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

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

Saddle joint

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

• 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
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    – Knee as a hinge...
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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.

Three non-collinear 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

\[
\mathbf{R}^{a \rightarrow g} = \begin{bmatrix}
\cos(z) & \cos(y) & \cos(z) \\
\cos(z) & \cos(y) & \cos(z) \\
\cos(z) & \cos(y) & \cos(z)
\end{bmatrix}
\]

with \( \det(R) = 1 \)

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

Five steps to define a local frame

– step 1: define the first axis
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All three axes / direction vectors
Definition of local coordinate systems in Movement Studies

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

Order preference when defining local coordinate system

- First axis: long axis
- Second axis: perpendicular to the plane through three landmarks
- Third axis perpendicular to 1 and 2.
**Parameterization of orientation matrices**

- **Euler angles**
  - z-x-z: x-convention (applied mechanics)
  - z-y-z: y-convention (quantum mechanics, nuclear physics)
  - x-y-z: Cardan angles (aeronautics, 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.

\[ R = R_{prox}^{-1} R_{dist} \]

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

\[ R = R_{seg}^{-1} R_{x} \]
What decomposition order is the most suitable?

- Many different orders of rotations
  - xyz, zxy, yzx, zyx, zyx, 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!