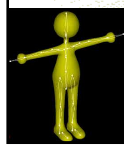
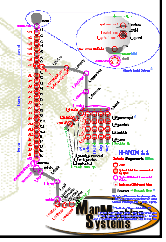
Human motion control

Kinematics

Background: Kinematics and (kinematic) models

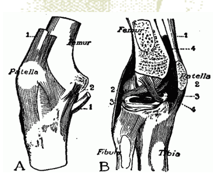
- What you see is what you get, or
- What you model is what you see
  - Your model of reality determines what you see
  - The model determines the necessary kinematic input
  - The available kinematic input determines the model





What you see is how you look at it

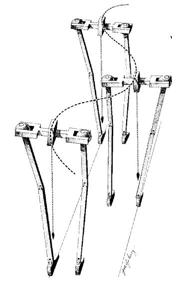
- Interpretation of kinematic data is always dependent on the underlying (implicit) assumptions
- Choice of measurement method is directly related to the underlying (implicit) assumptions about form-function relationships
  - Knee as a hinge...
  - Knee as a four-bar linkage system with cruciate ligaments



kinematic analysis

2-D versus 3-D

- Pro:
  - simple!
  - fast!



Con:
- projection error
- simplification of function

3-D analysis preferable, but not always necessary

Why not use the standard anatomical motion description?

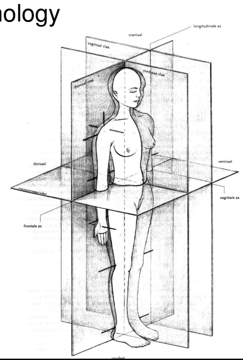
- Medical or clinical terminology unsuitable
  - Anatomical language

Clinical motion description

- Based on anatomical terminology / language
- Goal:
  - Characterising pathology vs healthy
  - Evaluation of intervention
- Use:
  - Judgement: Improvement or deterioration
  - Information exchange between medical professions
  - Clinical Science
- Requirements
  - Uniform, unambiguous

Clinical terminology

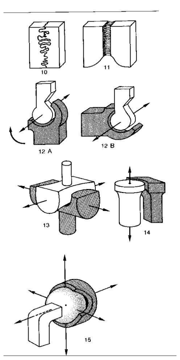
- based on anatomic position
- based on movement in main (perpendicular) planes
- essentially 2-D!
- “Planar thinking”



Clinical terminology is not unambiguous, nor uniform

Codman’s paradox
Exorotation or endorotation?

‘horizontal abduction’?



Junctura Fibrosa - Junctura Cartilaginea
Fibrous connection - Cartilage connection
(Skull bones) - (Pubic bones)

Junctura Synovialis

Hinge joint

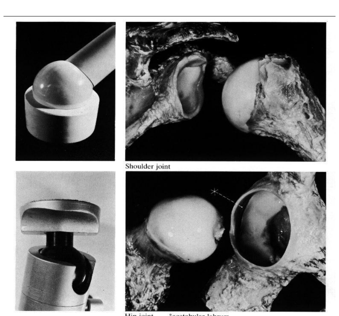
Saddle joint - Pivot joint

Ball-and-socket joint

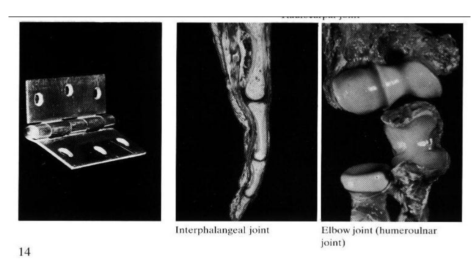
Joint Degrees-of-Freedom

- # Degrees of Freedom joint depends on:
  - Shape of articular surface
  - Number of ligaments
- Model Choice !!
  - Small translations & rotations are neglected

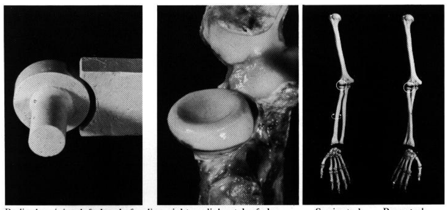
Ball-and-socket joint



Hinge joint

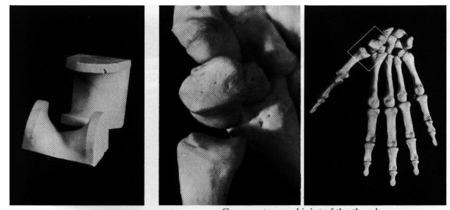


Pivot joint

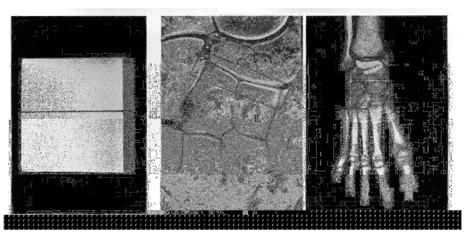


Radioulnar joint; left: head of radius, right: radial notch of ulna

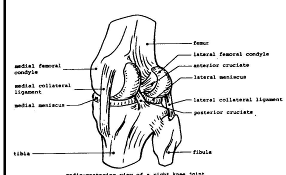
Saddle joint

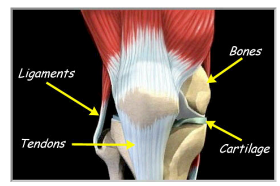

Carpometacarpal joint of the thumb

Plane joint



Constraints knee joint

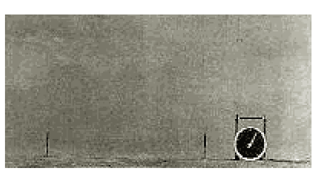




 # Degrees-of-Freedom joint depends on:
- **shape of articular surface**
- **number of ligaments**

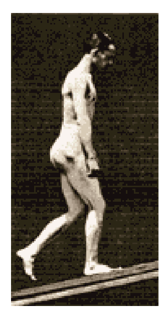
Kinematics
overview

- Marey (1830 - 1904)



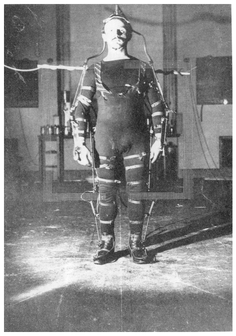
Kinematics
overview

- E. Muybridge (1830 - 1904)

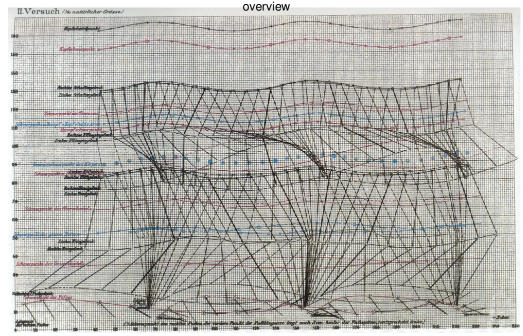


Kinematics
overview

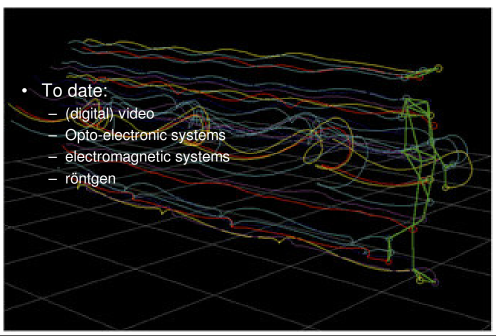
- Braune & Fischer ~ 1890 - 1900
  - two camera-view
  - stereo x-ray
  - mathematical reconstruction
    - extremely laborious



Kinematics
overview



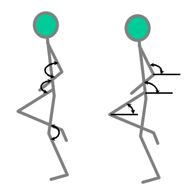
Kinematics
overview



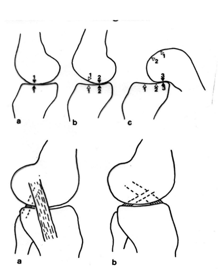
- To date:
  - (digital) video
  - Opto-electronic systems
  - electromagnetic systems
  - röntgen

Side step:
Arthrokinematics and osteokinematics

- Arthro-kinematics
  - Description of motion in a joint, often described as the motion of articular surfaces with respect to each other:
    - Roll
    - Slip
    - Spin
- Osteo-kinematics
  - Segment motions (w.r.t. outside world)
  - Joint motions (w.r.t. proximal bone)



Arthro-kinematics

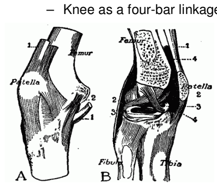


Description of motion of articular surfaces with respect to each other:
• Roll
• Slip
• Spin

Not well possible in vivo
Mainly from cadaver recordings

Again: what you see is how you look at it

- Interpretation of kinematic data is always dependent on the underlying (implicit) assumptions
- Choice of measurement method is directly related to the underlying (implicit) assumptions about form-function relationships
  - Knee as a hinge...
  - Knee as a four-bar linkage system with cruciate ligaments



If Clinical terminology is inadequate for 3-D movement analysis, what is?

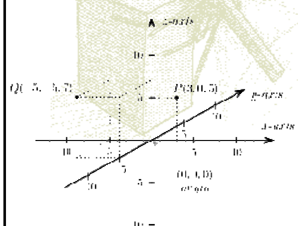
- Technical motion description
  - Pose, position and orientation
  - Unambiguous, specific

(But technical motion description is not the language that clinicians and movement scientists speak!)

Technical description of motion

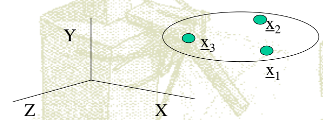
- Rotation matrix and translation vector
- 6 Independent parameters:
- 3 rotations, 3 translations, parameterized by
  - Euler angles
  - Screw axis or helical axis

Kinematic descriptions in 3D



- Description of an object in Cartesian space
- Three sets of coordinates can describe the pose of an object (position + orientation)

The pose of an object relative to a global coordinate system has six d.o.f.

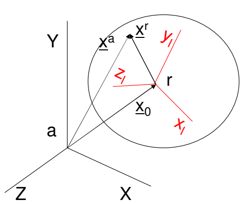


QuickTime™ and a YUV420 codec decompressor are needed to see this picture.

Three non-colinear points can define the orientation of an object
These can describe a plane with a unique pose in space

Two points can describe position, but not all three orientations

A Rotation matrix can describe the relation between global and local coordinate systems



$$\underline{x}^a = \underline{x}_0^a + R^{ra} \cdot \underline{x}^r =$$
$$= \underline{x}_0^a + \begin{bmatrix} \cos(x,X) & \cos(y,X) & \cos(z,X) \\ \cos(x,Y) & \cos(y,Y) & \cos(z,Y) \\ \cos(x,Z) & \cos(y,Z) & \cos(z,Z) \end{bmatrix} \cdot \underline{x}^r$$
$$= \underline{x}_0^a + \begin{bmatrix} \underline{n}_1 & \underline{n}_2 & \underline{n}_3 \end{bmatrix} \cdot \underline{x}^r$$

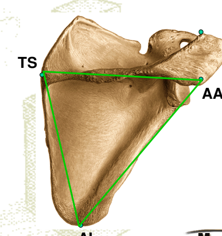
with

$$\det(R^{ra}) = 1$$

BK9-29

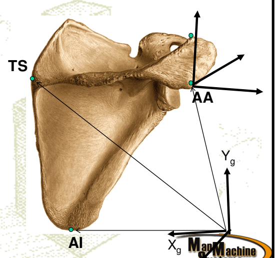
Construction of a local coordinate system in 3D

- Orientation definition of a segment requires three markers
- These three markers describe a plane
- In motion analysis these points can be landmarks or technical markers

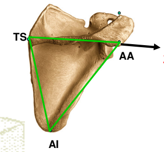


Construction of a local coordinate system in 3D

- From x-y-z global coordinates markers markers we can construct a local coordinate system (or: frame)
- Frame describes its orientation and position (= pose) in global space



- Five steps to define a local frame
  - step 1: define the first axis
  - Step 2: define a support axis to define the plane orientation
  - Step 3: define a second axis perpendicular to the plane
  - Step 4: orthogonize your system: calculate the axis in the plane perpendicular to the first two
  - Step 5: construct the orientation matrix



$$\bar{z}_u = \frac{AA - TS}{\|AA - TS\|}$$

- Five steps to define a local frame
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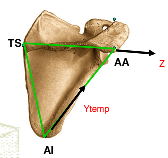

$$\bar{z}_u = \frac{AA - TS}{\|AA - TS\|}$$

$$\bar{y}_{temp} = \frac{AA - AI}{\|AA - AI\|}$$

- Five steps to define a local frame
  - step 1: define the first axis
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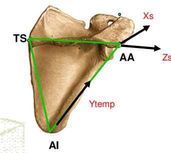

$$\bar{z}_u = \frac{AA - TS}{\|AA - TS\|}$$

$$\bar{y}_{temp} = \frac{AA - AI}{\|AA - AI\|}$$

$$\bar{x} = \bar{y}_{temp} \times \bar{z}_u, \quad \bar{x}_u = \frac{\bar{x}}{\|\bar{x}\|}$$

- Five steps to define a local frame
  - step 1: define the first axis
  - Step 2: define a support axis to define the plane orientation
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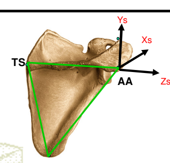


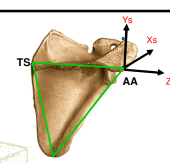
$$\bar{z}_u = \frac{AA - TS}{\|AA - TS\|}$$

$$\bar{y}_{temp} = \frac{AA - AI}{\|AA - AI\|}$$

$$\bar{x} = \bar{y}_{temp} \times \bar{z}_u, \quad \bar{x}_u = \frac{\bar{x}}{\|\bar{x}\|}$$

$$\bar{y} = \bar{z}_u \times \bar{x}_u, \quad \bar{y}_u = \frac{\bar{y}}{\|\bar{y}\|}$$

- Five steps to define a local frame
  - step 1: define the first axis
  - Step 2: define a support axis to define the plane orientation
  - Step 3: define a second axis perpendicular to the plane
  - Step 4: orthogonize your system: calculate the axis in the plane perpendicular to the first two
  - Step 5: construct the orientation matrix = all three axes / direction vectors



$$\bar{z}_u = \frac{AA - TS}{\|AA - TS\|}$$

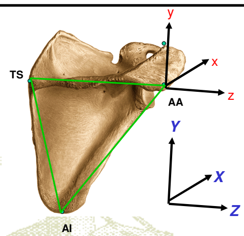
$$\bar{y}_{temp} = \frac{AA - AI}{\|AA - AI\|}$$

$$\bar{x} = \bar{y}_{temp} \times \bar{z}_u, \quad \bar{x}_u = \frac{\bar{x}}{\|\bar{x}\|}$$

$$\bar{y} = \bar{z}_u \times \bar{x}_u, \quad \bar{y}_u = \frac{\bar{y}}{\|\bar{y}\|}$$

$$R = [\bar{x}_u \quad \bar{y}_u \quad \bar{z}_u]$$

- The resulting 3x3 matrix describes the **orientation** of a **segment** in the global system
- The matrix contains the three direction vectors,
- Each direction vector defines the angle of that axis with the three axes of the global coordinate system



2.3.3. Scapula coordinate system—$X_sY_sZ_s$ (see Figs. 1 and 4)

O_s: The origin coincident with AA.
Z_s: The line connecting TS and AA, pointing to AA.
X_s: The line perpendicular to the plane formed by AI, AA, and TS, pointing forward. Note that because of the use of AA instead of AC, this plane is not the same as the visual plane of the scapula bone.
Y_s: The common line perpendicular to the X_s- and Z_s-axis, pointing upward.

$$R_{scapula} = \begin{bmatrix} \cos(x,X) & \cos(y,X) & \cos(z,X) \\ \cos(x,Y) & \cos(y,Y) & \cos(z,Y) \\ \cos(x,Z) & \cos(y,Z) & \cos(z,Z) \end{bmatrix}$$

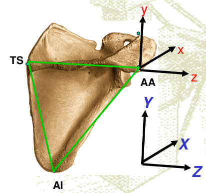
$$\underline{P}_{scapula} = AA_{global} + R_{scapula} \cdot \underline{x}_{local} =$$

with

$$\det(R_{scapula}) = 1$$

$$AA_{global} = Origin\ scapula\ frame$$

global coordinates ⇔ local coordinates



$$x^G_{scapula} = AA^G + R^{L\to G} \cdot x^L_{scapula}$$

$$R^{L\to G} = \begin{bmatrix} \cos(x,X) & \cos(y,X) & \cos(z,X) \\ \cos(x,Y) & \cos(y,Y) & \cos(z,Y) \\ \cos(x,Z) & \cos(y,Z) & \cos(z,Z) \end{bmatrix}$$

$$x^L_{scapula} = R^{G\to L} \cdot \underline{\left(x^G_{scapula} - AA^G\right)} =$$

$$= \begin{bmatrix} \cos(X,x) & \cos(Y,x) & \cos(Z,x) \\ \cos(X,y) & \cos(Y,y) & \cos(Z,y) \\ \cos(X,z) & \cos(Y,z) & \cos(Z,z) \end{bmatrix} \cdot \left(x^G_{scapula} - AA^G\right)$$

$$R^{G\to L} = inv(R^{L\to G})$$

Definition of local coordinate systems in Movement Studies

QuickTime™ en een
TIFF (ongecomprimeerd)-decompressor
zijn vereist om deze afbeelding weer te geven.

Use of *anatomical landmarks* for axis definitions

- Easily defined
- If chosen well: more or less coincident with axes and centers of rotation
- Mostly easy to define

Definition of local coordinate systems in Movement Studies

- Different **use of landmarks** influences unit vectors and thus matrix R
- Different **order of axis definition** influences unit vectors and thus matrix R

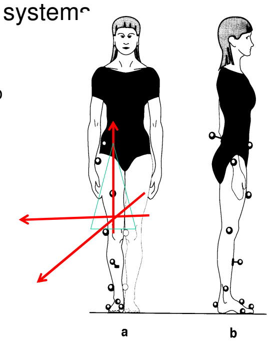
QuickTime™ en een

Helen Hayes marker set

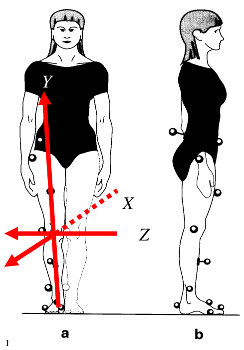
Vaughan marker set

Order preference when defining local coordinate systems

- First axis: long axis
- Second axis: perpendicular to the plane through three landmarks
- Third axis perpendicular to 1 and 2.



Example thigh



$$y = \frac{xyz\_hip - xyz\_knee}{|xyz\_hip - xyz\_knee|}$$

$$\bar{y} = \frac{y}{\|y\|}$$

$$z_{temp} = \frac{xyz\_LE - xyz\_ME}{|xyz\_LE - xyz\_ME|}$$

$$x = y \times z_{temp}$$

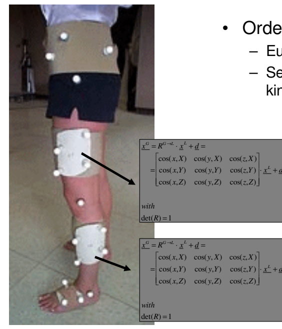
$$\bar{x} = \frac{x}{\|x\|}$$

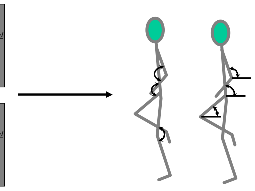
$$z = x \times y$$

$$\bar{z} = \frac{z}{\|z\|}$$

$$^{L}R^{G} = [\bar{x} \quad \bar{y} \quad \bar{z}]$$

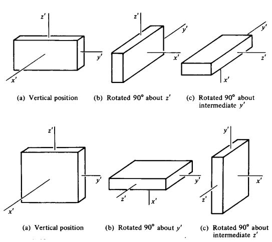
Parameterization of orientation matrices





- Order of rotation
  - Euler angles
  - Segment kinematics versus joint kinematics

Rotation is not a vector



rot(z')+rot(y') ≠ rot(y')+rot(z')

(order of rotation can not be interchanged)

Standard matrices for rotation of a vector

$$Rz = \begin{pmatrix} c\gamma & -s\,\gamma & 0 \\ s\,\gamma & c\,\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad Ry = \begin{pmatrix} c\beta & 0 & s\beta \\ 0 & 1 & 0 \\ -s\beta & 0 & c\beta \end{pmatrix} \quad Rx = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c\alpha & -s\alpha \\ 0 & s\alpha & c\alpha \end{pmatrix}$$

- Can be used to rotate a vector to a given position in a plane over angle γ (Rz), β (Ry) or α (Rx)

Parameterization of orientation matrices

Agreement within scientific field!!

- Euler angles
  - z-x-z: x-convention (applied mechanics)
  - z-y-z: y-convention (quantum mechanics, nuclear physics)
  - x-y-z: Cardan angles (astonomy, aerospace, biomechanics)

- screw axis or helical axis
- Cayley-Klein parameters
- Euler parameters

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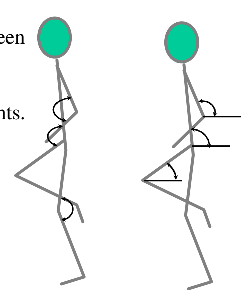
Measuring Angles

Relative Angles
(joint rotations)
The angle between the longitudinal axis of two adjacent segments.



Absolute Angles
(segment rotations)
The angle between a segment and the right horizontal of the distal end.

$R = R_{prox}'*R_{dist}$

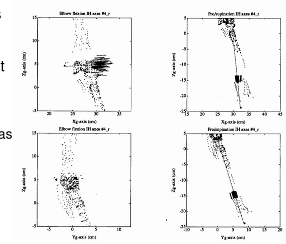
$R = R_g'*R_{seg}$

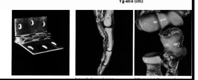
What decomposition order is the most suitable?

- Many different orders of rotations
  - xyz, zxy, yxz, yzx, zxy, zyx
  - xyx, xzx, yxy, yzy, zxz, zyz
- Preference of order in standardization:
  - As much as possible resembling clinical rotations (flexion/extension, abduction/adduction, etc
  - Last rotation axial rotation around longitudinal axis of segment
  - Then the first two rotations determine the orientation of the segment
  - Gimbal Lock orientations should be avoided

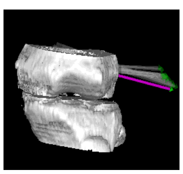
Parameters from segmental motions are **not** pure joint rotations!

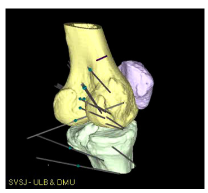
- Euler, or Cardan angles are rotations around coordinate systems of segments
- Local coordinate axes do (mostly) not equal joint kinematic axes
  - Elbow, FE-axis is not the line EM-EL
- Improvement possible, by determining kinematic joint axes and choosing these as local segment axes.
- Even then: rotation is not the same as motion **in the joint**





Joint Motion description: screw axes





Can be used for estimation of kinematic axis (or center) of rotation, which can then be used as the basis for the local coordinate systems

Effect of positioning error of landmarks on knee angles

Epicondyl-marker 9 mm too much anterior or posterior: ~ 5° deviation on local coordinate system

Rotation van 5° around the long axis of the leg induces effects on especially the abduction-adduction axis (blue). These are artificial and angle dependent!