Chapter 4
Modelling the human joints
- Part 2 -

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The musculoskeletal system

- Steps for movement analysis:
  1. Identify at least 2 adjacent segments (bones) to define an anatomical joint;
  2. Measure at least 3 points 'solid' with each segments/bones;
  3. Define a ***technical coordinate system*** (**CS**$_T$) for each segment starting from the measured points;
  4. Find at least 3 anatomical landmarks of those segments;
  5. Define the ***anatomical coordinate systems*** (**CS**$_A$) starting from the anatomical landmarks;
  6. Define the ***anatomical calibration*** ${}^{A}\mathbf{T}_{T}$ for each segment;
  7. Define the ***Joint Coordinate System*** (**JCS**) that better models each joint.

The musculoskeletal system

1. Identify at least 2 adjacent segments (bones) to define an anatomical joint
   - e.g. knee joint: we need femur and shank
2. Measure at least 3 points ‘solid’ with each segments/bones
   - Mind that segments are considered rigid but they are not
   - Number and position of the ALs are chosen as a compromise between feasibility and ‘clean’ results (?)
3. Define a ***technical coordinate system*** (**CS**$_T$) for each segment starting from the measured points
   - No particular rules. Frequently, the **CS**$_T$ origin of a segment is close to its center of gravity.

The musculoskeletal system

4. Find at least 3 anatomical landmarks of those segments
   - Landmarks should be easily detectable and have good inter- and intra-subject repeatability, and reproducibility
5. Define the ***anatomical coordinate systems*** (**CS**$_A$) starting from the anatomical landmarks
   - Axes of a **CS**$_A$ are preferably aligned with the joint rotation axes

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6. Define the ***anatomical calibration*** $^{A}\mathbf{T}_{T}$ for each segment
   - Calculation of the position of the ALs in $\mathbf{CS}_T$
   - $\mathbf{CS}_A$ definition expressed in $\mathbf{CS}_T$
   - **Advice**: after the static trial and local CSs ($\mathbf{CS}_A$) registration, if we write the coordinates of the markers directly in $\mathbf{CS}_A$, we could save a step

$$\mathbf{C} = \mathbf{P}_{Ai}\mathbf{P}_{As}^{T} \rightarrow [\mathbf{U}, \mathbf{W}, \mathbf{V}] = \mathrm{svd}(\mathbf{C}) \rightarrow {}^{0}\mathbf{R}_{Ai} = \mathbf{U}_{Ai}\mathbf{V}_{Ai}^{T}$$

- $^{A}\mathbf{P}_{As}$ is the matrix containing the cluster of points relative to the static trial, i.e. the set of points expressed in CS_A
- $^{0}\mathbf{P}_{Ai}$ is the matrix containing the cluster of points relative to the i-th frame, i.e. the set of points expressed in CS_0 at the i-th frame

The musculoskeletal system

7. Define the ***Joint Coordinate System*** (**JCS**) that better models each joint
   - Not easy… In general, it is a good practice to define the $\mathbf{CS}_A$ orientation consistently with medical agreements
   - The better Cardan/Euler sequence is needed to model the anatomical joint avoiding, as much as possible, the Gimbal Lock condition

Comments…

- The following definitions are not standard:
  a. Technical coordinate systems for the segments
  b. Anatomical landmarks
  c. **CS_A**
  d. Joint Coordinate System (**JCS**) for each joint

- Comparing results of human movement analyses performed in different laboratories is not easy

- Frequently the **CS_T** is chosen coincident to the **CS_A**: the steps (4) and (5) are not needed anymore.

Joint Coordinate System standardization (International Society of Biomechanics)

ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip, and spine

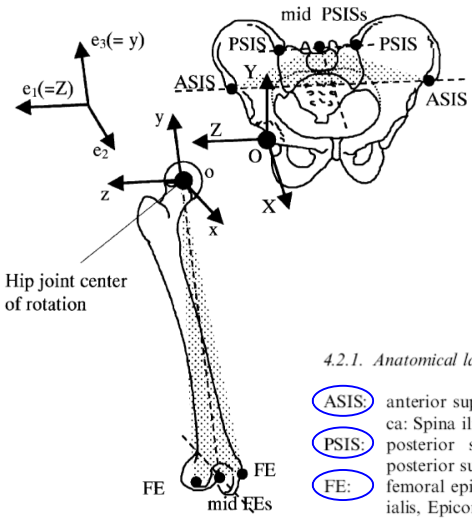
Abstract

The Standardization and Terminology Committee (STC) of the International Society of Biomechanics (ISB) proposes a general reporting standard for joint kinematics based on the Joint Coordinate System (JCS), first proposed by Grood and Suntay for the knee joint in 1983 (J. Biomech. Eng. 105 (1983) 136). There is currently a lack of standard for reporting joint motion in the field of biomechanics for human movement, and the JCS as proposed by Grood and Suntay has the advantage of reporting joint motions in clinically relevant terms.

In this communication, the STC proposes definitions of JCS for the ankle, hip, and spine. Definitions for other joints (such as shoulder, elbow, hand and wrist, temporomandibular joint (TMJ), and whole body) will be reported in later parts of the series. The STC is publishing these recommendations so as to encourage their use, to stimulate feedback and discussion, and to facilitate further revisions.

For each joint, a standard for the local axis system in each articulating bone is generated. These axes then standardize the JCS. Adopting these standards will lead to better communication among researchers and clinicians.

Hip: anatomical landmarks



Originally, a more universally acceptable reference system was sought, to be suitable for different biomechanical investigations, including gait analysis, radiographic analysis, in vitro studies, and finite element modeling. However, it was recognized that these different fields tend to use different anatomical landmarks and different reference axes. One reason is that the most reproducible landmarks of the bones are not necessarily accessible in vivo in standard practice. The present proposal defines landmarks easily accessible in humans from external palpation or from estimation methods, therefore not necessarily optimal for in vitro investigations, when the bone is entirely accessible. For these latter applications, different reference systems have been proposed and discussed (Ruff and Hayes, 1983; Yoshioka et al., 1987; Cristofolini, 1997).

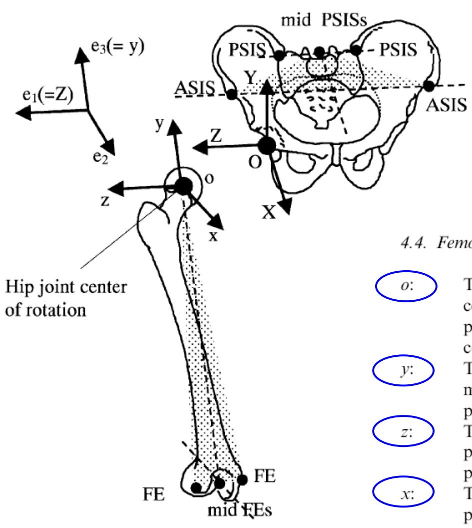
4.2.1. Anatomical landmarks used

ASIS: anterior superior iliac spine (Nomina anatomica: Spina iliaca anterior superior).

PSIS: posterior superior iliac spine (Spina iliaca posterior superior).

FE: femoral epicondyle (Epicondylus femoris medialis, Epicondylus femoris lateralis).

Hip: coordinate systems



4.2.2. Definition of hip center of rotation

For most areas of biomechanical research, the normal human hip joint is treated as a ball and socket joint, with the center of rotation defined as the center of hip joint, even if a measurable incongruity of ball and socket does exist. The location of the hip center of rotation has been estimated using either a "functional" approach (Cappozzo, 1984; Leardini et al., 1999) or a "prediction" approach (Bell et al., 1990; Davis et al., 1991; Seidel et al., 1995). The recommendation is to use the functional approach. This method seems appropriate

4.4. Femoral coordinate system—xyz (Fig. 3)

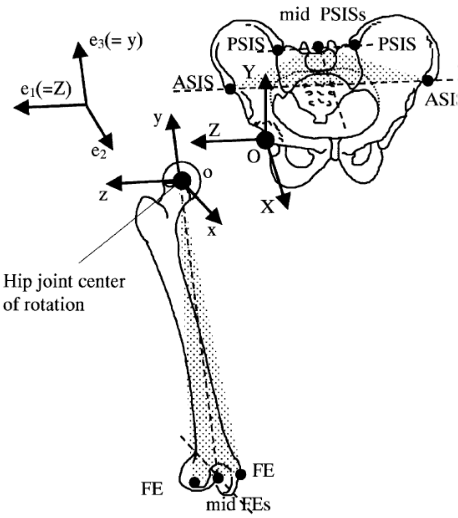
o: The origin coincident with the right (or left) hip center of rotation, coincident with that of the pelvic coordinate system (O) in the neutral configuration.

y: The line joining the midpoint between the medial and lateral FEs and the origin, and pointing cranially.

z: The line perpendicular to the *y*-axis, lying in the plane defined by the origin and the two FEs, pointing to the right.

x: The line perpendicular to both *y*- and *z*-axis, pointing anteriorly (Cappozzo et al., 1995).

Hip: Joint Coordinate System JCS



4.5. JCS and motion for the right (or left) hip joint

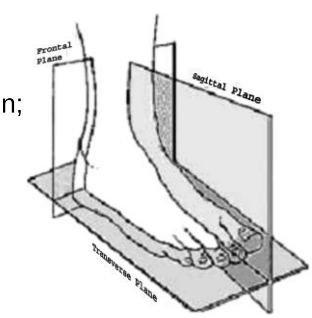
e_1: The axis fixed to the pelvis and coincident with the Z-axis of the pelvic coordinate system.
Rotation (α): flexion or extension.
Displacement (q_1): mediolateral translation.

e_3: The axis fixed to the femur and coincident with the y-axis of the right (or left) femur coordinate system.
Rotation (γ): internal or external rotation.
Displacement (q_3): proximo-distal translation.

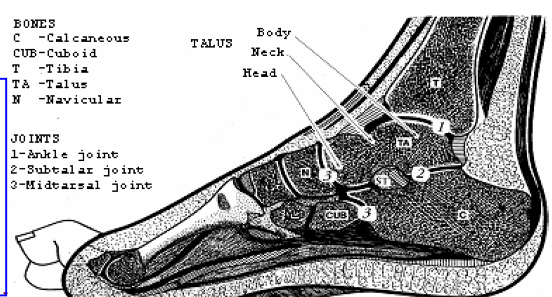
e_2: The floating axis, the common axis perpendicular to e_1 and e_3.
Rotation (β): adduction or abduction.
Displacement (q_2): antero-posterior translation.

Foot-ankle complex

- Angle α (sagittal plane): plantar/dorsiflexion;
- Angle β (frontal plane): inversion/eversion;
- Angle γ (transverse plane): abd/adduction



According to our terminology, the ankle joint complex is composed of the talocrural and the subtalar joints. A complete standard must include a separate set for each of these individual joints and an additional standard for the entire ankle joint complex (i.e. calcaneus relative to tibia/fibula). However, a standard for the foot to shank system will address the needs of a great majority of the biomechanical community that is concerned with functional activities such as walking and running. In these studies external anatomical landmarks are being used and it is not possible to directly distinguish between talocrural and the subtalar joints. It was therefore decided to propose a standard for the ankle joint complex first, and to develop the standards for the talocrural joint and for the subtalar joint at a later time. Tibio-fibular articulation could also be addressed at a later time.



Ankle: anatomical landmarks

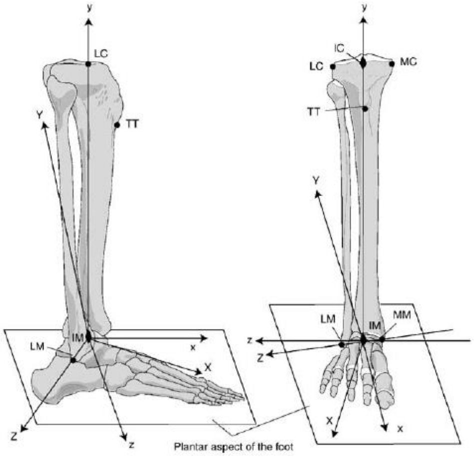


Fig. 1. Illustration of the tibia/fibula coordinate system (*XYZ*) and the calcaneus coordinate system (*xyz*) with the ankle joint complex in the neutral position.

3.2.1. Joint definition

The ankle (talocrural) joint: The articulation formed between the talus and the tibia/fibula.
The subtalar (talocalcaneal) joint: The articulation between the talus and the calcaneus.
The ankle joint complex: The structure composed of the ankle and the subtalar joints.

3.2.2. Anatomical landmarks used in this proposal

MM: Tip of the medial malleolus.
LM: Tip of the lateral malleolus.
MC: The most medial point on the border of the medial tibial condyle.
LC: The most lateral point on the border of the lateral tibial condyle.
TT: Tibial tuberosity.
IM: The inter-malleolar point located midway between MM and LM.
IC: The inter-condylar point located midway between the MC and LC.

Ankle: anatomical planes

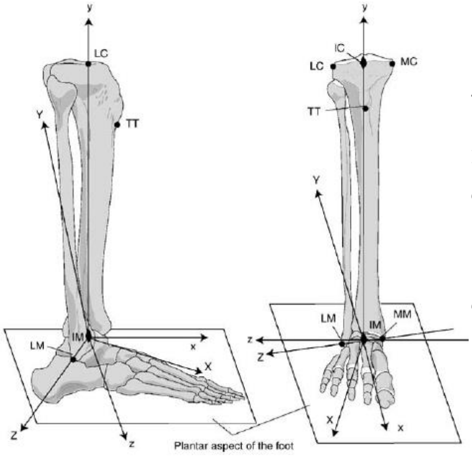


Fig. 1. Illustration of the tibia/fibula coordinate system (*XYZ*) and the calcaneus coordinate system (*xyz*) with the ankle joint complex in the neutral position.

3.2.3. Definition of standard anatomical planes of the tibialfibula (Fig. 1)

Frontal plane: The plane containing points IM, MC and LC.
Torsional plane: The plane containing points IC, MM and LM.
Sagittal plane: The plane perpendicular to the frontal plane and containing the long axis of the tibia/fibula (the line connecting points IC and IM).
Transverse plane: The mutual plane perpendicular to the frontal and sagittal planes.

Ankle: coordinate systems

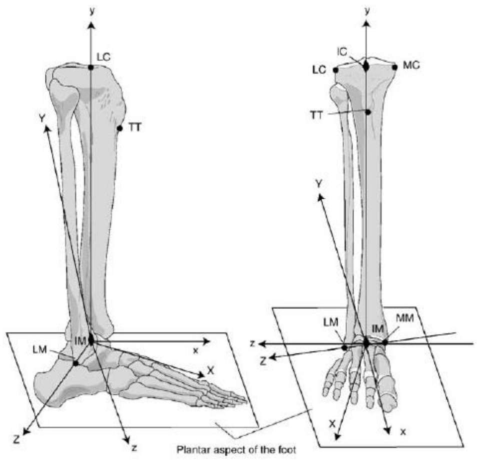


Fig. 1. Illustration of the tibia/fibula coordinate system (XYZ) and the calcaneus coordinate system (xyz) with the ankle joint complex in the neutral position.

3.3. Tibialfibula coordinate system—XYZ (Fig. 1)

O: The origin coincident with IM.

Z: The line connecting MM and LM, and pointing to the right.

X: The line perpendicular to the torsional plane of the tibia/fibula, and pointing anteriorly.

Y: The common line perpendicular to X- and Z-axis.

3.4. Calcaneus coordinate system—xyz (Fig. 1)

o: The origin coincident with that of the tibia/fibula coordinate system (O) in the neutral configuration.

y: The line coincident with the long axis of the tibia/fibula in the neutral configuration, and pointing cranially.

x: The line perpendicular to the frontal plane of the tibia/fibula in the neutral configuration, and pointing anteriorly.

z: The common line perpendicular to x- and y-axis.

Ankle: JCS

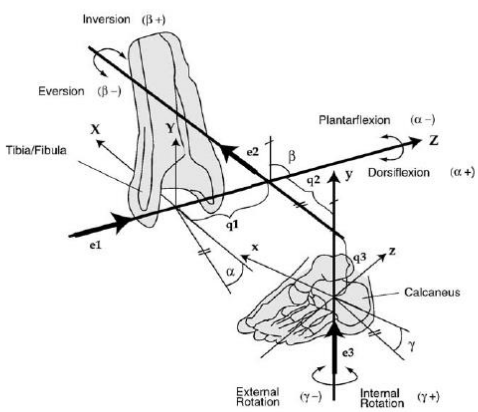


Fig. 2. Illustration of the JCS for the right ankle joint complex.

3.5. JCS and motion for the ankle complex (Fig. 2)

e_1: The axis fixed to the tibia/fibula and coincident with the Z-axis of the tibia/fibula coordinate system.
Rotation (α): dorsiflexion (positive) or plantar-flexion (negative).
Displacement (q_1): medial (negative) or lateral (positive) shift.

e_3: The axis fixed to the calcaneus and coincident with the y-axis of the calcaneal coordinate system.
Rotation (γ): internal rotation (positive) or external rotation (negative).
Displacement (q_3): correspond to compression (positive) or distraction (negative).

e_2: The floating axis, the common axis perpendicular to e_1 and e_3.
Rotation (β): inversion (positive) or eversion (negative).
Displacement (q_2): anterior (positive) or posterior (negative) drawer.