, this measurement is NOT the shortest distance between the ASIS and medial malleoli, but rather the measure of the skeletal leg length.

Knee Width
Knee width is the distance between the lateral and medial femoral epicondyles. Measure this distance with the subject standing if possible. This contradicts what is

written earlier in the manual as follows…..
Knee Width (required): This is the measurement of the knee width, about the flexion axis, in centimeters.

Ankle Width
 Ankle width is the distance across the malleoli. Measure this distance with the subject standing if possible.

ASIS-trochanter distance
This is the vertical distance, in the sagittal plane, between the ASIS and greater trochanter when the subject is lying supine. Measure this distance with the femur rotated such that the greater trochanter is positioned as lateral as possible. When this measurement is entered in subject measurements PIG calls upon the hip joint centre model referenced in Davis, Ounpuu, Tyburski and Gage (1991) to be used during analysis.

Note   If this distance is not entered in the subject's Session Form, PIG calculates the ASIS-greater trochanter distance based upon the following linear regression equation:
distance = (0.1288*leg length) - 48.56
PIG calls upon the hip joint centre model referenced in Davis, Ounpuu, Tyburski and Gage (1991) to be used during analysis.

Tibial torsion
This measure is only necessary when a KAD is used. In this case it is used to adjust the ankle flexion axis for subject's static calibration trial. Tibial torsion, for PIG purposes, is defined as the angle between the bi-malleolar axis and the knee flexion/extension axis.

Note   If a KAD is used, the ankle flexion/extension axis will be assumed to be parallel to the knee flexion/extension axis, unless tibial torsion is used to process the static trial and offset the ankle flexion/extension axis.

The rest of the subject measurements will be calculated by the static Plug In Gait model and do not need to be entered.

If only lower body gait analysis is performed and no upper body markers are captured there is no need to enter any of the upper body subject measurements.

Upper body measurements are:

Shoulder Offset - vertical offset from the base of the acromion marker to shoulder joint centre
Elbow Width - Width of elbow along flexion axis (roughly between the distal epicondyles of the humerus)
Wrist Width - Anterior/ Posterior thickness of wrist at position where wrist marker bar is attached.
Hand Thickness - Anterior/ Posterior thickness between the dorsum and palmar surfaces of the hand.

Placement of Markers

A consistent and accurate method for marker placement and data acquisition is essential to ensure that data can be compared between patients and with normal values. The accurate placement of kinematic markers is essential if accurate results are to be obtained. Marker placement becomes more consistent, and results obtained therefore become more reliable, with experience. The following is a complete list of the markers needed for both static and non-static trials.

Note   The name indicated for each marker (for example; SACR) is the internal variable name which must be used on the left-hand side of the assignment for each marker in the [Autolabel] group in the PlugInGait.mkr file.

Pelvic Markers
LASI (Left Anterior Superior Iliac Spine)
RASI (Right Anterior Superior Iliac Spine)

Both markers should be placed directly over the anterior superior iliac spines. In some patients, especially those who are obese, the markers either can't be placed exactly over (anterior in the frontal plane) 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 recorded and entered in the Subject Measurements. These markers, together with the sacral marker or PSIS markers, define the pelvic axes.

Note   The pelvic markers may need to be placed medially to the ASIS to get the marker to the correct position due to the curvature of the abdomen.

LPSI, RPSI or SACR (Sacral Marker)
LPSI   Left Posterior Superior Iliac Spine
RPSI   Right Posterior Superior Iliac Spine
These are slight bony prominences which can be felt
immediately below the dimples (sacro-iliac joints), at the
point where the spine joins the pelvis.

The SACR marker must be located in one of two alternative positions. If there are sufficient cameras (normally at least six) to permit a clear view of this marker throughout the experiment, it is ideally placed on the skin mid-way between the posterior superior iliac spines (PSIS) described above.
Sometimes, a sacral marker placed on the skin doesn't become visible to at least two cameras (for three-dimensional reconstruction) until mid-way through the experiment, thus causing the first half of the trial data to be lost. To overcome this problem of losing the sacral marker, the standard PIG marker kit contains a base plate and selection of short "sticks" or "wands" to allow the marker to be extended away from the body.

To use the sacral wand, rather than a marker on the skin's surface, place the base-plate over the sacrum and then adjust its location. It may help to visualize this plane from the side, using a ruler or other straight edge, to connect the ASIS and PSIS points and then place the SACR marker on this same line. The SACR marker must therefore be at the same height as the ASIS markers.

Note   The medio-lateral position of the SACR marker doesn't influence the PIG

calculations. Only its position in the pelvis' frontal plane and the ASIS markers are used to calculate pelvic kinematics.

Knee Markers
LKNE (Left Knee Joint)
RKNE (Right Knee Joint)

The analysis used in the VCM program assumes that the flexion, abduction, and rotation axes all pass through a single, imaginary point within the knee. This point is mid way between the points where the flexion axis passes through the skin. The knee markers should be placed on the lateral of these two points.

Passively flex and extend the knee while watching the skin surface on the lateral aspect of the knee joint. Find the point which comes closest to remaining fixed in the thigh, while being 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.

If a KAD is being used for a static trial, it will be placed over the point. If not, a marker is placed there.

Note   If the femoral epicondyles are not used for marker placement, the knee width should be measured between the two points used.

Thigh Markers
LTHI (Left mid-Thigh Stick) – do we need to use the word sticks ? some labs don't
RTHI (Right mid-Thigh Stick)

Ideally, the location and alignment of the knee flexion axis would be tracked in a walking subject by keeping a medial knee marker or some sort of axis alignment device in place. In practice, particularly in pathological gait, this method is unusable because the medial marker or device would be knocked off, or at least impede walking.

Instead, a marker is placed on a short stick/or directly on the skin over the lower lateral 1/3 surface of the thigh, just below the swing of the hand, although the height is not critical. The antero-posterior placement of the marker is critical for correct alignment of the knee flexion axis, when a KAD is not used.

Use a pen to mark the lateral projection of the hip joint. This may lie over the greater trochanter but remember to allow for any fixed rotation of the hip. The PIG marker kit contains a set of four plastic base plates, each with a short rod with a marker on the end. The marker can either be placed directly on the skin or pace a base plate with its long axis along the line joining the knee and hip marks. The marker must be placed so that it is aligned in the plane that contains the hip and knee joint centers and the knee flexion/extension axis.

Ankle Markers
LANK (Left Ankle Joint)
RANK (Right Ankle Joint)

The analysis used in the PIG model assumes that the flexion, abduction, and rotation

axes all pass through a single, imaginary point within the ankle. This point is mid way between the points where the ankle flexion axis passes through the skin. The ankle marker should be placed on the lateral of these two points, the lateral malleolus under most circumstances.

Note   If a KAD is used, but Tibial Torsion is not, the ankle flexion/extension axis is assumed to be parallel to the knee flexion/extension axis. If tibial torsion is present or foot deformity affects the malleoli, the lateral point of the ankle flexion/extension axis may be anterior or posterior to the malleolus.

Shank Markers
LTIB (Left mid-Shank Stick) – stick ???
RTIB (Right mid-Shank Stick)

Ideally, the location and alignment of the ankle flexion axis would be tracked in a walking subject by keeping a medial ankle marker (medial malleolus) or some sort of axis alignment device in place. In practice, particularly in pathological gait, this method is unusable because the medial marker or device would be knocked off, or at least impede walking.

The marker can either be placed directly on the skin or a base-plate and stick-mounted marker is placed over the lower 1/3 of the shank to determine the alignment of the ankle flexion axis. If a KAD is not used, the shank marker should lie in the plane that contains the knee and ankle joint centers and the ankle flexion/extension axis.

Note   In a normal subject the ankle joint axis, between the medial and lateral malleoli, is externally rotated by between 5 and 15 degrees with respect to the knee flexion axis. The placements of the thigh and shank markers should reflect this.

Forefoot Markers
LTOE (Left Toe)
RTOE (Right Toe)

The forefoot markers should be placed on the dorsal surface of the foot, most commonly over the second metatarsal head, on the mid-foot side of the equinus break between fore-foot and mid-foot.

Note   The toe and heel markers should be placed such that a line between the centre of these markers is parallel to the long axis of the foot.

Heel Markers
LHEE (Left Heel)
RHEE (Right Heel)

The Heel marker is in place during static trials and then removed for walking trials in VCM !!!! you can leave it on for PiG . It should be placed on the back of the heel such that the line joining it to the Forefoot marker reflects the long axis of the foot. This is best achieved with the patient standing, while the tester looks down on the foot from above.

If the subject is able to stand with the foot plantargrade (flat on the ground), the height of

the Heel marker is not important, provided that the Assume Horizontal check box in the Workstation 'pipeline' 'Run static gait model' is set before processing the static trial. If, however, the subject is unable to stand with the foot flat on the ground, the Heel marker should be placed at the same height above the plantar surface of the foot as the Forefoot marker and the Assume Horizontal check box should be left unmarked.

Upper Body

LFHD Left front head (Located approximately over the left temple)
RFHD Right front head (Located approximately over the right temple)
LBHD Left back head (Placed on the back of the head, in a horizontal plane of the front head markers)
RBHD Right back head
The markers over the temples define the origin, and the scale of the head. The rear markers define it's orientation. If they cannot be placed level with the front markers, and the head is level in the static trial, tick the "Head Level" check box in the Workstation 'pipeline' 'Run static gait model' before processing the static trial.
Many users buy a head band and permanently attach markers to it.

C7   Spinous process of the 7th cervical vertebrae. This is the most prominent spinal process on the back of the neck. Ask the subject to bend their head forward. Locate the C7 vertebra and then ask the subject to straighten their neck. Place the marker on this point.
CLAV Jugular Notch where the clavicle meets the sternum. The marker should be placed on the bone and not in the jugular notch.
T10   Spinous Process of the 10th thoracic vertebrae. This marker position is located by finding the inferior angle of the scapula. Move horizontally across to the vertebrae. This should be T7. Get the subject to slump forward and count down to T10 by feeling for the bony spines of each vertebra.
STRN Xiphoid process of the Sternum. This marker must be placed on the bone just above the Xiphoid process.
These four markers define a plane with the previous two and hence their lateral positioning is most important. (Add comment re positioning where Xiphoid process is not visible ?? i.e. women ??)

LBAK or RBAK   (Optional) Placed mid scapula, acts as an anti-symmetry marker strictly for autolabel purposes. Only LBAK or RBAK should be used, not both

LSHO Left shoulder marker, placed on the Acromio-clavicular joint. (Shoulder offset is the vertical offset from base the LSHO marker to the centre of the shoulder joint - the model takes care of the marker diameter)
LELB   Left elbow (placed on lateral epicondyle approximating elbow joint axis)

LWRA Left wrist bar thumb side
LWRB Left wrist bar pinkie side
These are placed at the ends of a bar attached symmetrically on the posterior of the wrist, as close to the wrist joint centre as possible.

LFIN   Left "finger". Actually placed on the dorsum of the hand just below the head of

the second metatarsal

Note on Marker Movement

All markers should be placed as accurately as possible. Incorrect placement can introduce errors (for example, 5 mm at the knee = approx. 2 degrees error).

Reflective markers placed over the ASIS, knee, forefoot, ankle and heel and all the upper body markers are attached directly to the skin. In extreme cases, skin may move by as much as 25mm over the skeleton during walking due to its inherent elasticity and the change in shape of muscle bulk under the skin (Macleod and Morris, 1987). This movement is generally the largest source of error in gait analysis measurements.

Markers on the sacrum, and intermediate markers over the femur and tibia may be on wands. This enables them to be seen more easily, and also allows the position of the marker to be adjusted.

The wand bases are firmly fixed to the skin, preferably with some sort of strapping. As long as this is done, the frequency of marker movement caused by wobble is higher than that due to the motion of the patient and can therefore be largely discounted.

Understanding the Plug in Gait Model

This chapter is intended to give a detailed description of the way in which Plug In Gait performs calculations to measure kinematics and kinetics of subjects. The descriptions are intended to give enough detail to allow an understanding of the modelling, such that a better understanding of the marker placement can be gained, and to help in the interpretation of the results.

This document does not describe the internal structure of the program, or the specific algorithms used. It is intended to describe the geometrical relationships between markers, and segments, and to give fixed values applied to the kinetic segments. Others should be able to replicate the same results, given the same inputs.

Introduction

This chapter discusses only the modelling stage of the process as a separate entity. Modelling may be performed on the real marker data independently from the filtering and event detection processes, simply by selecting the appropriate check box in the pipeline.

Segment meshes

The models also output data that are used 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.

Multiple models

In fact the modelling stage internally consists of four interdependent models. A kinematic lower body, a kinematic upper body, and kinetic lower and upper bodies. The kinematic models are responsible for the definitions of the rigid body segments, and the calculations of joint angles between these segments. The two kinetic models then apply masses and moments of inertia to the segments, and allow the calculations of "reactions" that occur on the segments.

The lower body kinematic and kinetic model is equivalent to the model used in Vicon Clinical Manager (VCM).

General modelling approach

To run the models, different inputs are required. These inputs include the correct markers with the correct marker labels and the correct subject measurements. An initial stage checks that the required components are present. These include checks for required markers present in the trial, and subject parameter values. The modelling only continues if these requirements are met. The pelvis markers are the minimum required for the lower body model, and the thorax markers are the minimum required for the upper body model.

Second, 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.

Third, the positions of the rigid segments are then 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.

Outputs required from the modelling are then calculated, based on the frame by frame positions of the segments.
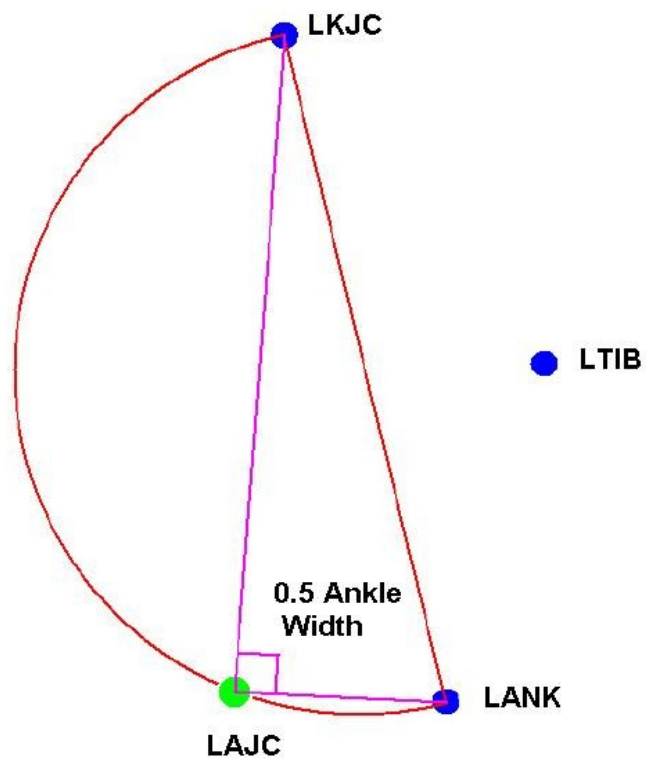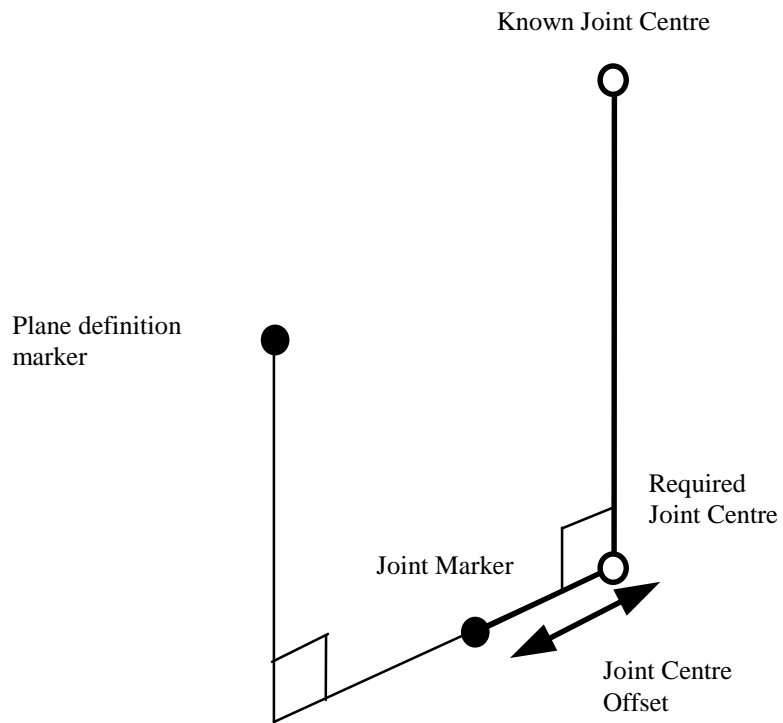
Static and Dynamic models

The kinematic models are run slightly differently for the static trials, to calculate certain static 'calibration' angles that are required for the dynamic modelling. 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 modelling 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 were calculated internally to allow the model to be run.

The "Chord" function

This function is used extensively in these models for defining joint centers. Three points are used to define a plane. One of these points is assumed to be a previously calculated joint centre, and a second is assumed to be a real marker, at some known, perpendicular distance (the Joint Centre Offset) from the required joint centre.

Known Joint Centre

Plane definition
marker

Required
Joint Centre

Joint Marker

Joint Centre
Offset

LKJC

LTIB

0.5 Ankle
Width

LANK

LAJC

[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.]

There is also a modified version of the function, which calculates the required joint centre position when the plane definition marker is rotated out of this plane by a known angle around the proposed joint centre axis. See the diagram below for the dynamic knee joint centre calculation for an illustration of this.

Lower Body Kinematics

Fixed Values

The position of the top of the lumbar vertebra 5 (the reference point for Dempster data) is found so that the segment inertia properties can be calculated and the whole body centre of mass can be estimated. The L5 position is estimated as
(LHJC + RHJC)/2 + (0.0, 0.0, 0.828) * Length(LHJC - RHJC)
where the value 0.828 is a ratio of the distance from the hip joint centre level to the top of the lumbar 5 compared to distance between the hip joint centers on the pelvis mesh in "GolemBones.obj" used in Polygon.

The general direction of the subject walking in the global coordinate system is 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 Progression Frame. 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 800 mm 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 centre point of the LPSI and RPSI markers. The front of the pelvis is calculated as the centre 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.

Model & Assumptions
In this section, the basics of the model used to process data in PIG will be presented. The segment co-ordinate system is described with a set of orthogonal axes. All figures in this section include these axes with color coding. Green is the X axis, Blue is the Y axis and Red is the Z axis.
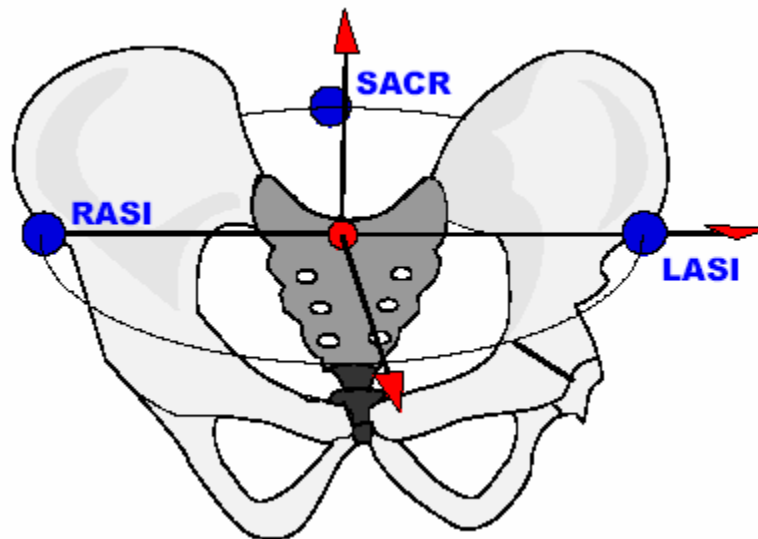
Pelvis

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 upwards, perpendicular to this plane, and the X axis 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.
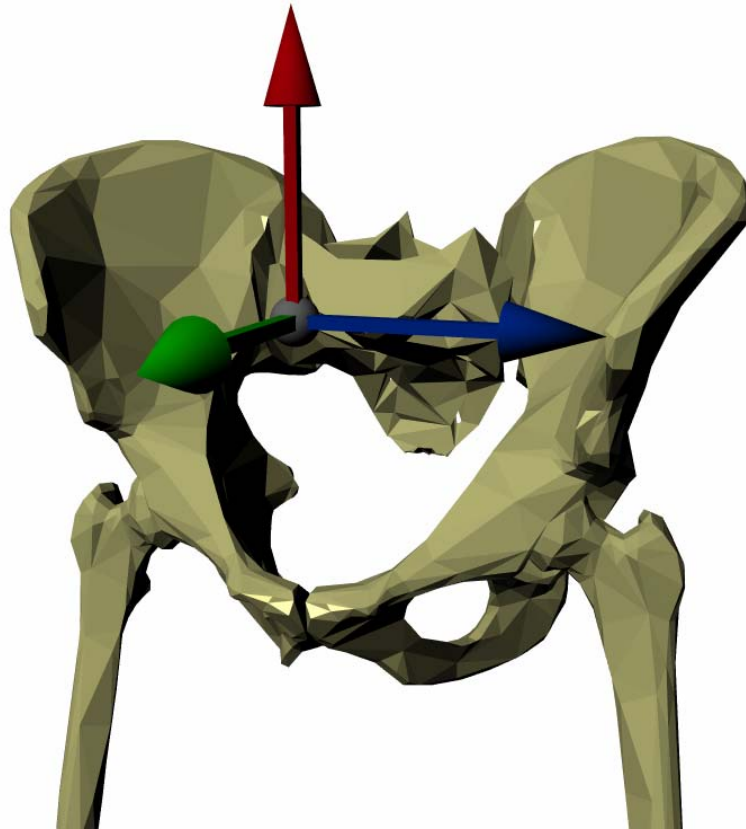
Calculating Hip Joint Centers:
The Newington - Gage model is used to define the positions of the hip joint centers in the pelvis segment. A special vector in the pelvic coordinate system defines the hip joint centre using pelvis size and leg length as scaling factors (Davis, Õunpuu, Tyburski and Gage, 1991).

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 Trocanter distances have not been entered, they are calculated from the left and right leg lengths using the formula
AsisTrocDist = 0.1288 * LegLength - 48.56
This is done independently for each leg.

The value C is then calculated from the mean leg length :-
C = MeanLegLength*0.115 - 15.3, 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(theta)*sin(beta) - (AsisTrocDist + mm) * cos(beta)
Y = -(C*sin(theta) - aa)
Z = -C*cos(theta)*cos(beta) - (AsisTrocDist + mm) * sin(beta)

where theta is taken as 0.5 radians, and beta as 0.314 radians. For the right joint centre, the Y offset is negated (since Y is in the lateral direction for the pelvis embedded coordinate system).

Knee Alignment Device

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 judgement 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 centre. 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 centre without the KAD. This technique relies on the accurate placement of the KAD, rather than the accurate placement of the wand marker.

The Knee Allignment device is explained in more detail in the Appendix.

Knee joint centre

The Knee joint centre (KJC) is calculated in the same manner in the static and dynamic model if no KAD is used.

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 (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.

If a KAD is used the knee joint centre is 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. The thigh wand offset angle is only calculated if a KAD is used.
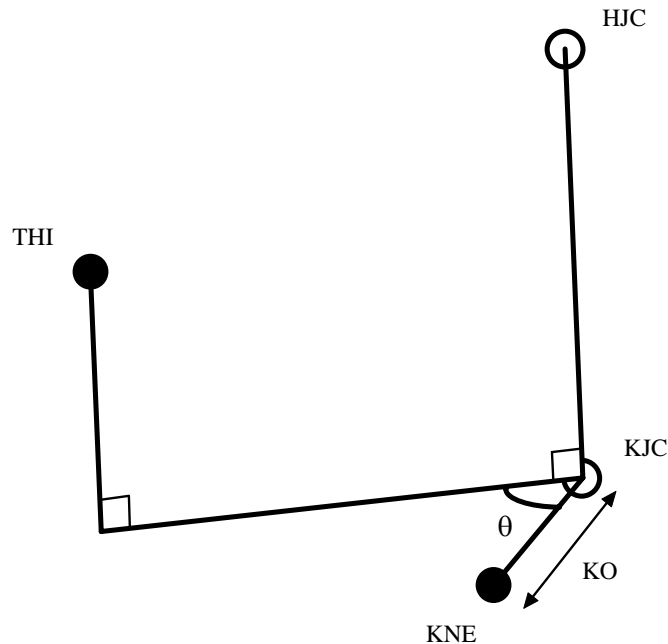
There is only one position for the KJC that satisfies these two conditions.

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.

Femur

The femur origin is taken as the knee joint centre. The primary Z axis is taken from the knee joint centre (KJC) to the hip joint centre (HJC). The secondary axis is taken parallel to the line from the knee joint centre 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 can be used to determine the plane in which the knee joint centre 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.
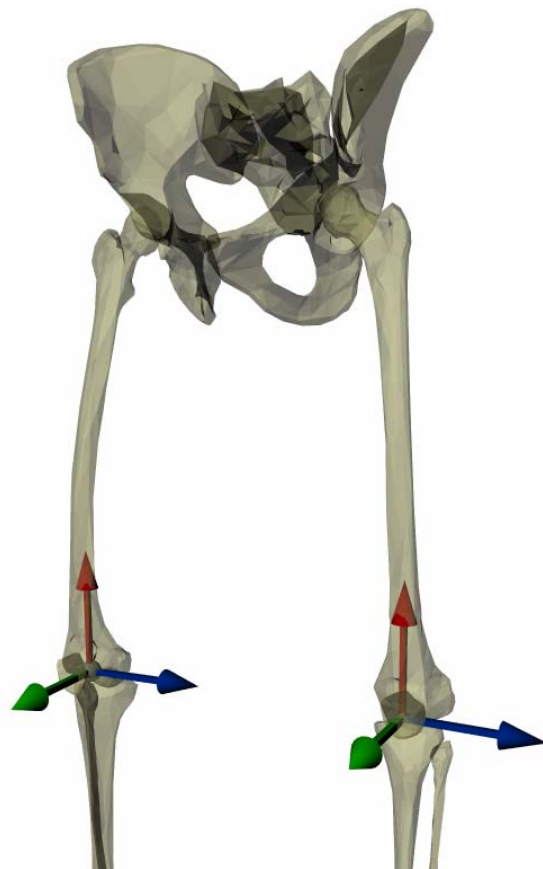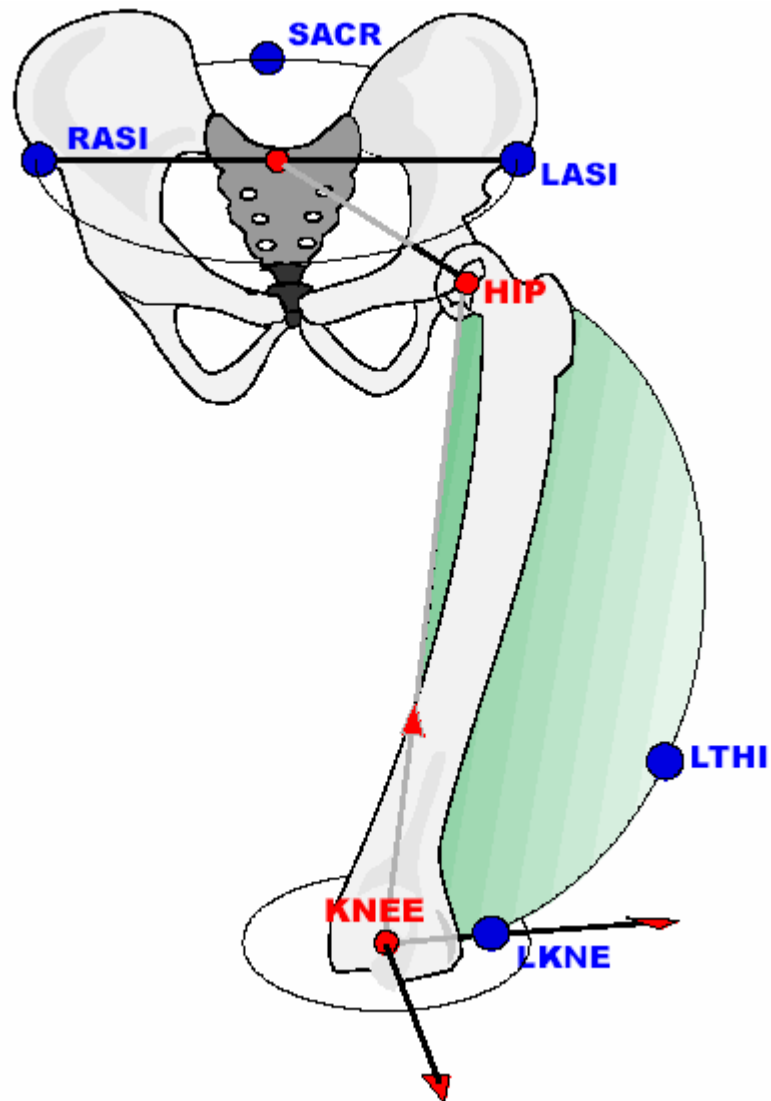
Ankle Joint Centre

The ankle joint centre is determined in a similar manner to the knee joint centre.

In the dynamic trial, and static trials without a KAD, the ankle joint centre is calculated from the knee joint centre, shank wand marker and ankle marker with the ankle offset and shank rotation offset using the modified chord function. Thus the ankle joint centre 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.
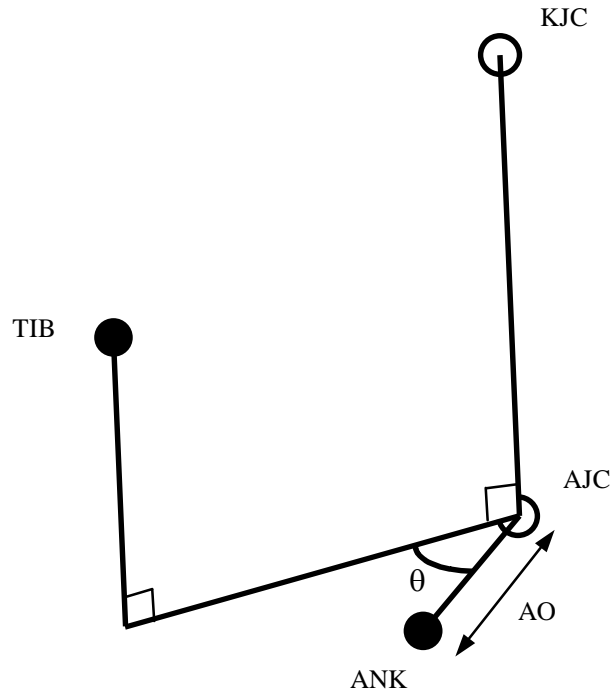
Torsioned Tibia

The tibial rotation offset as determined by the static trial already takes into account the tibial torsion. Thus a "Torsioned 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.

Untorsioned Tibia

A second tibia is also generated representing the tibia before tibial torsion is applied, by rotating the X and Y axes of the Torsioned 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.

Shank
The first axis joins the ankle and knee joint centers. The first and second axes both lie in the plane formed by the knee joint centre and the markers LTIB and LANK. The second axis passes through marker LANK and the ankle joint centre, which lies at a distance equal to half ankle width plus half marker diameter from LKNE. The third axis is perpendicular to the first and second. The Chord function described above is used to estimate the Ankle Joint Centre.
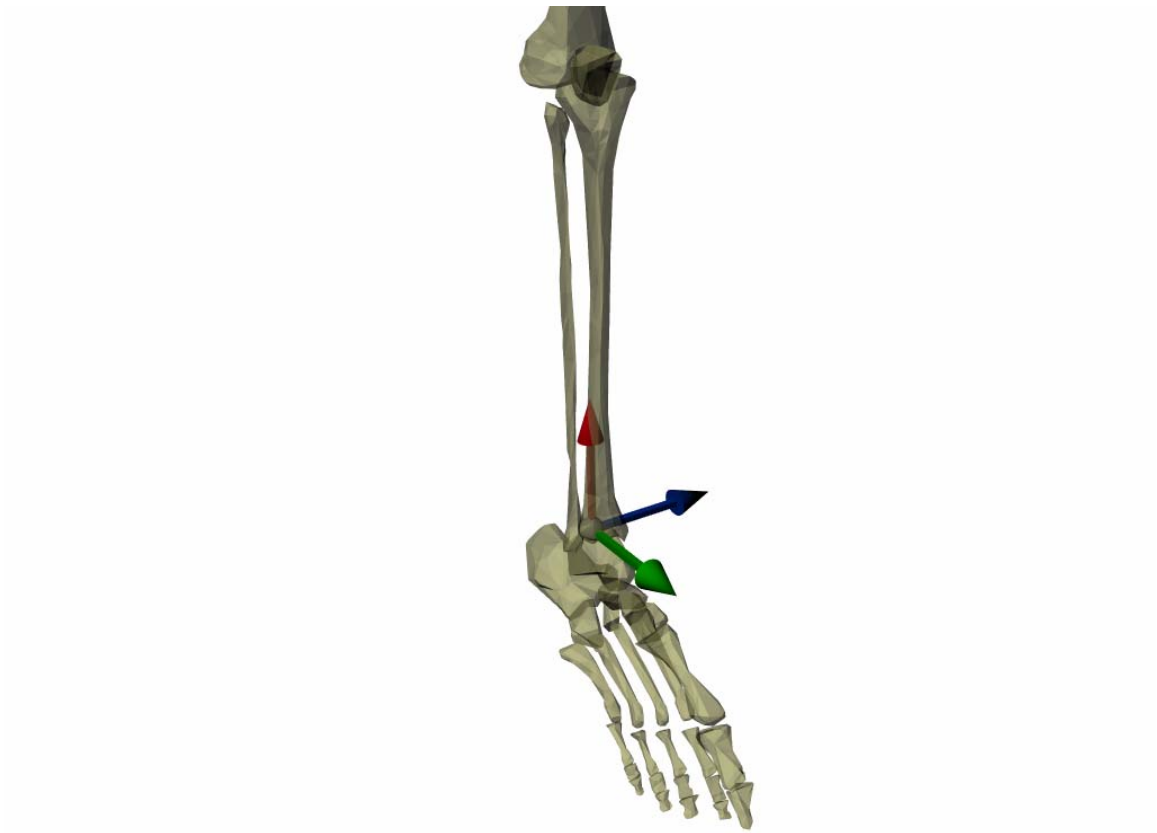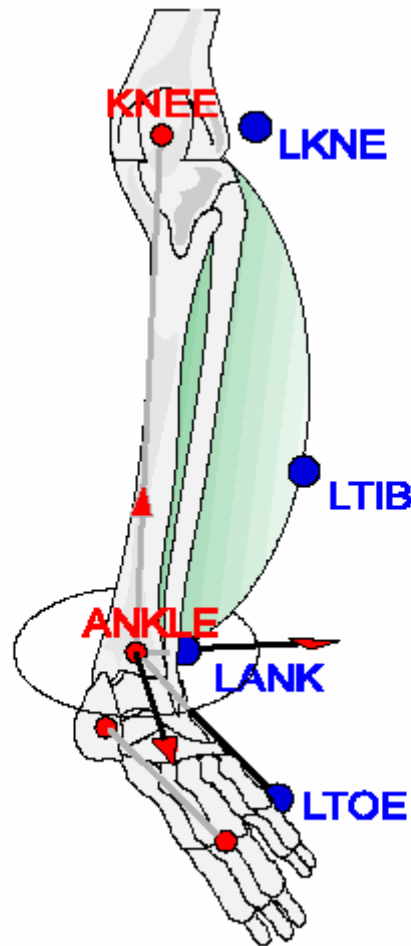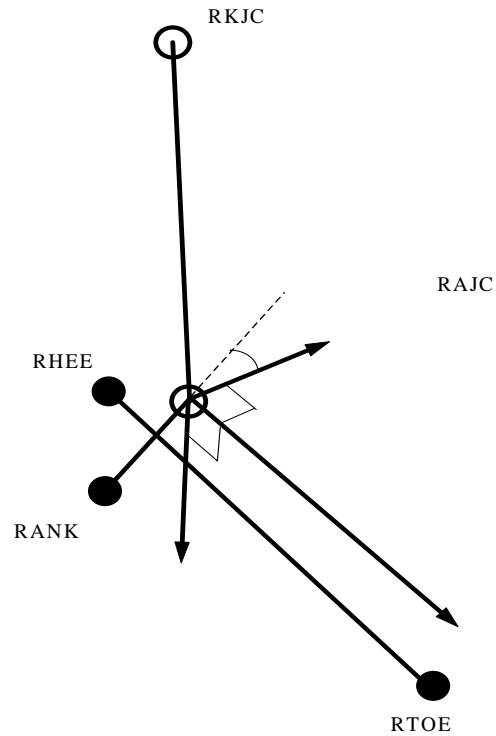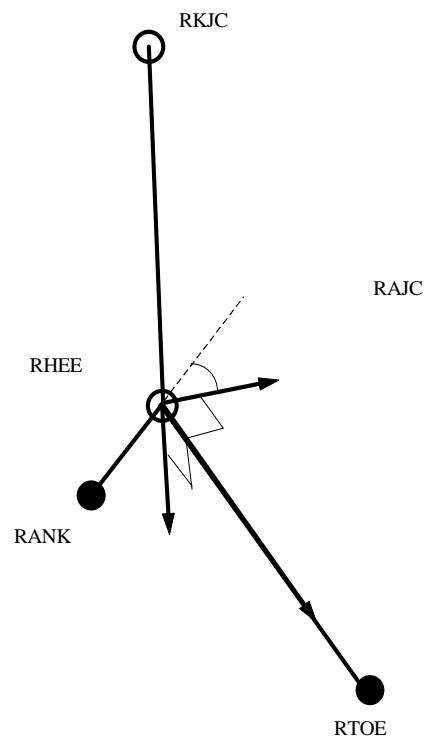
Foot

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 first 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 checked, then the HEE point 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 untorsioned tibia is used to define the secondary Y axis. The X axis thus points down, and the Y axis to the left.

RKJC

RAJC

RHEE

RANK

RTOE

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

RKJC

RAJC

RHEE

RANK

RTOE

The Static offset angles (Plantar Flexion offset and Rotation offset) are then calculated

from the 'YXZ' 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 around the X axis. The angle around the Z axis is ignored. The angle is measured between the line joining the heel and toe markers and the line joining the ankle centre and toe marker. A positive Static Foot Rotation value corresponds to a foot vector internally rotated with respect to the line joining the ankle centre and toe marker.

Note   If the Foot Flat button is set the vertical coordinate of the heel marker is adjusted to equal that of the toe marker before this angle is calculated.

Note   If the foot flat button is selected or if the heel and toe markers are placed at the same height, the foot rotation axis will be vertical. If the foot is not flat, the line joining the heel and toe markers will not be horizontal, therefore the foot rotation axis will not be vertical.
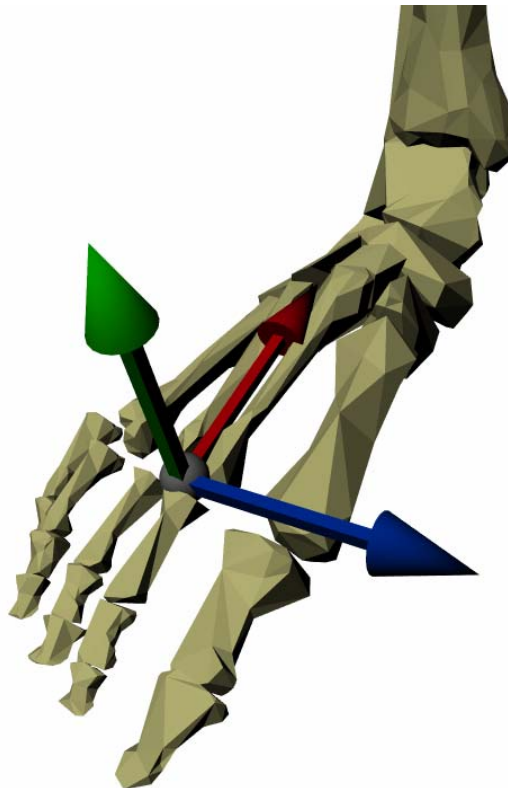
Dynamic Processing

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 it's X axis by the rotation offset.

RAJC

RANK

RTOE

RAJC

RANK

RTOE
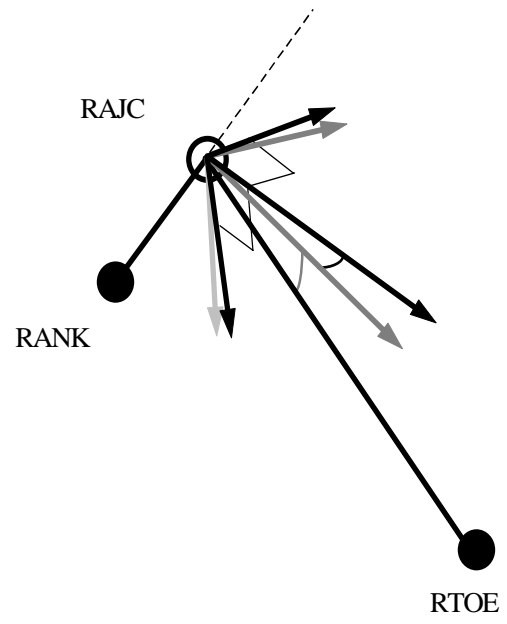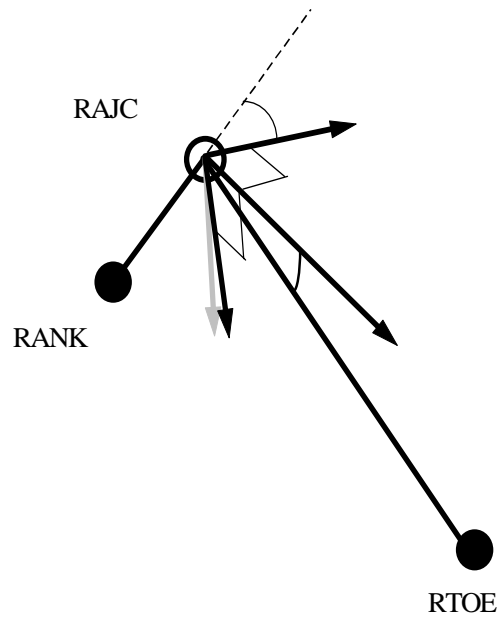
Foot Axes and Offset Angles

Upper Body Kinematic

Fixed Values
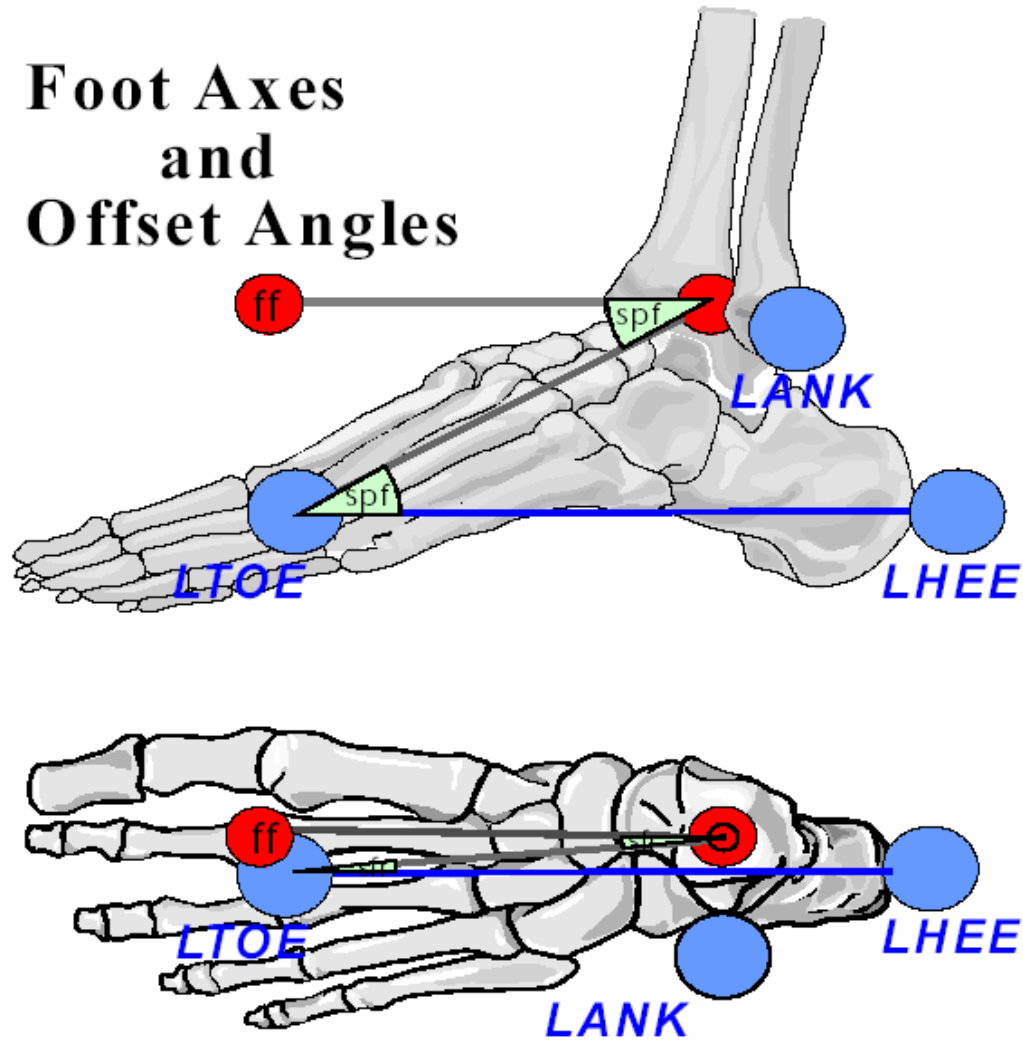
A Shoulder offset value is calculated from the Subject measurement value entered, plus half the marker diameter. Elbow, Wrist and Hand offset values are also calculated from the sum of the respective thickness with the marker diameter divided by two.

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.

Head

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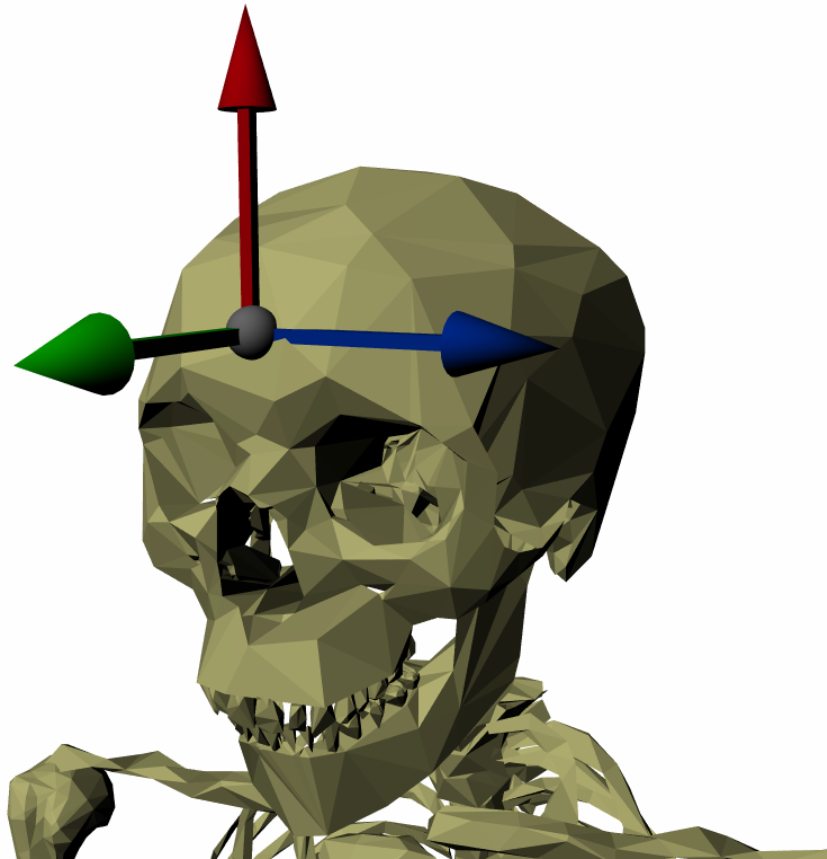
For the static processing, the YXZ Euler angles representing the rotation from the head segment to the lab axes are calculated. The Y rotation is taken as the head Offset angle, and the mean of this taken across the trial.

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

Thorax

The orientation of the thorax is defined before the origin. The Z axis, pointing

downwards, is the predominant axis. This is defined as the direction from the midpoint of the CLAV and C7 to the midpoint o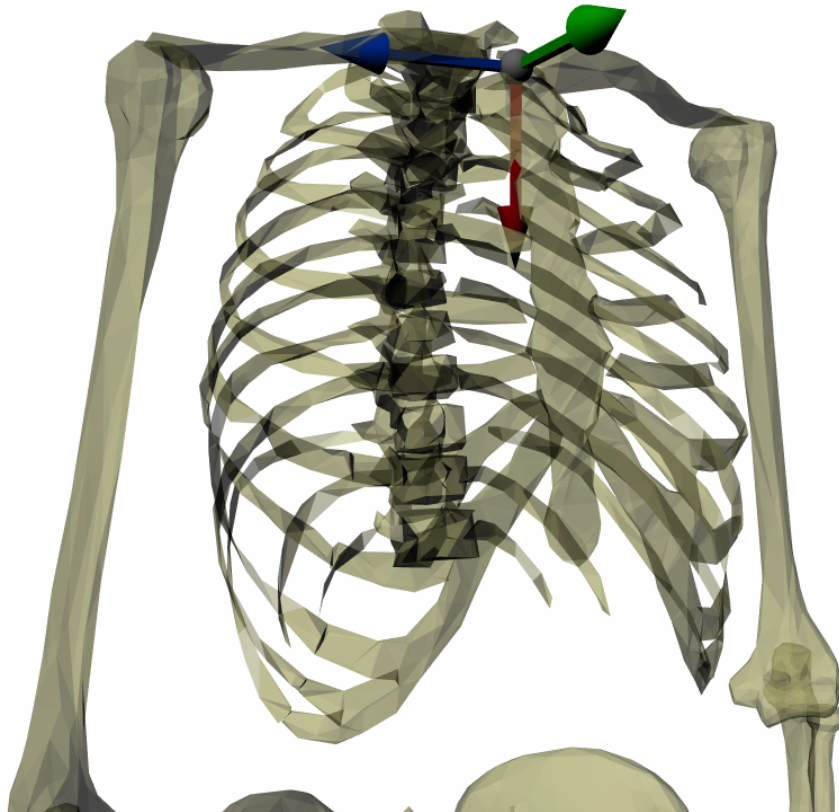f STRN and T10. A secondary direction pointing forwards is the midpoint of C7 and T10 to the midpoint of CLAV and STRN. The resulting X axis points forwards, and the Y axis points rightwards.

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

Shoulder Joint Centre

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 centre (SJC) from the Shoulder offset, thorax Origin, SHO marker and shoulder 'wand'.
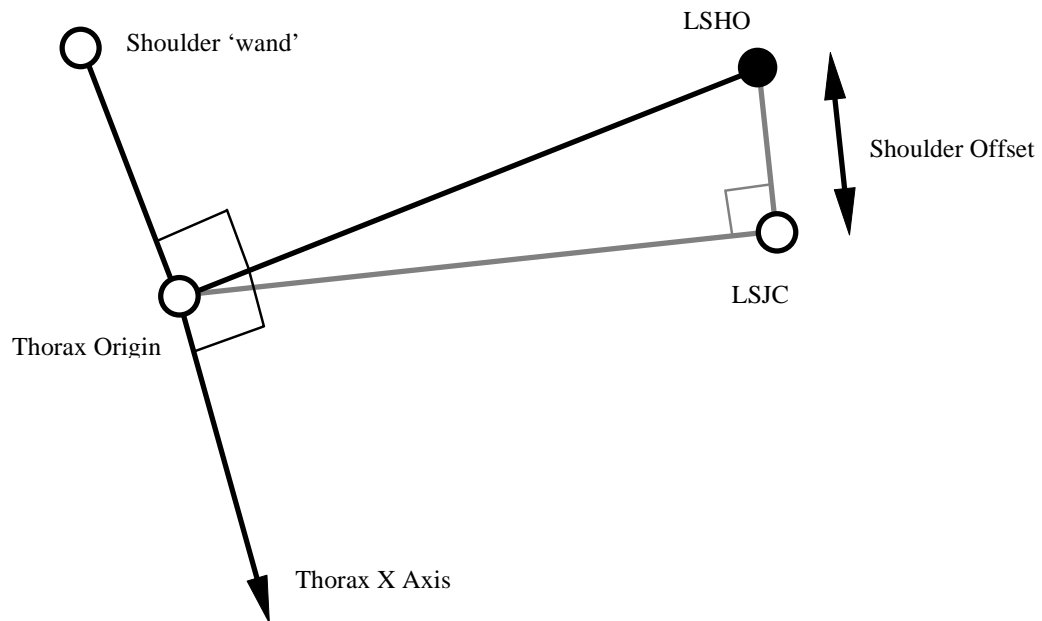
Clavicle

The clavicle segment is defined with the direction from the joint centre 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. As the clavicle segment is used as an intermediate axis there is no figure displaying its axes.

Elbow Joint Centre

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

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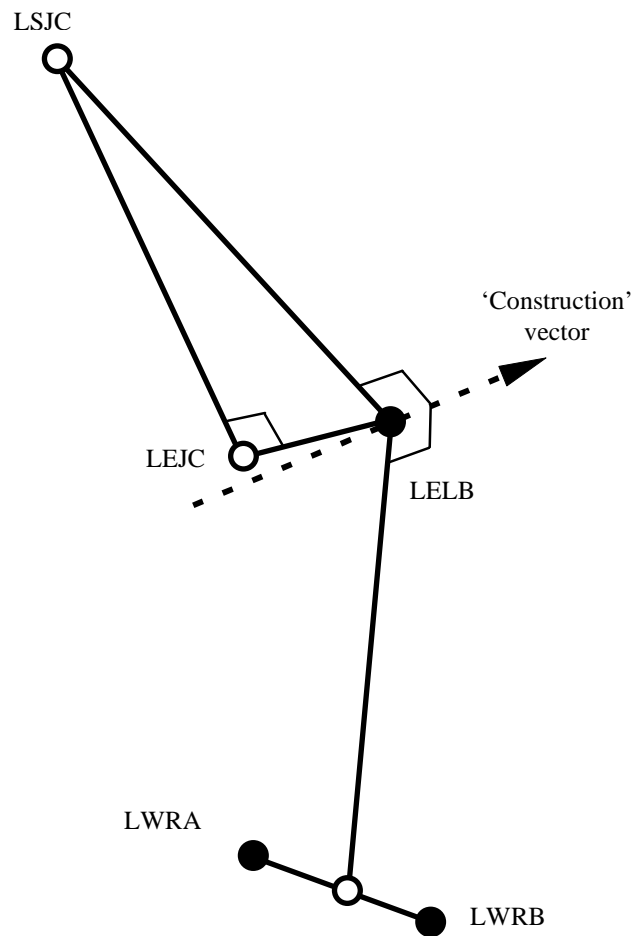
Wrist Joint Centre

The wrist joint centre (WJC) is then calculated. In this case the chord function is not used. The wrist joint centre 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 centre.
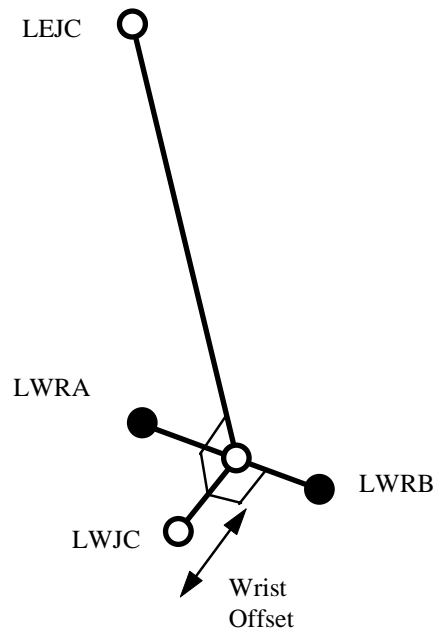
Humerus

The Humerus is then defined with it's origin at the EJC, a principal Z axis from EJC to SJC. A secondary line between the EJC and the WJC is described and a cross product between this line and the Z axis of the Humerus is calculated to define the Y axis of the Humerus. The X axis points orthogonally to the Y and Z axes.
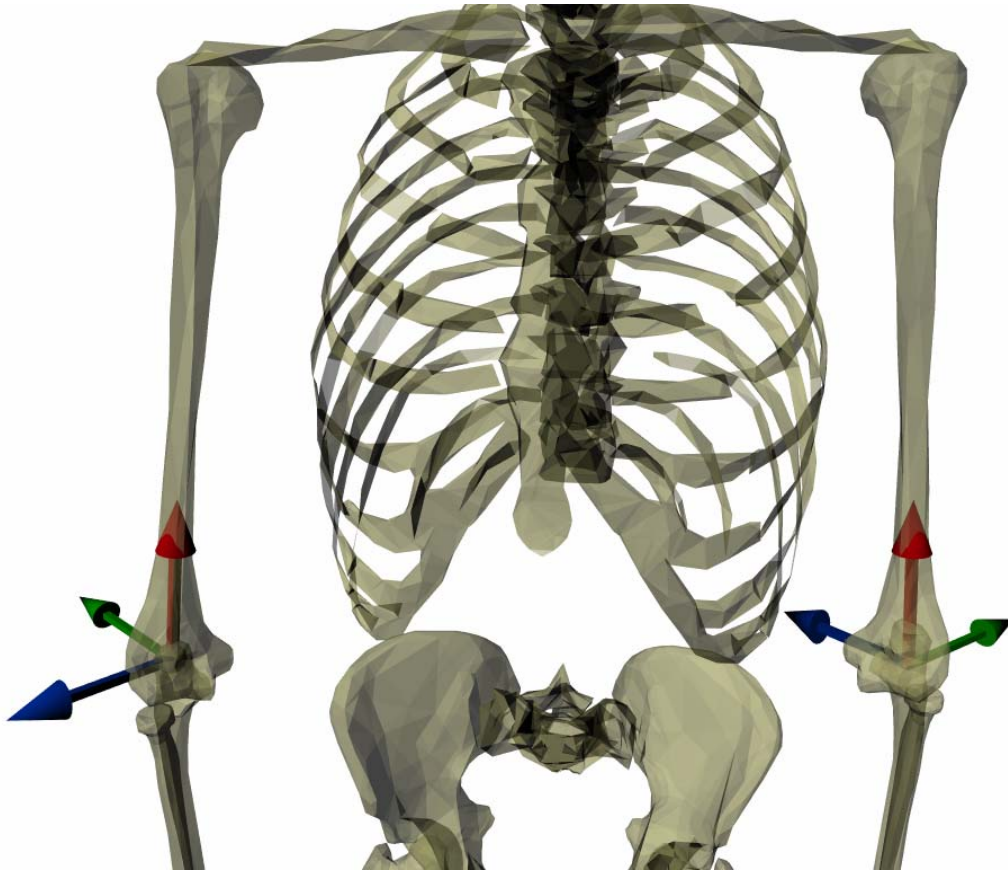
Radius

The radius origin is set at the wrist joint centre. The principal axis is the Z axis, from the WJC to the EJC. A secondary line is defined as the Y axis of the Humerus segment. The X axis points orthogonally to the Y and Z axes. The definition of the Humerus and Radius Segments will result in the X and Y axes of both segments being shared and a Hinge joint is therefore defined at the Elbow.
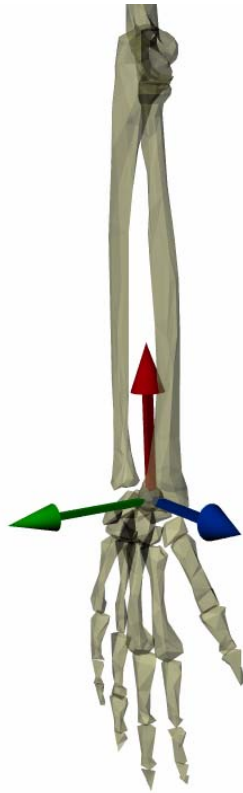
Hand

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.
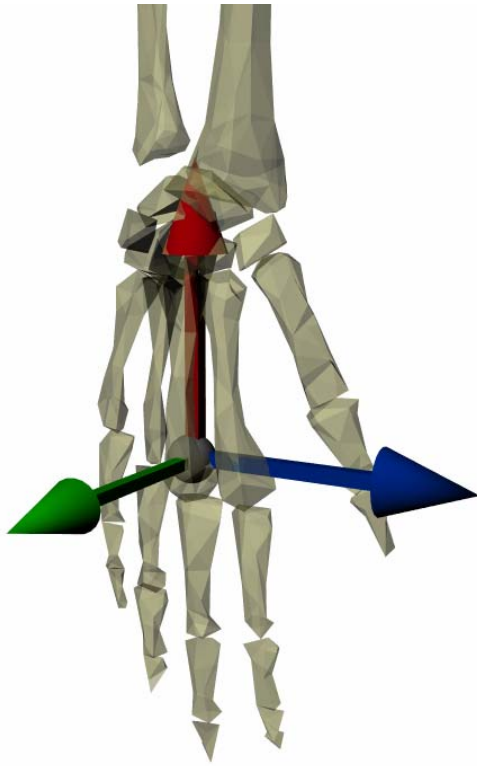
PIG Angle Outputs

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 Untorsioned tibia segments, whilst the ankle joint angles are calculated from the Torsioned 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.

Angle Definitions

PIG uses Cardan angles, modified in the case of the ankle angles, to represent both (a) absolute rotations of the pelvis and foot segments and (b) 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), or as one rotation fixed in either segment and one 'floating' rotation (goniometer). The two descriptions are mathematically equivalent. For more information about the use of Cardan angles to calculate joint kinematics, please refer to Kadaba, Ramakrishnan and Wooten (1990) and Davis, Õunpuu, Tyburski and Gage (1991).

The rotations are measured about embedded axes. The implication of using embedded axes are described in Kadaba, Ramakrishnan and Wooten (1990).

Ordered Rotations
In order 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.

Angle Goniometric Description
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.

Note   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.
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. 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.

For a demonstration of this, follow the sequence below:
(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.
(4) Note that the forearm now points 180 degrees externally rotated from its original position with no rotation about the humeral longitudinal axis actually having occurred.
(5) Appreciate the difficulty then 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 modelling is carried out. In practice, the shoulder is the only joint commonly analysed 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 particular poses and the inconsistencies that occur as a result of Codman's Paradox.

Plug In Gait does include some steps that make an effort to minimise 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.

PIG Kinematic Variables
When the gait cycle event timing has been labeled in the Cycles window, the following derived kinematic quantities can be calculated and written to file. Most of the kinematic variables are depicted in Figure .

Note   Throughout this section axes are described as the following: 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 centre of the body through the top of the head.
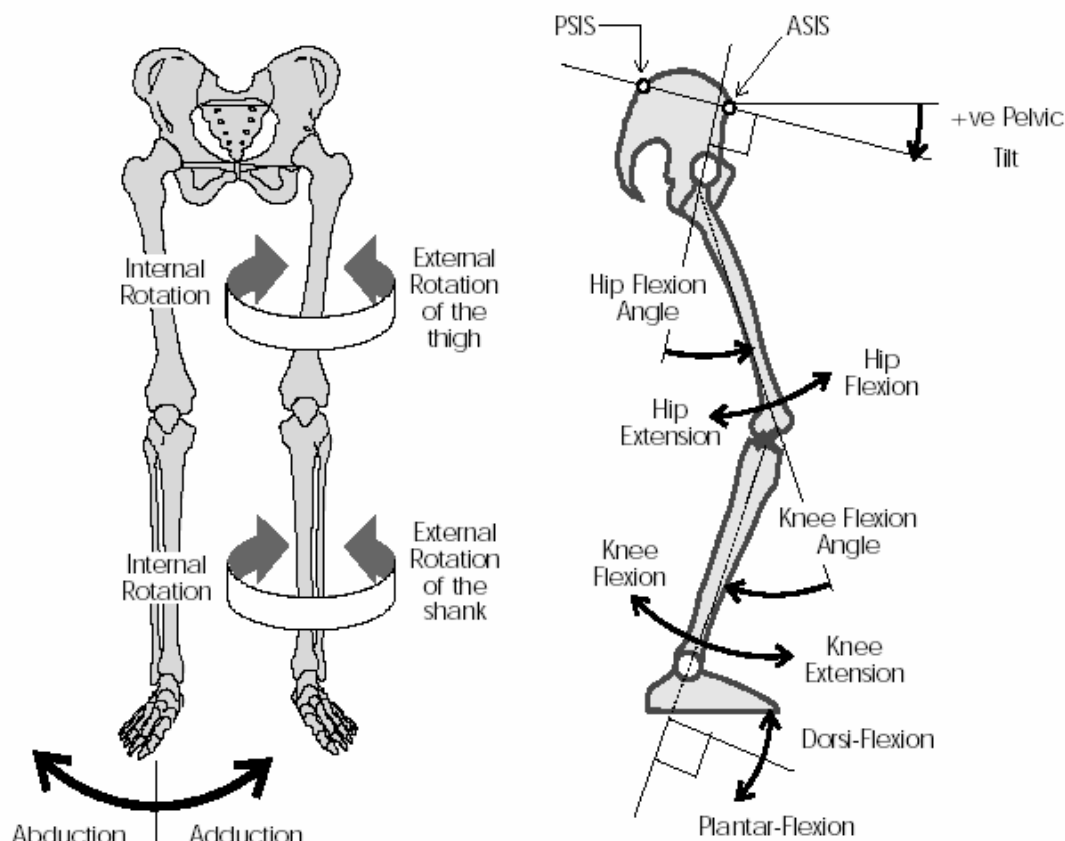
Figure 3. PIG kinematic variable definitions.

Pelvic Tilt
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. 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.

Pelvic Rotation
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.

Pelvic Obliquity
Pelvic 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 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 negative pelvic obliquity value (down) relates to the situation in which the opposite side of the pelvis is lower.

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.

Note   The transverse and frontal plane kinematics of all joints are influenced by the mathematics involved with embedded axes. 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 PIG will show 10 degrees of pelvic obliquity. For more clarification about the effect of embedded axes on joint kinematics, please refer to Kadaba, Ramakrishnan and Wooten (1990).

Hip Flexion/Extension
Hip flexion is calculated about an axis parallel to the pelvic transverse axis which passes through the hip joint centre. 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.

Hip Rotation
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.

Hip Ab/Adduction
Hip adduction is measured in the plane of the hip flexion axis and the knee joint centre. 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.

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 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.

Knee Flexion/Extension

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 Rotation

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.

Knee Valgus/Varus

This is measured in the plane of the knee flexion axis and the ankle centre, 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).

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.

Foot Progression

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.

Ankle Dorsi/Plantar Flexion

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

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.

Head Tilt

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 forward head tilt.

Head Rotation
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.

Head Obliquity
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 negative head obliquity value (down) relates to the situation in which the opposite side of the head is lower.

Thorax Tilt
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.

Thorax Rotation
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 in front.

Thorax Obliquity
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.

Neck Flexion/Extension
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 Rotation
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.

Neck Lateral Flexion
The angle between the long axis of the head and the long axis of the thorax around a floating transverse axis

Spine Flexion/Extension
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.

Spine Rotation
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.

Spine Lateral Flexion
The angle between the long axis of the thorax and the long axis of the pelvis, around a floating transverse axis.

Shoulder Flexion/Extension
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 Rotation
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.

Shoulder Ab/Adduction
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.

Elbow Flexion/Extension
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
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 Rotation
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.
st Ab/Adduction
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.

Following is a table of the kinematic variables calculated by PIG. This table includes the information describing each variable in terms of ordered rotations or goniometric definitions:

Angle Rotation	Goniometric
Pelvic Tilt	Absolute
Pelvic Obliquity	Absolute
Pelvic Rotation	Absolute
PelvisHip Flexion/Extension	Relative
Hip Ab/Adduction	Relative
Hip Rotation	Relative
Knee Flexion/Extension	Relative
Knee Ab/Adduction	Relative
Knee Rotation	Relative
Ankle Dorsi/Plantarflexion	Relative
Foot (Ankle) Rotation	Relative
Foot Progression	Absolute
Head Tilt	Absolute
Head Obliquity	Absolute
Head Rotation	Absolute
Thorax Tilt	Absolute
Thorax Obliquity	Absolute
Thorax Rotation	Absolute
Neck Flexion/Extension	Relative
Neck Lateral Flexion	Relative
Neck Rotation	Relative
Spine Flexion/Extension	Relative
Spine Lateral Flexion	Relative
Spine Rotation	Relative
Shoulder Flexion/Extension	Relative
Shoulder Ab/Adduction	Relative
Shoulder Rotation	Relative
Elbow Flexion/Extension	Relative
Wrist Flexion/Extension	Relative
Wrist Ab/Adduction	Relative
Wrist Rotation	Relative

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. The laboratory axis closest to the subject's direction of progression will be labeled the laboratory sagittal axis in PIG.

Kinetic Modelling

The estimates of net joint moment are made by solving the equations of motion for the six segments of the lower limbs (excluding the pelvis) (Ramakrishnan, H.K., Kadaba, M.P. & Wooten, M.E., 1987). To do this, the program needs to know:

- values of all external forces applied to the limbs
- distribution of mass within the limb segments
- kinematics of the limb segments, including the location of the joint centers

Two assumptions, true for most circumstances, are made:
1. no external forces are applied, other than gravity and force plate measurements
2. the segment masses, centers of gravity, and radii of gyration can be approximated from published tables (David A Winter, Wiley 1990, Biomechanics and Motor Control of Human Movement 2nd Ed.)

The medical convention that positive flexion moments, also called "internal" joint moments, are generated by active flexor muscles, and so on, has been followed. Thus active quadriceps and inactive hamstrings generate an extensor moment at the knee. It should be noted this is the reverse of the 'force reaction vector' convention.

Note   When plotting graphs in reports, this convention is easily reversed by introducing a 'minus sign' in front of the variable name in the graph definition in the RPT file.

Joint Power is calculated as the "scalar product" of moment and angular velocity. Both the Total Power and three "components" of the scalar product are written to the C3D file. It should be noted that these are not true vector components, but they do provide a convenient means of dividing the total power into axis related parts.

The kinetic modelling 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 centre of mass is required in the segment. This is defined as a point at a given proportion along a line from the distal joint centre (normally the origin of the segment) towards the proximal joint centre 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. These values can be changed by the user in the Settings dialogue.

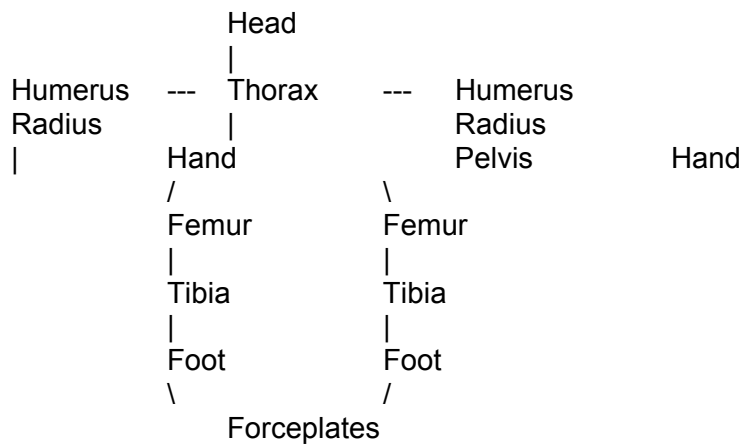The kinetic hierarchy is shown below.

Note that the clavicles are not considered to have mass in themselves, so reactions for the humerus segments are considered to be acting 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 "untorsioned" tibiae are used for the kinetic modelling. 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 "untorsioned" 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 centre is moved backwards, then the "untorsioned" tibia is calculated by rotating the torsioned tibia round the Z axis, keeping the ankle joint centre in position. Thus, for a given trial, as tibial torsion is increased, and the joint centre is rotated backwards around the ankle marker, the ankle flexion moment will generally become more positive.

```
                    Head
                     |
    Humerus   ---   Thorax      ---    Humerus
    Radius            |                 Radius
    |               Hand                Pelvis          Hand
                    /             \
                    Femur         Femur
                    |             |
                    Tibia         Tibia
                    |             |
                    Foot          Foot
                    \             /
                        Forceplates
```

Segment	CoM	Mass	Radius of Gyration
Pelvis	0.895	0.142	0.31
Femur	0.567	0.1	0.323
Tibia	0.567	0.0465	0.302
Foot	0.5	0.0145	0.475
Humerus	0.564	0.028	0.322
Radius	0.57	0.016	0.303
Hand	0.6205	0.006	0.223
Thorax	0.63	0.355	0.31
Head	See Below	0.081	0.495

Pelvis

The centre of mass is defined along a line from the midpoint of the hip joint centers, to the centre 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.

Hand

The length of the hand in this model is defined as the distance from the wrist joint centre 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.

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 localised 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 Centre of mass is deemed to lie at a proportion of 0.63 along this line.

Head

The centre 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 markers). The length of the head used for the inertial normalisation is the distance from this point to the C7 vertebra (the mean position localised to the head segment).

The inertia value for the head is applied around all three axes.
The resultant components of moments are normalized by body weight and have the units of Newton meters/kilogram:
The total value and components of joint power are normalized by body weight and have the units of Watts/kilogram:

Whole Body Centre of Mass

The centre 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 as the hands, for example, do not have markers. The centre of mass is the centre of mass of all the modeled segments.

Please note that this centre 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 centre 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 centre of mass for the whole body.

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

Data Error due to Marker Placement (Lower body only)

Marker placement can greatly influence the reliability and validity of joint kinematic data. In the most basic VCM processing method (see Chapter II VCM Model and Assumptions on page), the knee flexion/extension axis is defined by the hip joint centre, thigh wand and a lateral knee marker. The ankle flexion/extension axis is defined by the knee joint centre, tibial wand and lateral ankle marker.

The rotations of the hip and knee axes about the long axes of the femur and tibia are determined by the placement of markers on the "mid"-thigh and "mid"-shank. As the fixation of any one of these markers is moved anteriorly around the limb, there is an internal rotation of the flexion axis of the joint which lies below it. This rotation always occurs about the marker placed on the lateral side of the joint, so the flexion axis always passes through this joint marker, giving the user complete control over both the direction of the flexion axis and the centre of the joint.

Note   The proximal-distal placement of the thigh and shank wands has no effect on the results. Provided their antero-posterior location relative to the distal joint marker is carefully controlled, they can be placed almost anywhere wherever visibility and steady fixation to the limb are optimal. The wands can be placed anywhere, as long as the distance between the wand markers and joint markers is at least the diameter of a marker.

Thigh and Tibial Markers
The correct antero-posterior alignment of the thigh and tibial markers is not an easy task. If the knee and ankle flexion axes are incorrectly determined, a number of highly characteristic errors will result in the kinematic results. After learning to recognize the errors described in the previous section, the user can make mathematical adjustments to the thigh and shank rotation offsets in the Session Form which compensate for incorrect thigh and shank marker placement.

Knee Joint Centre Position
Since the thigh rotation offset is applied about the knee joint marker, changes in the placement of the thigh marker and thigh rotation offsets entered into the session form both cause the knee joint centre to move. Internal rotations of the knee flexion axis move the joint centre posteriorly. External rotations of the knee flexion axis move the joint centre anteriorly.

There are three important, related consequences:
a)   If a thigh marker is placed a long way anterior or posterior from its "correct" lateral position, the application of thigh rotation offsets, while still allowing a correct direction for the knee flexion axis, will place the knee joint centre too far posterior or anterior.
b)   This antero/posterior mis-location of the knee joint centre causes small changes in the flexion/extension axis of the knee.
c)   Knee joint moments which are calculated about the knee joint centre, will also change.

Recognizing Errors in Hip Rotation
Hip rotation is measured about the long axis of the femur. Its "neutral" position occurs when the flexion axis is aligned with the lateral axis of the pelvis. If the thigh marker is

placed too far forward the flexion axis of the knee is internally rotated and a corresponding internal rotation offset error appears in hip rotation.

It is almost impossible to obtain an independent measure of hip rotation in a standing subject, so a non-zero hip rotation may either be real or due to incorrect thigh marker placement. The standard physical examination and test for hip rotation involves lying the subject prone, flexing the knee to close to 90 degrees, and rotating the hip medially and laterally. The angle of the tibia to vertical is measured in internal and external hip rotation to understand the range available. Additionally, if the tibia is rotated so that the greater trochanter is most lateral, the "bias" or anteversion of the hip can be measured. This test relies on the assumption, true for many pathologies, that, as the foot is raised from the table, the knee moves in pure flexion. If the knee has any significant valgus/varus instability, hip rotation from this test will be unreliable.

Exactly the same assumption can be used by PIG to check for correct placement of the thigh marker and to correct offsets in hip rotation. If, in the report graphs from a walking trial, there is:
a)   hip external rotation offset AND a knee valgus "wave" during swing, the knee flexion axis has been externally rotated. The thigh marker was placed too far posteriorly.
b)   a hip internal rotation offset AND a knee varus "wave" during swing, the knee flexion axis has been internally rotated. The thigh marker was placed too far anteriorly.

In case (a), the hip external rotation offset and the knee valgus wave can both be corrected by entering a small internal (positive) Thigh Rotation Offset in the VCM Session form and reprocessing the walking trial.

In case (b), the hip internal rotation offset and the knee varus wave can both be corrected by entering a small external (negative) Thigh Rotation Offset in the VCM Session form and reprocessing the walking trial.

Use of the Knee Alignment Device (KAD)

When a subject's static trial is processed in PIG segment coordinate systems are established during the analysis process. In the case of the foot its coordinate system consists of a single vector. The segmental coordinate systems vary depending on whether or not a KAD was used. If a KAD was used offsets are calculated which affect the position of the thigh and shank markers. These coordinate systems and the effect of a KAD on the axes definitions are as follows and are illustrated in Figures:

The Knee Alignment Device (KAD) is an optional extra. Its purpose is to allow the VICON system to make a direct measurement of the three-dimensional alignment of the knee flexion axis during a static trial. PIG then calculates the relative transverse alignment of this axis to the transverse plane orientation of the thigh and shank, as calculated using the mid-thigh and mid-shank wand markers. These relative alignments are stored in the subject's measurement mp file as Thigh and Shank Rotation Offsets.

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 exactly equal distances from the point where the stem meets the jaws of the clamp allowing the 3D position of this point, known as the 'virtual knee marker', to be calculated

KAD placement defines the flexion axis of the knee. However, the lateral axis of the thigh coordinate system must be kept perpendicular to the principal thigh axis - the line joining the centers of the knee and hip joints. As a result, only that component of knee flexion axis alignment that corresponds to thigh rotation is calculated and stored.

The KAD alignment is also used to define the alignment of the ankle axis. During a KAD static trial, the knee and ankle flexion axes are assumed to be aligned. This means that the Shank Rotation offset can be calculated without resorting to an 'ankle alignment device'. If this assumption is for any reason invalid, the Shank Rotation offset should be reset manually after the processing of the static trial and before the processing of any other trials.

Over reliance on anatomical landmarks can be misleading. A safer method, but one which requires skill in visualizing an imaginary axis, is to examine the knee as it is flexed and extended, and to mark the skin at the medial and lateral points which are seen to remain in a constant position relative to both the thigh and shank. This task requires practice. The KAD pads are then placed on these marks. The outer pad of the KAD jaw is placed directly over the lateral surface intersection of the knee flexion axis and the inner pad is placed on the medial aspect of the knee, close to or over the medial epicondyle.

Note: When the knee is fully extended, particularly in the adult knee, the fibrous and fatty covering of the lateral joint capsule tends to push the lateral pad of the KAD

forward, internally rotating the measured knee flexion axis. This must be avoided by adjusting the KAD position.

The alignment of the KAD stem with the knee flexion axis must be thoroughly checked. While the medial and lateral epicondyles of the knee provide a good approximation for the correct positions of the KAD pads in normal adult knees, in abnormally shaped knees, these landmarks may not represent the optimal positions for the pads. The sole criterion is that: over the flexion range of the knee which is used when the subject is walking, both the location and alignment of the KAD stem must move as little as possible relative to both the thigh and shank

Note   Check the position of the KAD immediately prior to data collection. The KAD could slip if the patient moves much between placing the device and collecting data. If the KAD slipped for the static trial, there isn't a way to correct the data acceptably.

In general, the three markers on each KAD are identified internally by PIG through the Plug In Gait marker file:
L/RKAX
L/RKD1
L/RKD2

where L/R means either Left or Right, should have unique marker labels assigned to them. However, as there are no knee markers present during a KAD static trial, the same label can be used for both the knee markers, L/RKNE, and the KAD stem markers, L/RKAX. Both options must be present in the Marker file. When PIG detects the presence of the other KAD markers in a three-dimensional data file, recognizes the presence of KAD(s). As knee markers cannot be present at the same time as KADs, the program assigns the shared labels to the KAD stem marker(s). Clearly, it is important that the labels assigned to the other KAD markers, L/RKD1 and L/RKD2, are not shared by any other markers.

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

After the KAD(s) and all the other markers required for a static trial have been fixed to the subject, a normal standing measurement and a PIG Static Analysis is made. When the Stick figure is displayed in the Cycles window, the KAD markers are not shown. Instead the 'virtual knee marker' is plotted to allow its position to be checked. Stick figures in KAD trials should therefore look exactly the same as in non-KAD trials. When the static trial is processed, the calculated Thigh and Shank Rotations are stored and displayed in the Subject measurements.

Segment Definitions with a KAD

Knee Joint Centre
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.

The joint centre 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 ( ) is then calculated by projecting its position on to a plane perpendicular to the HJC-KJC line.
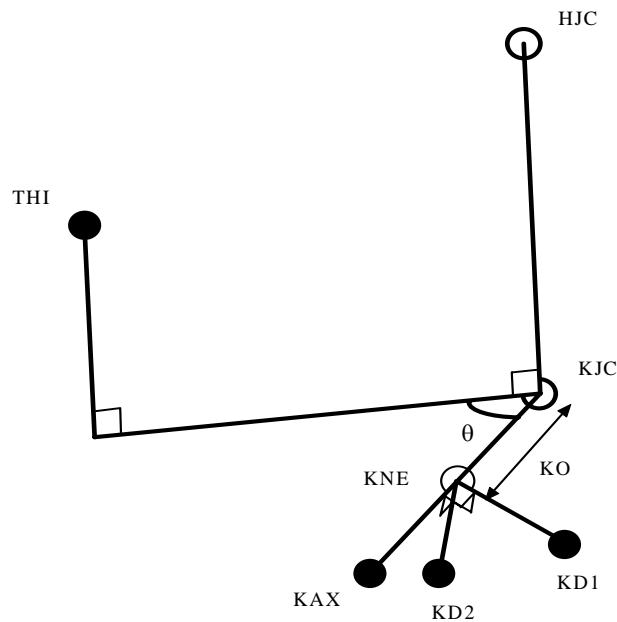
Thigh
If a KAD is used, the knee flexion axis passes through the virtual knee marker, perpendicular to the segment joining the hip and knee joint centers, in the plane defined by the hip centre, virtual knee marker and knee axis stick marker, irrespective of the placement of the thigh marker. The second axis passes through marker KNE and the knee joint centre, which lies at a distance equal to half knee width plus half marker diameter from KNE.

When the KAD is used a thigh rotation offset is calculated by PIG and stored in the subject's measurements file. Thigh rotation is the angle between the plane containing the knee flexion axis and the hip joint centre (knee axis plane) and the plane containing the thigh marker and the hip and knee joint centers (thigh marker plane). A positive thigh rotation offset means the thigh marker plane is externally rotated with respect to the knee axis plane by that number of degrees.

Ankle Joint Centre
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 in which the Ankle joint centre lies will be rotated by this amount relative to the plane containing the KAX maker.

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 a positive Tibial Torsion is thus considered as an internal rotation of the ankle axis relative to the knee axis.
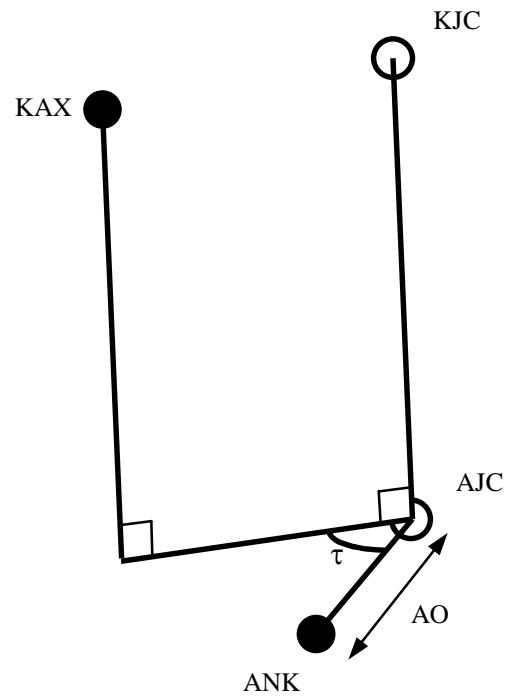
The shank marker rotation offset is then calculated by projecting it's position onto the same plane. Note that this value takes into account the value of the tibial torsion, and in general, you would expect it to be slightly less than the value for Tibial Torsion, if the TIB wand marker is conventionally placed.
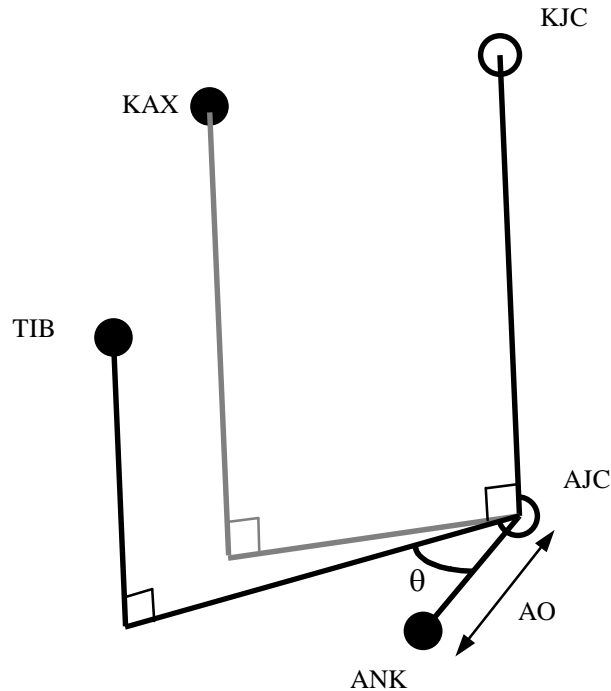
Shank

If a KAD is used, the ankle flexion axis is in the plane containing the knee flexion axis and the ankle marker, irrespective of the location of the shank marker. If Tibial Torsion is entered in the session form, the plane containing the ankle flexion axis and the knee centre is rotated by the amount of reported Tibial Torsion, with respect to the plane containing the knee flexion axis and the ankle centre. The sign convention is that if a negative value of Tibial Torsion is entered, the ankle flexion axis is rotated externally with respect to the knee flexion axis. In this case, the ankle joint centre will be located anteriorly with respect to the case of zero Tibial Torsion.

Note   The tibial torsion value stored in the subject measurements provides a constant offset to the knee rotation kinematics during dynamic trials.

When the KAD is used a shank rotation offset is calculated by PIG and stored in the subject measurements. Shank rotation is the angle between the plane containing the ankle flexion axis and knee joint centre (ankle axis plane, made up of the AJC, KJC and ANK markers) and the plane containing the ankle centre, shank marker and knee joint centre (shank marker plane). A positive shank rotation value means the shank marker plane is externally rotated with respect to the ankle axis plane by that number of degrees.

Note   During dynamic trials the shank rotation offset stored in the subject measurements is used to determine the "corrected" ankle joint centre position. Shank rotation and tibial torsion are both measured about the axis joining the ankle and knee centers, but they are not equivalent values. As ankle width increases, a Shank Rotation value becomes smaller than the corresponding Tibial Torsion value. This occurs because Shank Rotation modifies ankle position, whereas Tibial Torsion does not.

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