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PART I

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Abstract:

This Technical Annex defines the anatomical conventions, reference frame convention and joint system convention the VAKHUM project will use for internal data exchange. These conventions are mainly based on current international standards.

Keyword list:

Anatomical landmarks, reference systems, kinematics.

PART II

This Technical Annex defines the anatomical conventions, reference frame convention and joint system convention the VAKHUM project will use for internal data exchange.

A first part defines the general anatomical axes and planes. Then, segment anatomical systems are described for the pelvis, femur, tibio/fibula and foot segment. At least, joint systems are also given according two conventions. One (Joint Reference System, or JRS) is more suitable for animation, while the other (Joint Coordinate System, or JCS) is widely used and accepted in the Biomechanics field and is widely used in clinical situations.

The conventions in this report are mainly based on current international standards (e.g. from the International Society of Biomechanics) and therefore the authors recommend that they should be used when data is made available to public.

PART III

1. Anatomical coordinate systems

See figure 1.

1.1. General direction axes[1,2]

The directions of the three Cartesian axes are mutually perpendicular, one axis is vertical, and the directions of the remaining two horizontal axes are not usually contentious.

y-axis	the **y-axis** is generally vertical (parallel to the field of gravity $\vec{g}$) and points upwards.
z-axis	the **z-axis** is perpendicular to the **y-axis**, pointing to the right direction.
x-axis	the **x-axis** is perpendicular to both **y-axis** and **z-axis** and is pointing in the anterior direction (direction of progression).

1.2. Anatomical planes

transverse plane	this plane is perpendicular to the **y-axis**.
sagittal plane	this plane is perpendicular to the **z-axis** and parallel to $\vec{g}$.
coronal plane	this plane is mutually perpendicular to both **transverse** and **sagittal plane**.

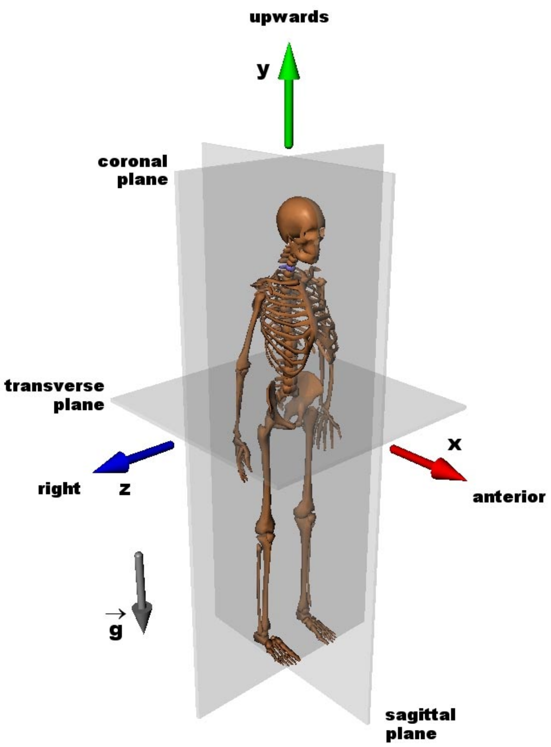

figure 1. Anatomical coordinate system and planes.

[1] Wu G., Cavanagh P.R. "ISB recommendations for standardization in the reporting data". *J.Biomech.*, vol. 28, pp. 1257-1261, 1995.
[2] A.Cappozzo, F.Catani, U.DellaCroce, A.Leardini. "Position and orientation in space of bones during movement: anatomical frame definition and determination". *Clin. Biomech.*, vol.10(4), pp. 171-178, 1995.

2. Segments anatomical systems

All following references systems can be dependent upon each other. For example, the knee anatomical frame can be dependent upon the pelvic anatomical frame; this is useful to study full-limb motion. On the other hand, studies of isolated joints require only independent frames.

Furthermore, the frames can also be within some supplementary frame, which are not defined in this report. For example, the pelvic anatomical frame (see below) can be located within a global reference frame (e.g. laboratory frame); this is useful to study the displacement of the pelvic bone within the global frame. If no displacement in an external frame is necessary, then the global reference system used for the animation can be similar to the pelvic anatomical frame.

2.1. Pelvic segment

See figure 2.

2.1.1. Pelvic anatomical landmarks[3,4]

rasis right anterior superior iliac spine.
lasis left anterior superior iliac spine.
rpsis right posterior superior iliac spine.
lpsis left posterior superior iliac spine.

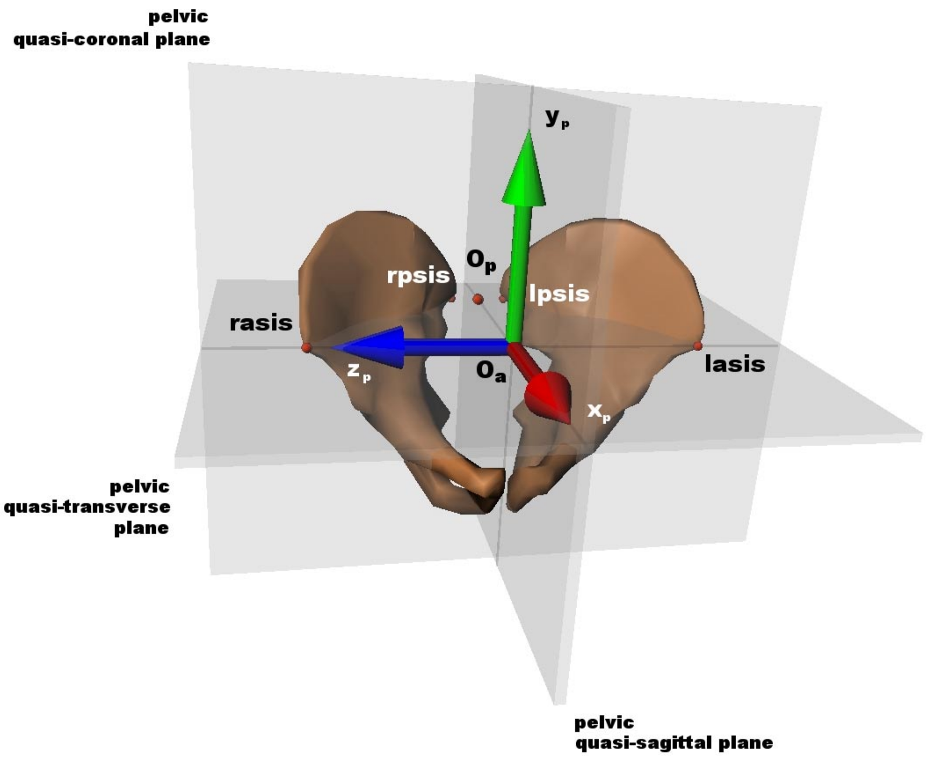

figure 2. Pelvic anatomical frame.

[3] Benedetti M.G., Capozzo A., Catani F., Leardini A. "Anatomical Landmark Definition and Identification". *CAMARC II Interanal Report*, 15 March 1994.
[4] Della Croce U., Capozzo A., Kerrigan D.C. "Pelvis and lower limbs anatomical landmark calibration precision and its propagation to bone geometry and joint angle". *Med. Biol. Eng. Comput.* vol 37, pp. 151-161, 1999.

2.1.2. Pelvic anatomical planes

pelvic quasi-transverse plane	this plane is defined by **rasis**, **lasis** and the point midway between **rpsis** and **lpsis** (**O_p**).
pelvic quasi-coronal plane	this plane is orthogonal to the **pelvic quasi-transverse plane** and containing both **rasis** and **lasis**.
pelvic quasi-sagittal plane	this plane is mutually perpendicular to both **quasi-transverse** and **quasi-coronal plane of the pelvis**.

2.1.3. Pelvic anatomical frame

O_a	the **O_a** point defines the origin of the anatomical frame of the pelvic segment **$x_py_pz_p$**.; this point is the midpoint between the **rasis** and **lasis**.
z_p-axis	this axis is oriented along the line passing through the **rasis** and **lasis** with its positive direction pointing right.
x_p-axis	this axis lies in the **pelvic quasi-transverse plane** and, is perpendicular to the **z_p-axis**, its positive direction is anterior.
y_p-axis	this axis is mutually perpendicular to both the **x_p-axis** and the **z_p-axis**, and is pointing upwards.

2.2. Femur segment

See figure 3.

2.2.1. Femur anatomical landmarks[5]

fh centre of the femoral head.
le lateral epicondyle.
me medial epicondyle.

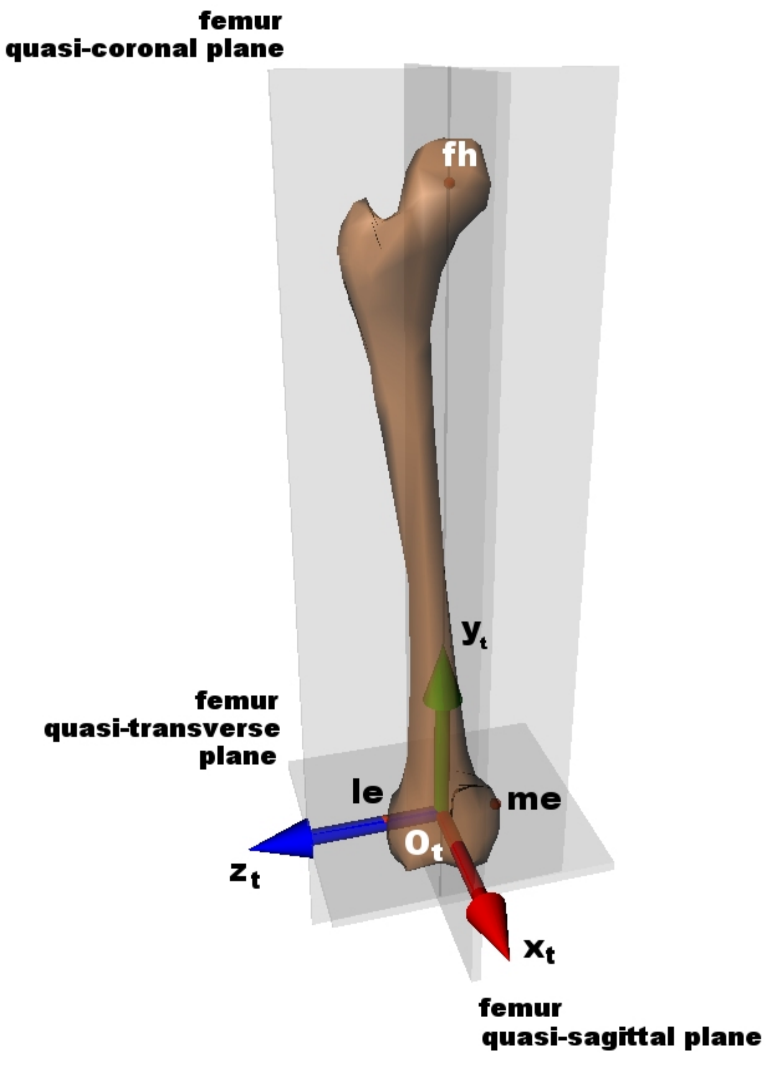

figure 3. Femur anatomical frame.

[5] Idem 3,4

2.2.2. Femur anatomical plane

femur quasi-coronal plane this plane is defined by **me**, **le** and **fh**.

femur quasi-sagittal plane this plane is orthogonal to the **femur quasi-coronal plane** and contains both **O_t** (midway between **me**, **le**) and **fh**.

femur quasi-transverse plane this plane is mutually perpendicular to both **quasi-coronal** and **quasi- sagittal plane of the femur**.

2.2.3. Femur anatomical frame

O_t the **O_t** point defines the origin of the anatomical frame of the thigh segment **$x_ty_tz_t$**. this point is the midpoint between the **le** and **me**.

y_t-axis this axis is oriented along the line passing through **O_t** and **fh**, with the positive direction upwards.

z_t-axis this axis is lying in the **femur quasi-coronal plane** and is perpendicular to the **y_t-axis**, with the positive direction pointing right

x_t-axis this axis is mutually perpendicular to the **y_t-axis** and the **z_t-axis** and is pointing to the anterior.

2.3. Tibial/Fibula segment

See figure 4.

2.3.1. Tibial/Fibula anatomical landmarks[6]

hf	apex of the head of the fibula.
tt	prominence of the tibial tuberosity
lm	distal apex of the lateral malleolus.
mm	distal apex of the medial malleolus.

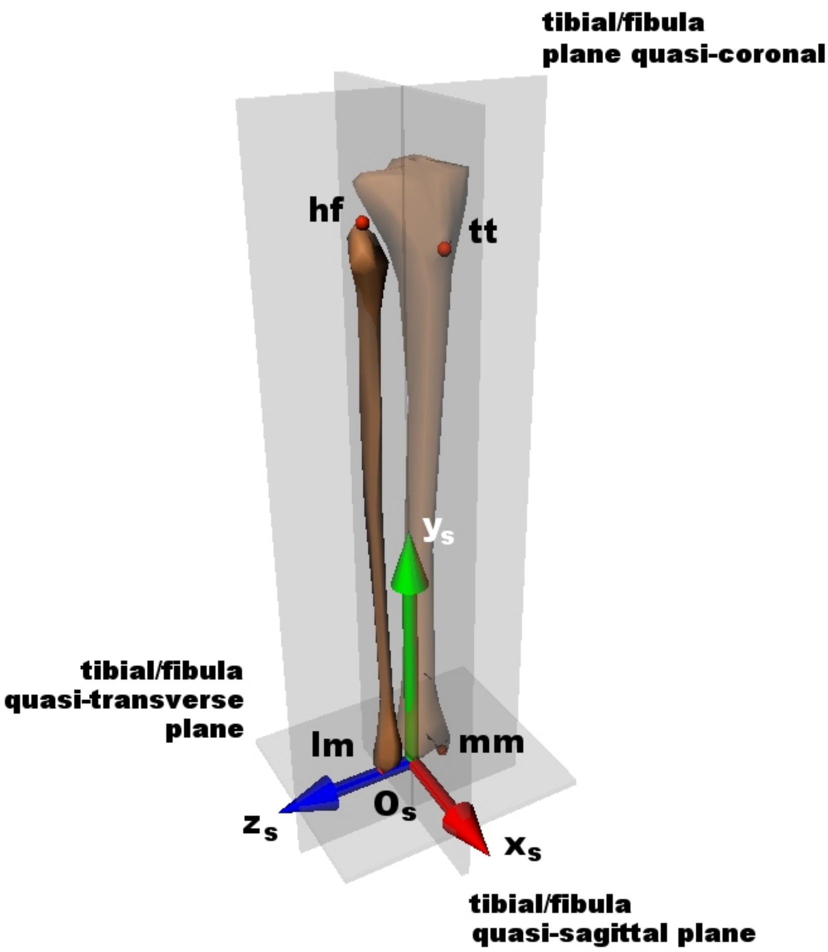

figure 4. Tibial/Fibula anatomical frame.

[6] Idem 3,4

2.3.2. Tibial/Fibula anatomical plane

tibial/fibula quasi-coronal plane	this plane is defined by **hf**, **lm** and the midpoint $\mathbf{O_s}$ between **lm** and **mm**.
tibial/fibula quasi-sagittal plane	this plane is orthogonal to the **tibial/fibula quasi-coronal plane**, and contains both $\mathbf{O_s}$ and **tt**.
tibial/fibula quasi-transverse plane	this plane is mutually perpendicular to the **tibial/fibula quasi-coronal** and **quasi- sagittal plane**.

2.3.3. Tibial/Fibula anatomical frame

$\mathbf{O_s}$	the $\mathbf{O_s}$ point defines the origin of the anatomical frame of the shank segment $\mathbf{x_s y_s z_s}$. and is located at the midpoint of the line joining **lm** and **mm**.
$\mathbf{y_s}$**-axis**	this axis is defined by the intersection between the **tibial/fibula quasi-coronal** and **quasi-sagittal plane** with positive direction upwards.
$\mathbf{z_s}$**-axis**	this axis is lying in the **tibial/fibula quasi-coronal plane** and is perpendicular to the $\mathbf{y_s}$**-axis**, with positive direction pointing right
$\mathbf{x_s}$**-axis**	this axis is mutually perpendicular to the $\mathbf{y_s}$**-axis** and the $\mathbf{z_s}$**-axis** and is pointing to the anterior.

2.4. Foot segment

See figure 5.

2.4.1. Foot anatomical landmarks[7]

ca upper ridge of the calcaneus.
fm dorsal aspect of first metatarsal head.
sm dorsal aspect of second metatarsal head.
vm dorsal aspect of fifth metatarsal head.

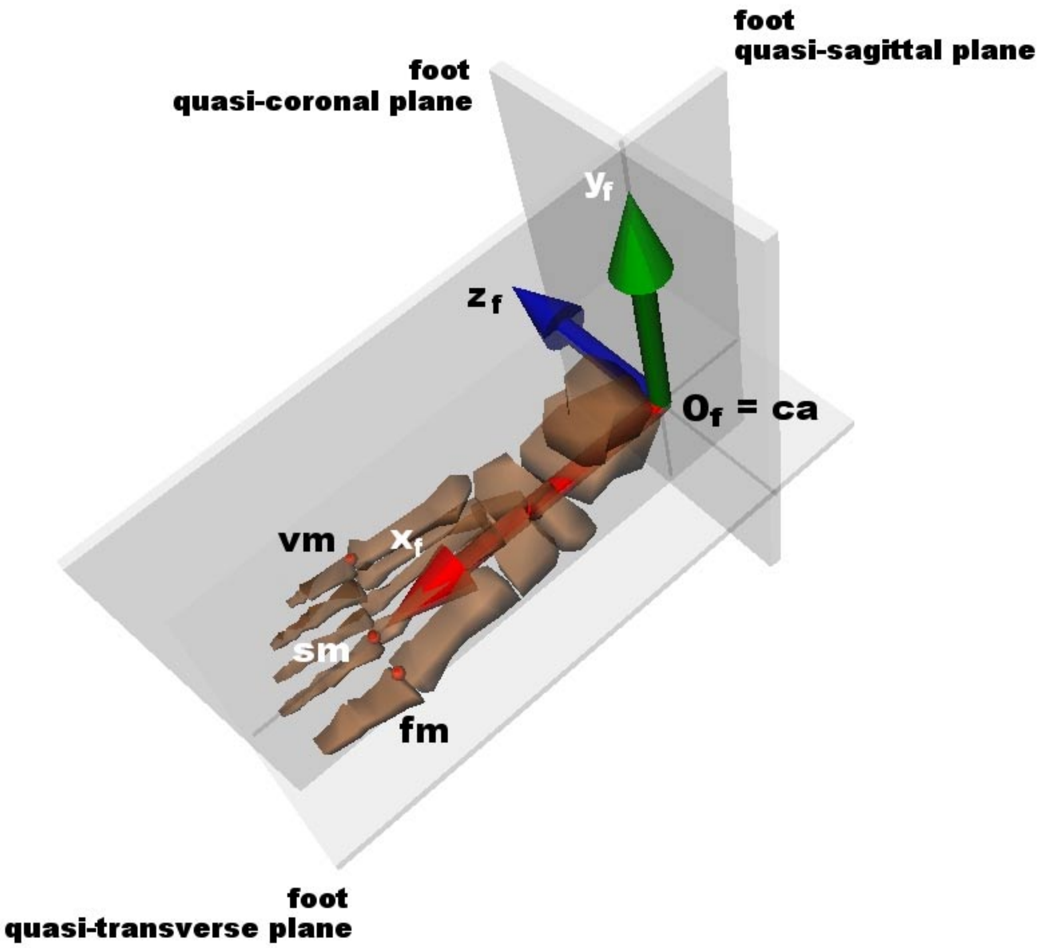

figure 5. Foot anatomical frame.

[7] Idem 2

2.4.2. Foot anatomical plane

foot quasi-transverse plane	this plane is defined by **ca**, **fm** and **vm**.
foot quasi-sagittal plane	this plane is orthogonal to the **foot quasi-transverse plane** and contains both **ca** and **sm**.
foot quasi-coronal plane	this plane is mutually perpendicular to the **foot quasi-transverse** and **quasi-sagittal plane**.

2.4.3. Foot anatomical frame

$\mathbf{O_f}$	the $\mathbf{O_f}$ point defines the origin of the anatomical frame of the foot segment $\mathbf{x_f y_t z_t}$. this point is **ca**.
$\mathbf{y_f}$**-axis**	this axis is defined by the intersection between the **foot quasi-coronal** and **quasi-sagittal planes** with positive direction upwards.
$\mathbf{z_f}$**-axis**	this axis is lying in the **foot quasi-transverse plane** and is perpendicular to the $\mathbf{y_s}$**-axis**, with positive direction pointing right.
$\mathbf{x_f}$**-axis**	this axis is mutually perpendicular to the $\mathbf{y_f}$**-axis** and the $\mathbf{z_f}$**-axis** and is pointing to the anterior.

3. Joint systems

The human body consists of several segments (see section 2), connected to each other by joints. In order to interpret data for the lower limb motion, joint coordinate systems must be defined. The joint coordinate system positions are dependent upon anatomical landmark positions. It must be clearly stated whether angles are relative (relating the position of one body segment to another) or absolute (segment orientation in terms of a laboratory coordinate system).

We modeled the lower limb as four segments, which are considered as rigid-bodies: (1) pelvic bone, (2) femur, (3) tibial bone and fibula (4) foot (including the talus, calcaneus, navicular, cuboid, cuneiforms, metatarsals and phalanxes). A reference frames is fixed in each segments (section 2). The relative motion of these segments is defined by models of the (1) pelvic (2) hip, (3) knee and (4) ankle joints[8].

It is important to define a system that allows the description of the three-dimensional joint position and that is applicable to experiences both *in vitro* and in the clinical context. The joint systems can be represented by joint reference systems (JRS, see 3.1. below) or by joint coordinate systems (JCS, see 3.2. below). The JRS is widely used in the biomechanics simulation field and allows representation by an Euler system or helical axis[9,10], while the JCS is used in the clinical situation. Because the VAKHUM project is dealing with both fields, a description of both systems is given.

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[8] Hilal I., Burdin V., Stindel E., Roux C., Lefevre C. "Human gait simulations using virtually reality". *In Proc. of the 20th Ann. Intl. Conf. of the IEEE Eng. Med. Biol. Soc*. vol. 20(3), pp. 1250-1253, 1998.

[9] Idem 8

[10] Aggard J.K., Cai Q. "Human motion analysis : review" *In Proc. of IEEE Nonrigid and Articulated Motion Workshop,* pp.90-102, 1997

3.1. Joint Reference System (JRS)

See figure 6.

3.1.1. Joint reference system of the pelvis

The position of the joint reference system of the pelvic $\mathbf{x_{pelvic}y_{pelvic}z_{pelvic}}$, is defined by $\mathbf{O_a}$ point.

3.1.2. Joint reference system of the hip

The hip angles reflect the motion of the thigh segment relative to the pelvic bone. The position of the joint reference system of the hip $\mathbf{x_{hip}y_{hip}z_{hip}}$, is defined by the **fh** point.

3.1.3. Joint reference system of the knee

The knee angles reflect the motion of the shank segment relative to the thigh segment. The position of the joint reference system of the knee $\mathbf{x_{knee}y_{knee}z_{knee}}$, is defined by the $\mathbf{O_t}$ point.

3.1.4. Joint reference system of the ankle

The ankle angles reflect the motion of the foot segment relative to the shank segment. The position of the joint local coordinate system $\mathbf{x_{ankle}y_{ankle}z_{ankle}}$, of the ankle is defined by the $\mathbf{O_s}$ point.

In the upright posture, the $\mathbf{x_{joint}}$**-axes** are pointing to the anterior, the $\mathbf{y_{joint}}$**-axes** are pointing upwards, and the $\mathbf{z_{joint}}$**-axes** are pointing to the right.

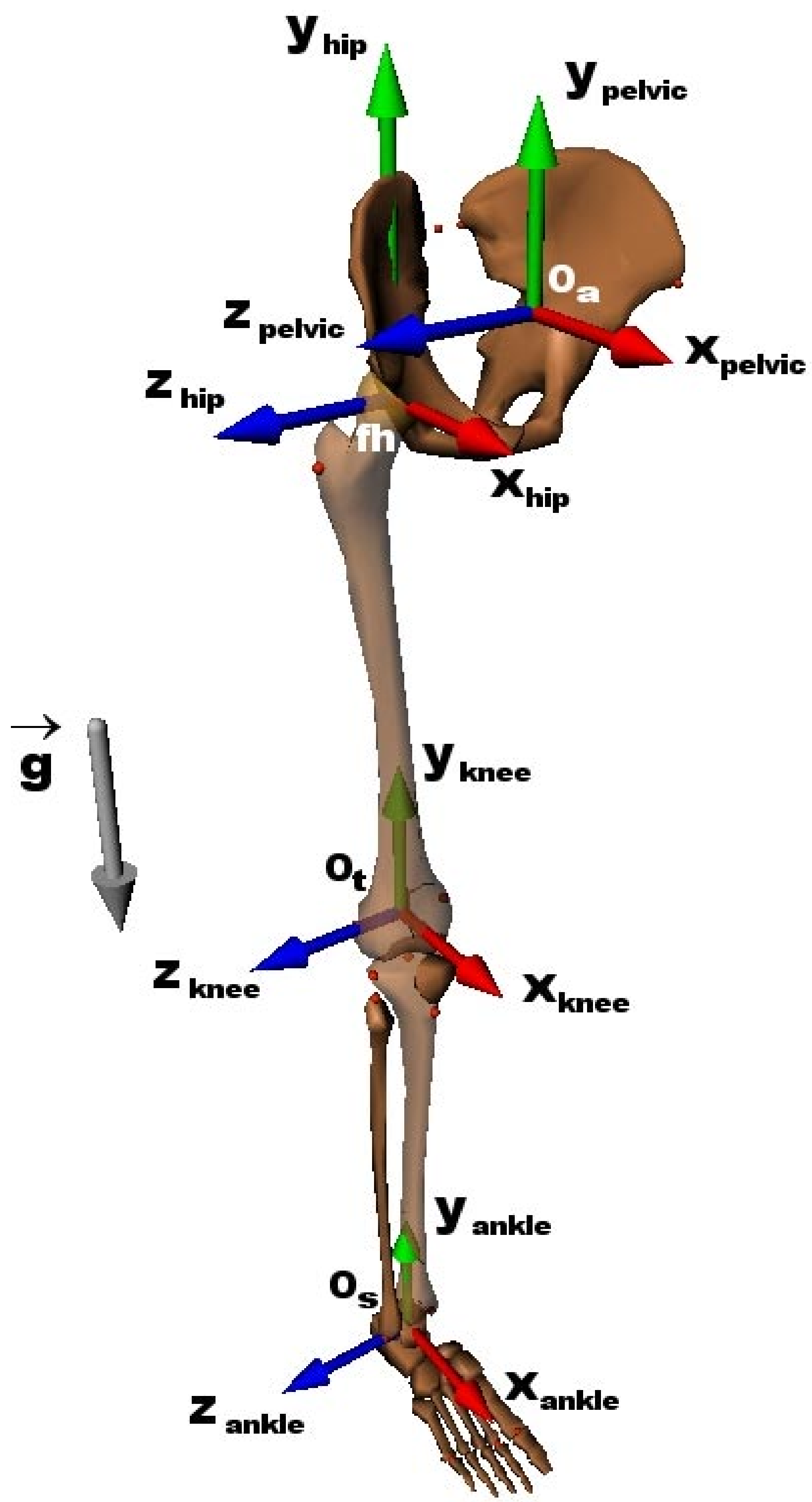

figure 6. Joint reference system of the lower limb.

3.2. Joint Coordinate System (JCS)

The joint coordinate system (JCS) reported by Grood and Suntay has the distinct advantages of being easily described in clinical terms and is independent of the order in which the rotational transformations are used.[11] The JCS system corresponds to conventions using Euler angles in the following order: flexion, adduction-abduction and internal-external rotation of the moving segment coordinate system with respect to the fixed segment coordinate system.

[11] D'Lima D., Leardini A., Witte H., Chung S., Cristofolini L., Wu G. "Standard for Hip Joint Coordinate System". Recommendations from the ISB Standardization Committee, 17 July 2000.

3.2.1. Hip joint coordinate system

See figure 7.

This report recommends a similar hip joint coordinate system of the ISB standards [12].

The origin of this system is at the **fh** point.

The flexion-extension: is defined around the **z_p-axis** (section 2.1.3), internal-external rotation around the **y_t-axis** (section 2.2.3) and the adduction-abduction around the *floating* axis mutually perpendicular to the **z_p-axis** and **y_t-axis**. For those wishing to reconcile these rotations with Euler angles these rotations would correspond to the ordered Euler angle rotations around **z**, **x** and **y** axes.
The medio-lateral translation is measured along the **z_p-axis**, proximal-distal translation along the **y_t-axis** and antero-posterior translation along the mutually perpendicular *floating* axis.

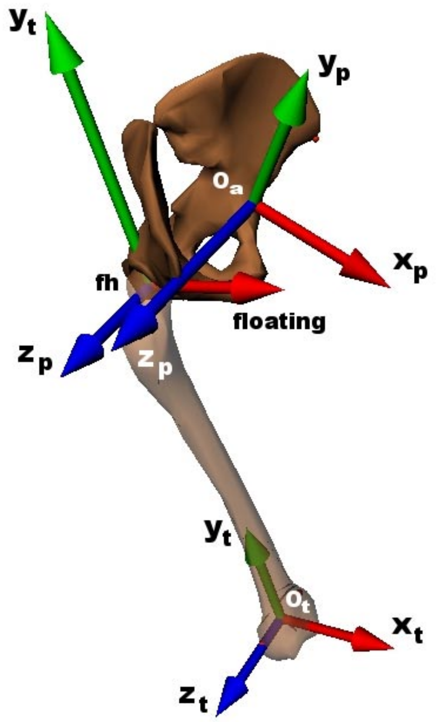

figure 7. Hip joint coordinate system

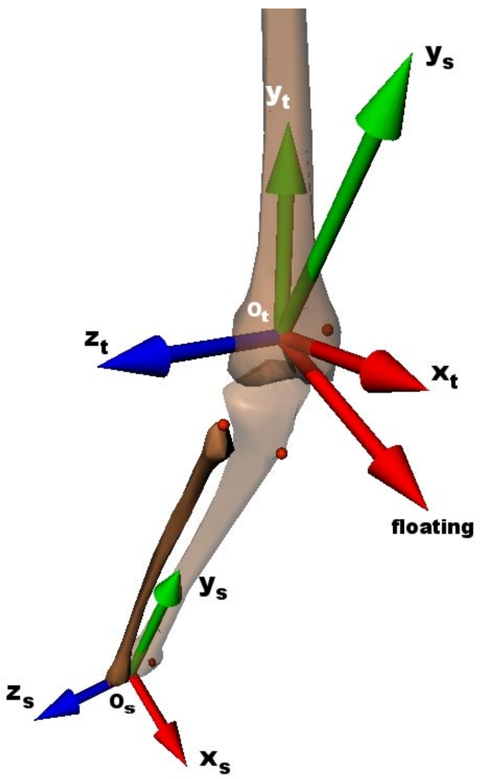

figure 8. Knee joint coordinate system

3.2.2. Knee joint coordinate system

See figure 8.

The origin of this system is at the **o_t** point.

The flexion-extension is defined around the **z_t-axis** (section 2.2.3), internal-external rotation around the **y_s-axis** (section 2.3.3) and the abduction-adduction around the *floating* axis mutually perpendicular to the **z_t-axis** and **y_s-axis.** For those wishing to reconcile these rotations with Euler angles these rotations would correspond to the ordered Euler angle rotations around **z**, **x** and **y** axes.

The medio-lateral translation is measured along the **z_t-axis**, proximal-distal translation along the **y_s-axis** and antero-posterior translation along the mutually perpendicular *floating* axis.

[12] Idem 11

3.2.3. Ankle joint coordinate system

See figure 9.

The origin of this system is at the $\mathbf{o_f}$ point.

The plantar flexion-dorsiflexion is defined around the **z_s-axis** (section 2.3.3), internal-external rotation around **y_f-axis** (section 2.4.3) and adduction-abduction around the *floating axis,* which is mutually perpendicular to the **z_s-axis** and **y_f-axis**. For those wishing to reconcile these rotations with Euler angles these rotations would correspond to the ordered Euler angle rotations around **z**, **x** and **y** axes.

The medio-lateral translation is measured along the **z_s-axis**, proximal-distal translation along the **y_f-axis** and antero-posterior translation along the mutually perpendicular *floating* axis.

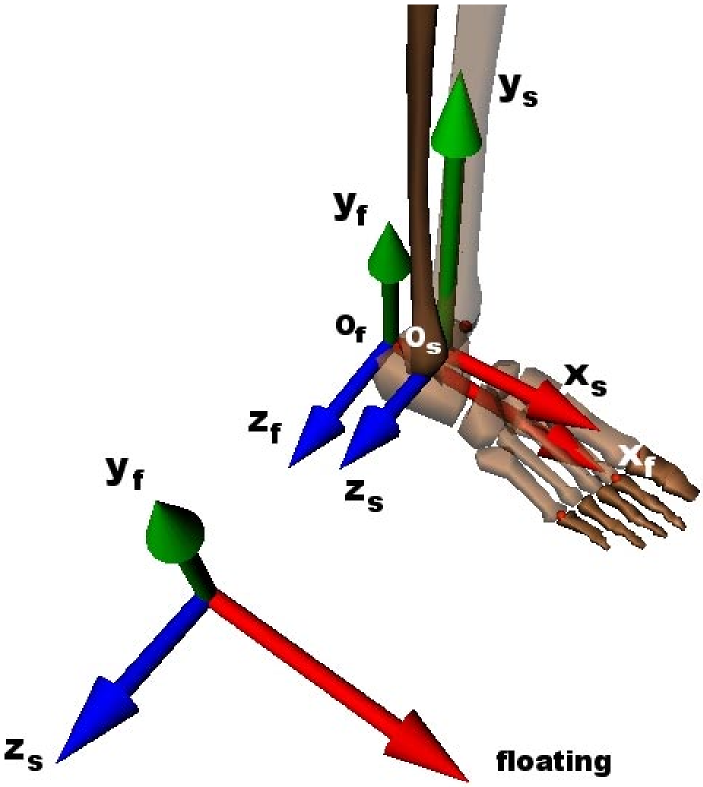

figure 9. Ankle joint coordinate system