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Letter to the editor

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. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

Since November 1993, the Standardization and Terminology Committee (STC) of the International Society of Biomechanics (ISB) has begun its journey of developing a set of standards for reporting joint motion. Headed by Drs. Peter Cavanagh and Ge Wu in 1993, an initial decision was made to adopt the Joint Coordinate System (JCS), first proposed by Grood and Suntay in 1983 (Grood and Suntay, 1983), as the standard. This decision was publicized to the biomechanics community via Biomech-L, an electronic discussion network. With the enormous amount of support received from the Biomech-L subscribers, the STC then decided to move forward with this decision. A group of volunteers was recruited via Biomech-L who would like to participate in the effort of developing the JCS for each of the major joints in the body. To date, nine subcommittees involving a total of 25 people have been established and, so far, eight proposals have been completed. They include ankle, hip, spine, shoulder, elbow, hand and wrist, TMJ, and whole body.

There are two main reasons as to why these JCSs are established. First, there is a lack of standard for reporting joint motion in the field of biomechanics for human movement. This makes the comparisons among various studies difficult, if not impossible. Secondly, the use of JCS as proposed by Grood and Suntay has the advantage of reporting joint motions in clinically relevant terms. This makes the application and interpretation of biomechanical findings easier and more welcoming to clinicians.

Although all of the JCS recommendations have been published in various forms, such as in previous ISB Newsletters, and on the ISB Home Page, only a few of them have been test-used and subsequently revised. The purpose of this paper is to present these JCS definitions to the biomechanics community so as to encourage the use of these recommendations, to provide first hand feedback, and to facilitate the revisions. It is hoped that this process will help the biomechanics community to move towards the development and use of a set of widely acceptable standards for better communication among various research groups, and among biomechanists, physicians, physical therapists, and other related interest groups.

2. Overview of JCS

All recommendations of JCS for various joints follow the similar procedures as proposed by Grood and

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Suntay (1983). First, a Cartesian coordinate system (CCS) is established for each of the two adjacent body segments. The axes in these CCSs are defined based on bony landmarks that are either palpable or identifiable from X-rays, and follow the ISB general recommendations (Wu and Cavanagh, 1995). The common origin of both axis systems is the point of reference for the linear translation occurring in the joint, at its initial neutral position. Secondly, the JCS is established based on the two CCSs. Two of the JCS axes are body fixed, and one is "floating". Lastly, the joint motion, including three rotational and three translational components, is defined based on the JCS.

3. JCS for the ankle joint complex

3.1. Introduction

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.

3.2. Terminology

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.

3.2.3. Definition of standard anatomical planes of the tibia/fibula (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.

3.2.4. Definition of the neutral configuration of the ankle joint complex

Neutral dorsiflexion/plantarflexion: Zero degrees between the long axis of the tibia/fibula and the line perpendicular to the plantar aspect of the foot projected onto the sagittal plane of the tibia/fibula.
Neutral inversion/eversion: Zero degrees between the long axis of the tibia/fibula and the line perpendicular to the plantar aspect of the foot

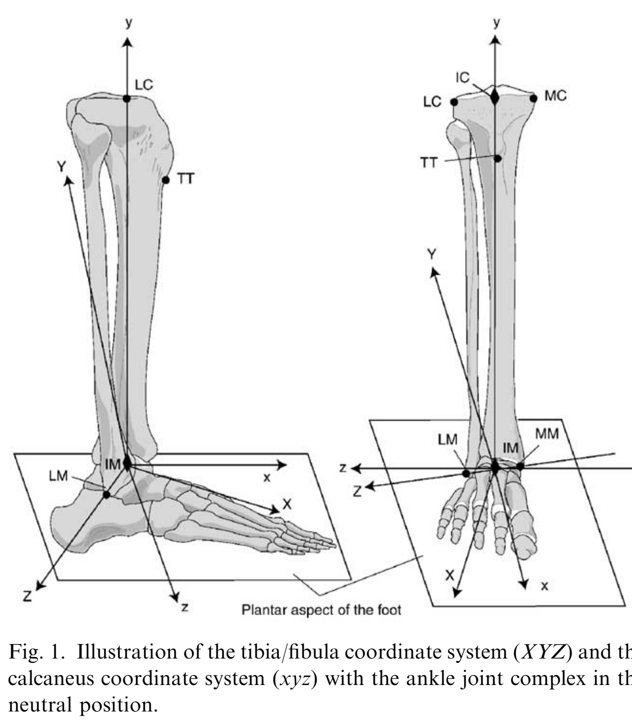

Fig. 1. Illustration of the tibia/fibula coordinate system (XYZ) and the calcaneus coordinate system (xyz) with the ankle joint complex in the neutral position.

projected onto the frontal plane of the tibia/fibula.

Neutral internal/external rotation: Zero degrees between the line perpendicular to the frontal plane of the tibia/fibula and the long axis of the second metatarsal, projected onto the transverse plane of the tibia/fibula.

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.

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 plantarflexion (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.

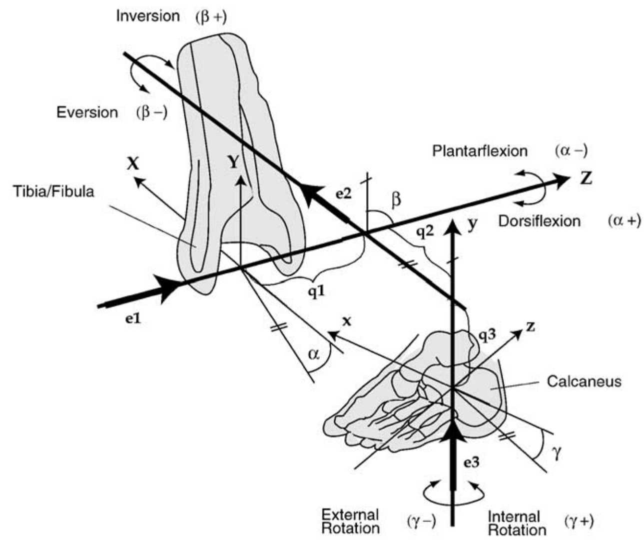

Fig. 2. Illustration of the JCS for the right ankle joint complex.

4. JCS for the hip joint

4.1. Introduction

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. Definitions

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).

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 when it is possible to analyze an adequate range of motion at the hip. More specific algorithms can also be examined for the optimal estimation of the center of this spherical rotation. Alternatively, when hip rotations cannot be effectively obtained, any of the prediction methods may be used. In choosing among them, a recent paper (Stagni et al., 2000) has demonstrated that the large inaccuracies reported for hip joint center estimation (Leardini et al., 1999) affect calculations of both angles and moments at the hip and knee joints. Hip moments showed the largest propagation error, with the flexion–extension component being particularly sensitive to errors in antero-posterior direction.

4.3. Pelvic coordinate system—XYZ (Fig. 3)

- O: The origin coincident with the right (or left) hip center of rotation.
- Z: The line parallel to a line connecting the right and left ASISs, and pointing to the right.
- X: The line parallel to a line lying in the plane defined by the two ASISs and the midpoint of the two PSISs, orthogonal to the Z-axis, and pointing anteriorly.
- Y: The line perpendicular to both X and Z, pointing cranially (Cappozzo et al., 1995).

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).

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

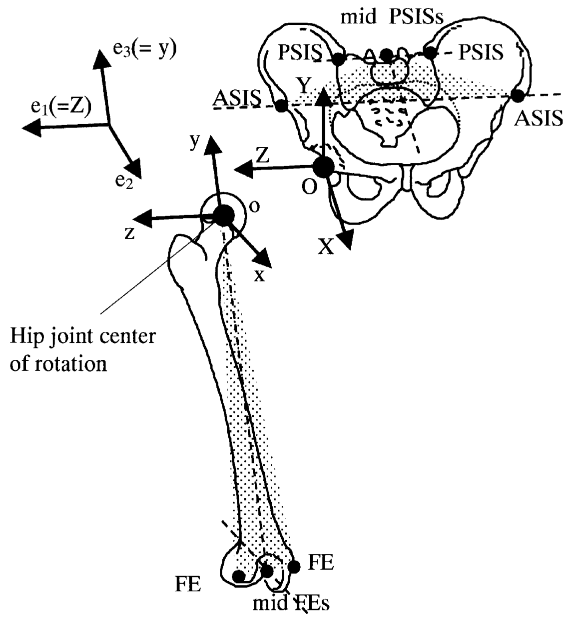

Fig. 3. Illustration of the pelvic coordinate system (XYZ), femoral coordinate system (xyz), and the JCS for the right hip joint.

- 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.

5. JCS for the spine

5.1. Introduction

Spinal motion occurs at intervertebral joints between adjacent vertebrae. These are the seven cervical vertebrae, twelve thoracic vertebrae and five lumbar vertebrae. Spinal motion is the summation of the intervertebral motion occurring at all mobile joints. Overall spinal motion is the motion that occurs between the head and the pelvis. Regional motion is the motion in a defined section of the spine (e.g. the lumbar spinal motion is the motion that occurs between the pelvis and the thorax).

Vertebrae articulate with their neighboring vertebrae via a flexible intervertebral disc and the two zygoapophyseal (facet) joints that are diarthroidial joints. The uppermost cervical vertebra articulates with the occiput. Thoracic vertebrae additionally articulate with the ribs (Schultz et al., 1974). The most caudal vertebra (L-5) articulates with the first of the sacral vertebrae (sacral vertebrae are fused together to form the sacrum). The sacrum articulates with the two innominate bones, also known as ilia that in turn have a flexible articulation with each other at the pubic symphysis. The ilia also include the acetabula that articulate with the femora.

This proposed standard concerns the intervertebral motion between adjacent vertebrae, but the principles can be extended to regional and overall spinal motion. The intervertebral articulations have six degrees of freedom (three translations and three rotations) each of which has a measurable stiffness. Therefore, there are six independent parameters of motion (three displacements and three rotations). The load-displacement characteristics of these joints has been described by a stiffness matrix (Panjabi et al., 1976). This stiffness matrix has off-diagonal ('coupling') terms as well as diagonal terms. Therefore the pattern of motion that occurs between two vertebrae depends on the combination of forces applied, and it is only possible to define an instantaneous axis of rotation, since no fixed joint axis exists. The helical axis of motion is as alternative to the three rotations and three translations description of intervertebral motion. Using the helical axis of rotation, the motion is described by the position and direction of an axis of motion, together with a scalar translation along this axis and a scalar rotation around it.

5.2. Vertebral coordinate system—XYZ (proximal) and xyz (distal) (Fig. 4)

O(o): The origin is the intersection of the axes Y and y in the reference, neutral position (see Fig. 5a. The neutral position must be specified, and must be in a position where the vertebral axes Y and y are coplanar. If Y and y are parallel (do not intersect at the common origin O) the Y- and y-axis are constrained to be colinear, and the origin O is the mid-point between adjacent endplates (see Fig. 5b).

Y(y): The line passing through the centers of the vertebra's upper and lower endplates, and pointing cephalad.

Z(z): The line parallel to a line joining similar landmarks on the bases of the right and left pedicles, and pointing to the right.

X(x): The line perpendicular to the Y- and Z-axis, and pointing anteriorly.

It should be noted that other axis conventions have been described. White and Panjabi (1978) have X left; Y cephalad, Z anterior. ISO 2631, SAE J-211, and the Scoliosis Research Society (Stokes, 1994) have X anterior, Y left and Z cephalad.

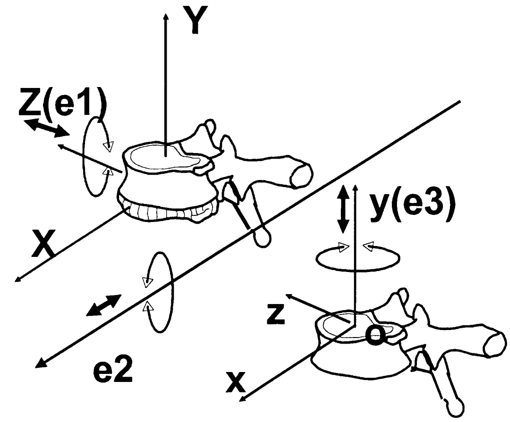

Fig. 4. Illustration of a proximal vertebral coordinate system (XYZ), a distal vertebral coordinate system (xyz), and the corresponding JCS.

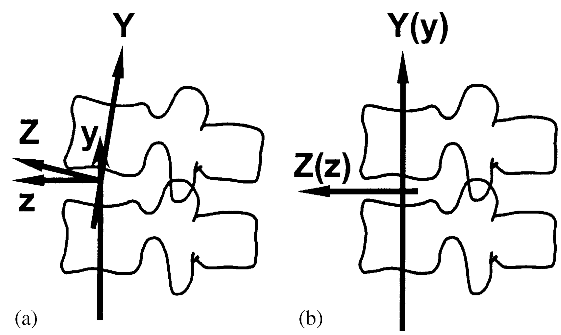

Fig. 5. Location of the common origin of axes: (a) the general case; (b) the specific case of Y and y being parallel. Note: the Y-and y-axis must be coplanar in the reference position of the two vertebrae.

5.3. JCS and motion for the spine (Fig. 4)

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

e_3: The axis fixed to the distal vertebra and coincident with the y-axis of the distal vertebra coordinate system.
Rotation (γ): axial rotation.
Displacement (q_3): proximo-distal translation.

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

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