



Al-Mustaqbal University / College of Engineering

Prosthetics & Orthotics Eng. Department

Third Class

Subject (**Biomechanics II**)

Code (**UOMU0103062**)

Asst. Lec. Mariam Ghassan Al-marroof

1st term – Lecture 4



Linear Kinematics, Centers of Gravity, Angular Kinematics, Dynamics of Joints.

Fundamental Concepts of Three-Dimensional Gait Analysis (3-D Gait Biomechanics)

1. Human Body Segment Model

In biomechanical gait analysis, the human body is modeled as a **system of rigid segments** connected by joints.

For the lower extremity, the main segments are:

- Thigh
- Calf (Shank)
- Foot

Each segment is defined by **Body Segment Parameters (BSPs)**:

- Segment mass
- Centre of gravity (CG)
- Moments of inertia

2. Linear Kinematics in 3-D Space

Each body segment in three-dimensional motion has **six degrees of freedom**:

Translational motion

- X direction
- Y direction
- Z direction

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Rotational motion

- Three angular rotations (Euler angles)

To uniquely determine segment motion, at least **three non-colinear markers** must be placed on each segment.

3. Marker-Based Motion Capture

The diagrams in the file illustrate a **15-marker model** placed on anatomical landmarks of:

- Pelvis
- Thighs
- Calves
- Feet

The marker coordinates are captured relative to a **global reference system (XYZ)**.

Diagram interpretation

- X axis → forward direction
- Y axis → Medio lateral direction
- Z axis → vertical direction

These coordinates vary as a function of time:

$$\text{Position} = f(t)$$



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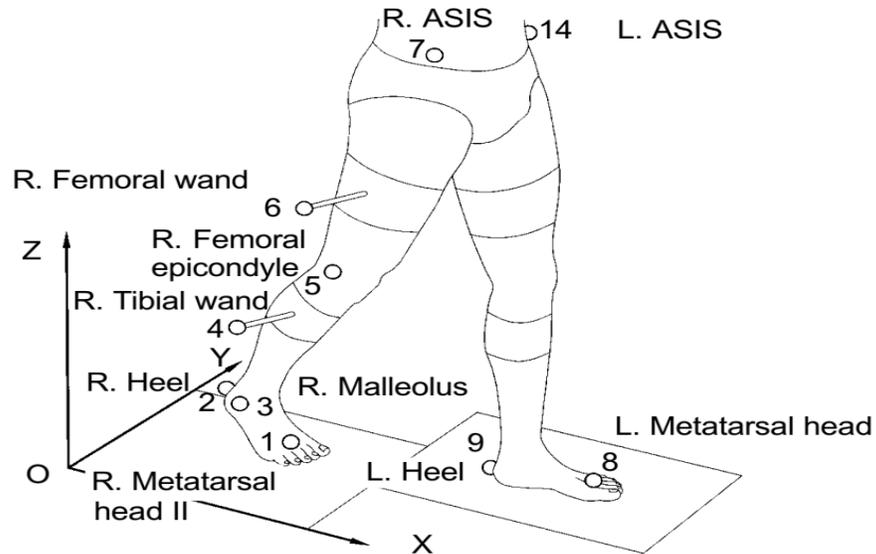
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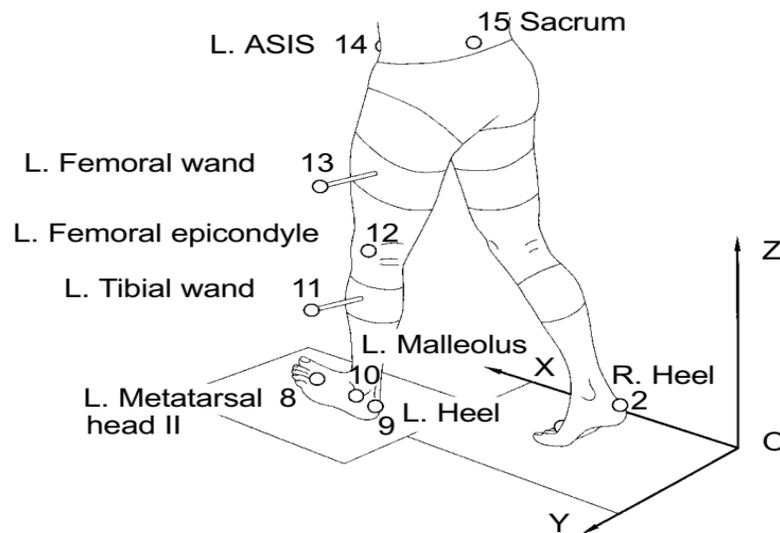
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a Global reference frame



b

Figure 3.4 The 15- marker system that uniquely defines the position of each segment in 3-D space: (a) anterior view; (b) posterior view.

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Note the position of the XYZ global reference system in Figure 3.4 with its origin at one corner of Force Plate 1. The X, Y, and Z coordinates of these 15 markers as a function of time may then be captured with standard equipment

Table 3.4 Three-Dimensional Displacement Data of External Landmarks at Time = 0.00 s (Right Heel Strike) of a Normal Male

Number	Name	X (m)	Y (m)	Z (m)
1	R. Metatarsal head V	0.157	0.142	0.057
2	R. Heel	-0.016	0.207	0.032
3	R Lateral malleolus	0.033	0.155	0.067
4	R. Tibial tubercle	0.002	0.181	0.443
5	R. Femoral epicondyle	-0.055	0.136	0.509
6	R. Greater trochanter	-0.207	0.082	0.880
7	R. ASIS	-0.161	0.141	0.979
8	L. Metatarsal head V	-0.578	0.392	0.032
9	L. Heel	-0.705	0.320	0.138
10	L. Lateral malleolus	-0.648	0.374	0.128
11	L. Tibial tubercle	-0.383	0.341	0.396
12	L. Femoral epicondyle	-0.369	0.393	0.495
13	L. Greater trochanter	-0.263	0.439	0.891
14	L. ASIS	-0.174	0.386	0.976
15	Sacrum	-0.369	0.242	0.962

Note. The XYZ positions refer to the global coordinate system defined in Figure 3.4, although the position of the subject in this figure is much later in the gait cycle (approaching right toe-off).



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Normal adult male

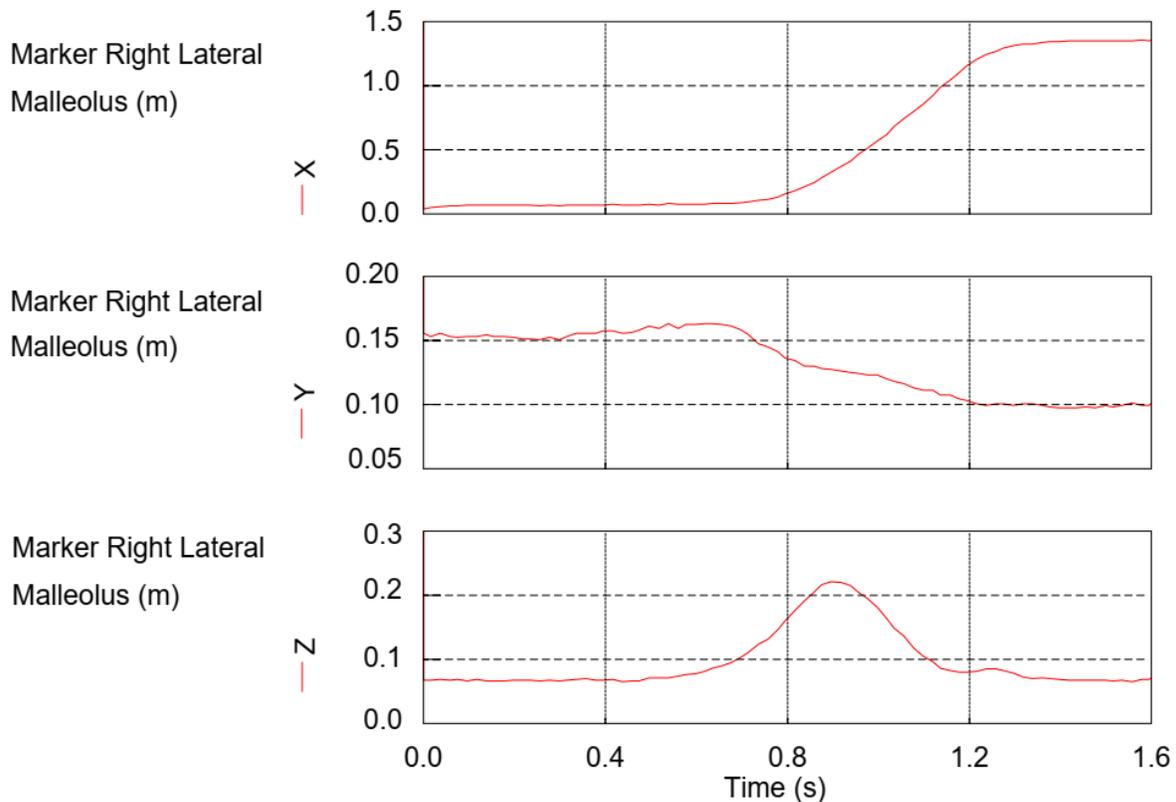


Figure 3.5 The 3-D coordinates of the right lateral malleolus plotted as a function of time. There are approximately one and a half gait cycles (i.e., from right heel strike beyond the next right heel strike) in this figure, as can be seen in the Z curve.



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4. Displacement, Velocity, and Acceleration

From marker displacement data:

Velocity

$$\text{Velocity} = \frac{\Delta \text{Position}}{\Delta \text{Time}}$$

Acceleration

$$\text{Acceleration} = \frac{\Delta \text{Velocity}}{\Delta \text{Time}}$$

Numerical differentiation is used after smoothing the data using digital filtering.

5. Prediction of Joint Centres

Because markers are placed on the skin rather than directly on bones, **joint centres must be estimated**.

The procedure illustrated in the diagrams includes:

1. Selecting three markers for each segment
2. Constructing a local coordinate system (uvw)
3. Applying anthropometric prediction equations

Foot segment

Markers:

- Heel
- Metatarsal head
- Lateral malleolus

Used to estimate:



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- Ankle joint centre
- Toe position

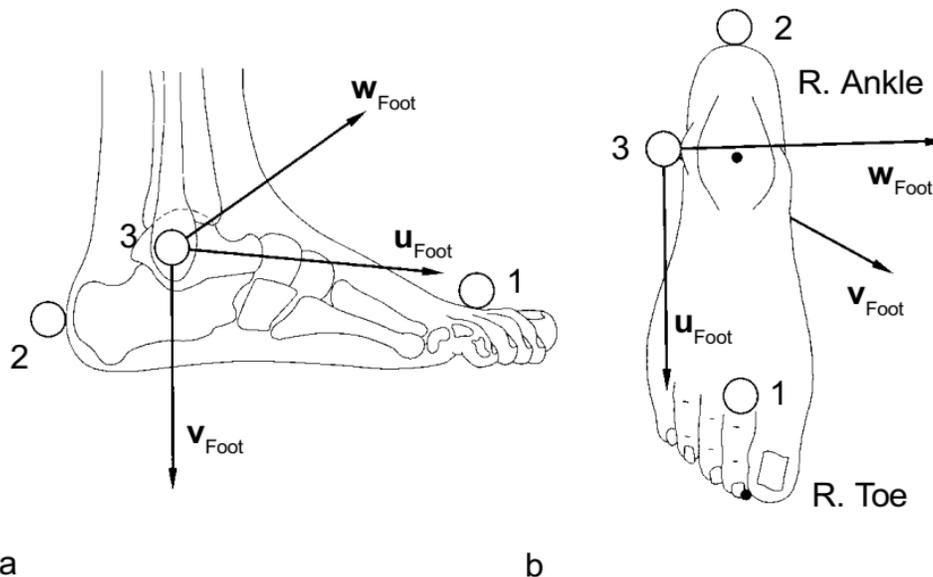


Figure 3.6 The three markers (1, 2, and 3) which define the position of the foot in 3- D space: (a) side view; (b) view from above. The uvw reference system may be used to predict the position of the ankle and toe.

When creating the uvw reference system, we first place the origin at Marker 3 (lateral malleolus). The three markers form a plane, and the **w axis is perpendicular** to this plane. The **u axis is parallel to the line between markers 2 and 1** although its origin is Marker 3. Finally, the v axis is at right angles to both u and w so that the three axes uvw form a so-called **right-handed system**. (To determine if a system is right-handed, point the fingers of our right hand in the direction of the u axis, curl them toward the v axis, and your thumb should be pointing in the w direction. This is called the right-handed screw rule.) Now that uvw for the foot has been defined, we can use this information in prediction equations to estimate the position of the ankle and longest toe:



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$$\begin{aligned} \mathbf{p}_{\text{Ankle}} &= \mathbf{p}_{\text{Lateral malleolus}} \\ &+ 0.016(\text{Foot length})\mathbf{u}_{\text{Foot}} \\ &+ 0.392(\text{Malleolus height})\mathbf{v}_{\text{Foot}} \\ &+ 0.478(\text{Malleolus width})\mathbf{w}_{\text{Foot}} \end{aligned} \quad (3.13)$$

$$\begin{aligned} \mathbf{p}_{\text{Toe}} &= \mathbf{p}_{\text{Lateral malleolus}} \\ &+ 0.742(\text{Foot length})\mathbf{u}_{\text{Foot}} \\ &+ 1.074(\text{Malleolus height})\mathbf{v}_{\text{Foot}} \\ &- 0.187(\text{Foot breadth})\mathbf{w}_{\text{Foot}} \end{aligned} \quad (3.14)$$

You should realise that these equations refer to the right ankle and toe. The mathematics for calculating uvw and distinguishing between the left and right sides may be found in Appendix B.

Calf segment

Markers:

- Lateral malleolus
- Tibial wand
- Femoral epicondyle

Used to estimate:

- Knee joint centre



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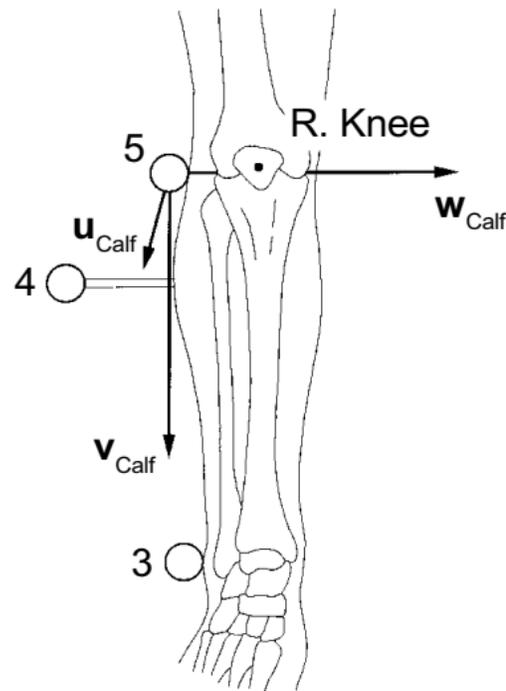


Figure 3.7 The three markers (3, 4, and 5), which define the position of the calf in 3-D space. This is an anterior view. The uvw reference system may be used to predict the position of the knee joint.

When creating the uvw reference system, we first place the origin at Marker 5, femoral epicondyle. The three markers form a plane, and the w axis is perpendicular to this plane. The v axis is parallel to the line between Markers 5 and 3. Finally, the u axis is at right angles to both v and w so that the three axes uvw form a right-handed system as before. We can now use this triad uvw for the calf to estimate the position of the knee joint centre based on the following prediction equation

$$\begin{aligned} \mathbf{p}_{\text{Knee}} &= \mathbf{p}_{\text{Femoral epicondyle}} \\ &+ 0.000(\text{Knee diameter})\mathbf{u}_{\text{Calf}} \\ &+ 0.000(\text{Knee diameter})\mathbf{v}_{\text{Calf}} \\ &+ 0.500(\text{Knee diameter})\mathbf{w}_{\text{Calf}} \end{aligned} \quad (3.15)$$



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As with the ankle, this equation refers to the right knee, but the mathematics for the left knee are essentially the same (see Appendix B).

Pelvis segment

Markers:

- Right ASIS
- Left ASIS
- Sacrum

Used to estimate:

- Right and left hip joint centres

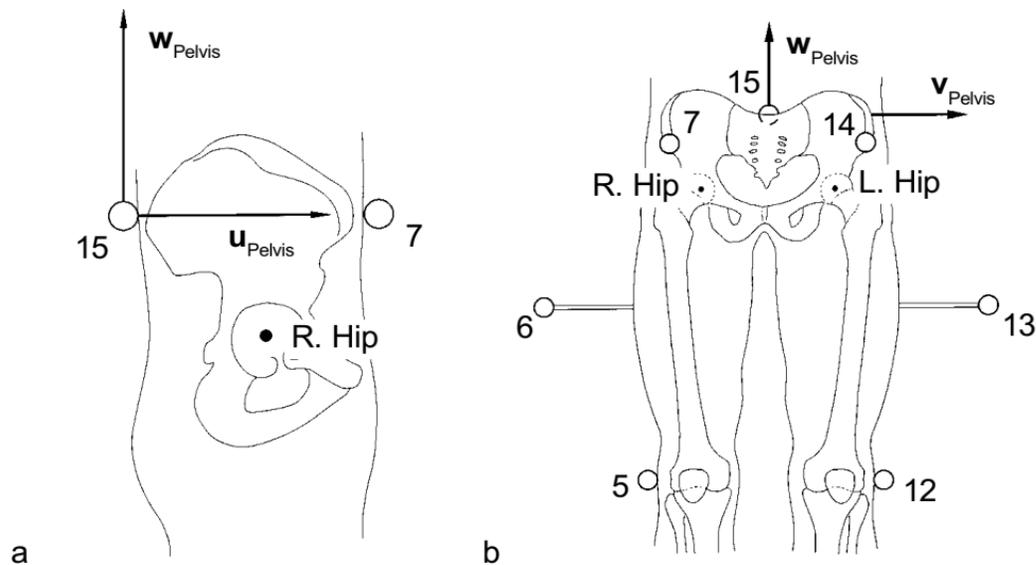


Figure 3.8 The three markers (7, 14, and 15), which define the position of the pelvis in 3-D space: (a) lateral view; (b) anterior view. The uvw reference system may be used to predict the position of the right and left hips



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When creating the uvw reference system for the pelvis, we first place the origin at Marker 15 (sacrum). The three markers form a plane, and the w axis is perpendicular to this plane. The v axis is parallel to the line between Markers 7 and 14, although its origin is Marker 15. Finally, the u axis is at right angles to both v and w so that the three axes uvw form a right-handed system. Now that uvw for the pelvis has been defined, we can use this information in a prediction equation to estimate the positions of the left and right hip joints:

$$\begin{aligned}
 \mathbf{P}_{\text{Hip}} = & \mathbf{P}_{\text{Sacrum}} \\
 & + (0.598)(\text{ASIS breadth})\mathbf{u}_{\text{Pelvis}} \\
 & +/- (0.344)(\text{ASIS breadth})\mathbf{v}_{\text{Pelvis}} \\
 & - (0.290)(\text{ASIS breadth})\mathbf{w}_{\text{Pelvis}}
 \end{aligned} \tag{3.16}$$

The – differentiates between the left (+) and right (-) hip joints.

Table 3.5 Three Dimensional Displacement Data of the Joint Centres and Foot Endpoints at Time= 0.00 s (Right Heel Strike) in a Normal Male

Joint/Point	X(m)	Y(m)	Z(m)
R. Hip	-0.193	0.161	0.905
L. Hip	-0.201	0.326	0.901
R Knee	-0.037	0.197	0.534
L. Knee	-0.327	0.326	0.509
R. Ankle	0.059	0.204	0.090
L. Ankle	-0.610	0.326	0.138
R. Heel	-0.007	0.205	0.036
L. Heel	-0.695	0.321	0.152
R. Toe	0.261	0.232	0.133
L. Toe	-0.441	0.308	0.018

Note. The XYZ positions refer to the global coordinate system defined in Figure 3.4.



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Normal adult male

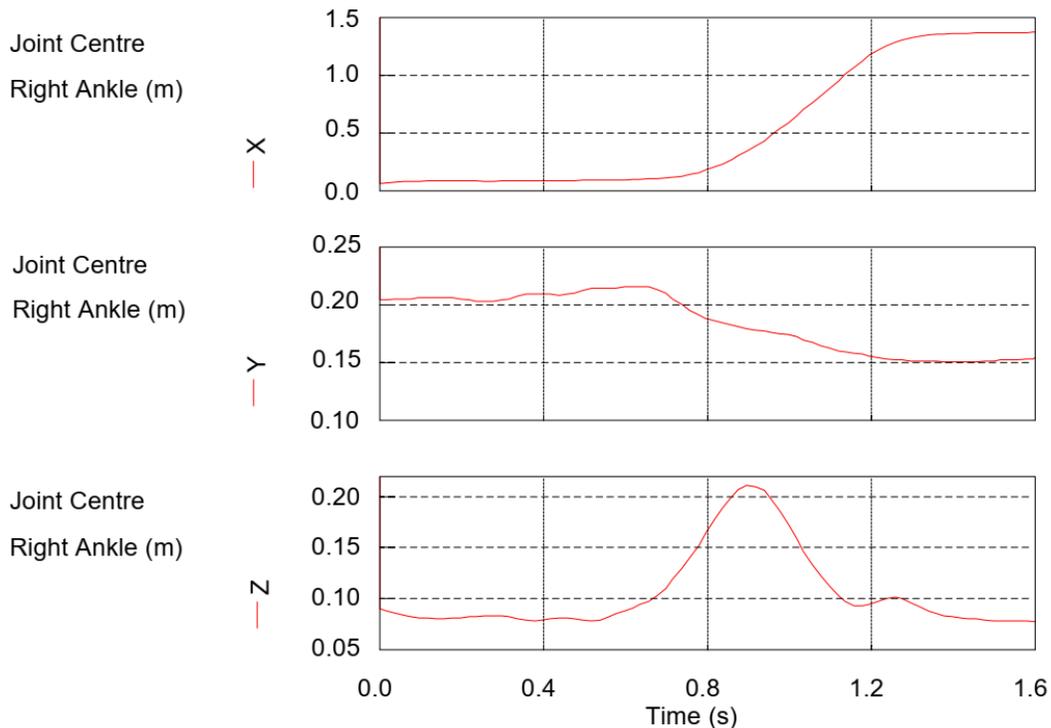


Figure 3.9 The 3-D coordinates of the right ankle joint while walking, plotted as a function of time. Note the similarities (and differences) between these curves and those in Figure 3.5, which are for the right lateral malleolus

6. Segment Orientation (Local Reference Frames)

After joint centres are calculated, a **local coordinate system (xyz)** is embedded in each segment.

Diagram interpretation

- x axis → distal to proximal direction
- y axis → anterior direction
- z axis → lateral direction



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Segment orientation is defined relative to the global coordinate system.

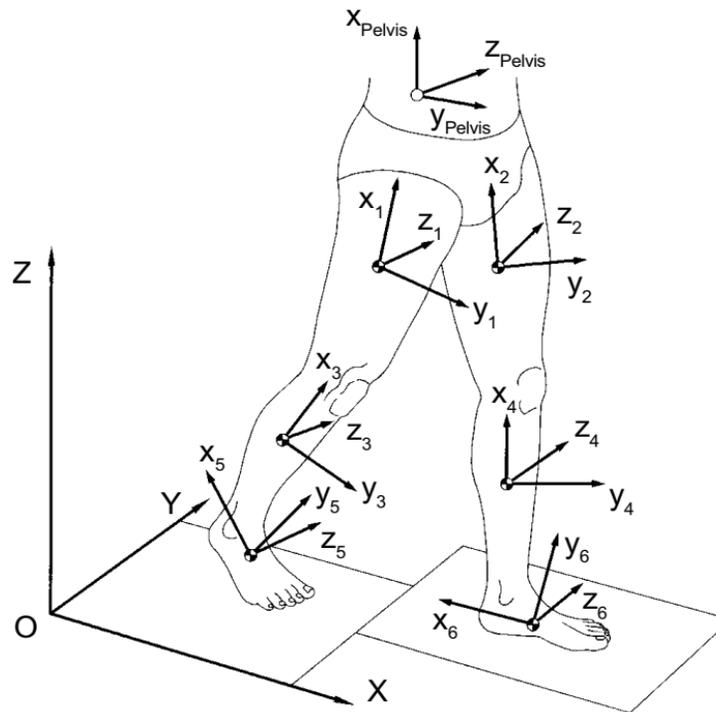


Figure 3.10 The segment reference frames (xyz) embedded at the centres of gravity of each segment. Note the segment numbering system: 1, right thigh; 2, left thigh; 3, right calf; 4, left calf; 5, right foot; and 6, left foot. Refer to the text for the definition of these reference frames.

Each segment has:

- x axis \rightarrow longitudinal direction
- y axis \rightarrow anterior direction
- z axis \rightarrow lateral direction

Required for:

- Angular kinematics
- Inverse dynamics



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7. Segment Centre of Gravity (CG)

The centre of gravity of each segment is calculated using joint centre locations and BSP ratios.

may be derived:

$$\mathbf{p}_{\text{Thigh.CG}} = \mathbf{p}_{\text{Hip}} + 0.39 (\mathbf{p}_{\text{Knee}} - \mathbf{p}_{\text{Hip}}) \quad (3.17)$$

$$\mathbf{p}_{\text{Calf.CG}} = \mathbf{p}_{\text{Knee}} + 0.42 (\mathbf{p}_{\text{Ankle}} - \mathbf{p}_{\text{Knee}}) \quad (3.18)$$

$$\mathbf{p}_{\text{Foot.CG}} = \mathbf{p}_{\text{Heel}} + 0.44 (\mathbf{p}_{\text{Toe}} - \mathbf{p}_{\text{Heel}}) \quad (3.19)$$

The diagrams show the CG positioned along each segment between proximal and distal endpoints.

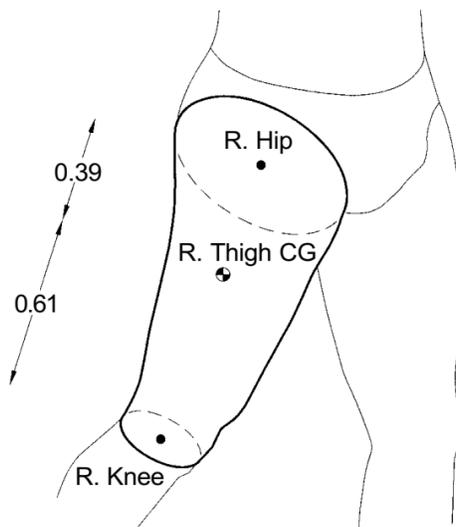


Figure 3.11 The location of the centre of gravity of the right thigh, with the joint centres (hip and knee) and corresponding body segment parameters (0.39, 0.61).