Kinematics

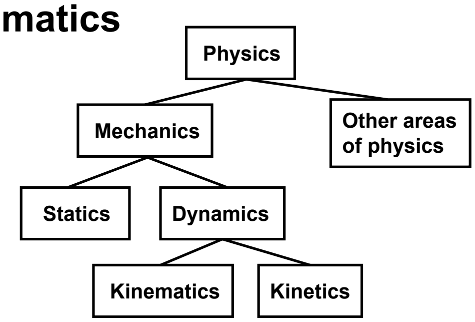
Kinematics theory

Processing techniques

Measurement techniques

Introduction to 3D kinematics

Kinematics



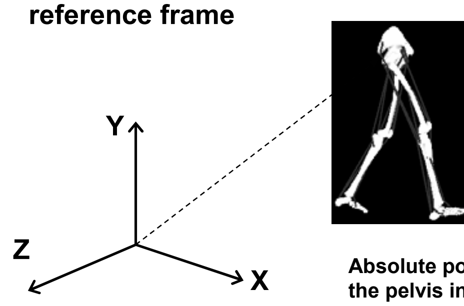
Kinematics: branch of dynamics which describes the motion of objects without reference to the forces which caused, or were generated by, the motion

Role of Kinematic Analysis in Biomechanics

- Kinematic data by themselves may provide useful information about a human movement
  - Initial description of a previously unstudied movement pattern
  - Assessment of the coordination pattern of a particular movement
- Kinematic data may be required as part of a more complete analysis of a movement
  - Kinematic and EMG data
  - Inverse dynamics (kinematic & kinetic data)

Frames of Reference

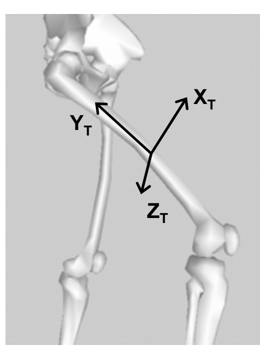
Inertial (fixed, global) reference frame



Absolute position of the pelvis in a fixed inertial reference frame

Frames of Reference

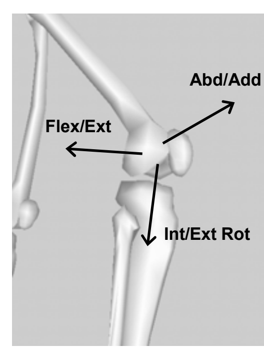
Local or segmental reference frames



reference frame fixed to the thigh segment

Frames of Reference

Joint-based reference frames



reference frame fixed in the knee joint

Kinematic variables

Linear kinematics of particles (points)

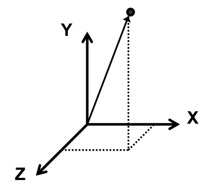
- **Position** - location at a given time
- **Displacement** - change in position over a period of time (compare with distance)
- **Velocity** - rate of change in position with respect to time (compare with speed)
- **Acceleration** - rate of change in velocity with respect to time
- **Jerk** - rate of change in acceleration with respect to time

*All are vector quantities (except distance and speed)

Position & Displacement

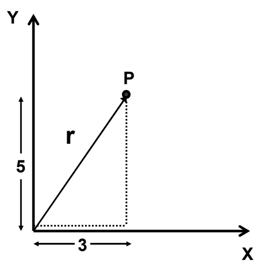
Degrees of freedom - the minimum number of independent parameters necessary to specify the configuration of a system

A point has 3 degrees of freedom, so its position is defined by 3 coordinates (x, y, and z)



Position & Displacement

In two-dimensional analysis, only two quantities are needed to completely describe the position of a point or particle

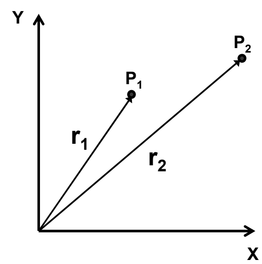


The position of point P can be conveniently denoted by a vector r, with r defined as

$r = 3\,i + 5\,j$

i and *j* are unit vectors in the directions of X and Y, respectively

Position & Displacement



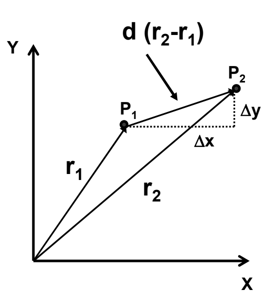
Say that the point moves from position 1 (P_1) to position 2 (P_2) such that

$r_1 = 3\,i + 5\,j$ and

$r_2 = 8\,i + 7\,j$

How do we represent the displacement as a vector?

Position & Displacement



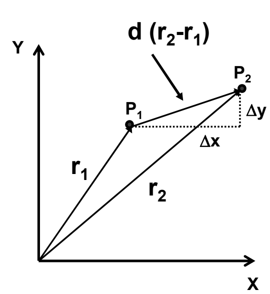
The displacement vector (d) is defined as

$d = r_2 - r_1$, so

$d = (8-3)\,i + (7-5)\,j = 5\,i + 2\,j$

That is, the position has changed 5 units in the X direction (Δx) and 2 units in the Y direction (Δy)

Velocity



Velocity is the rate at which the X and Y coordinates are changing

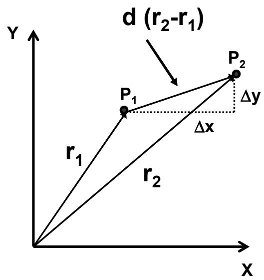
The average velocity in the X direction is given by

$$\bar{v}_X = \frac{\Delta x}{\Delta t}$$

and the instantaneous velocity in the X direction is given by

$$v_X = \lim_{\Delta t \to 0} \frac{\Delta x}{\Delta t} = \frac{dx}{dt} = \dot{x}$$

Velocity



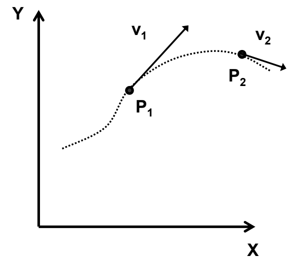
The average velocity in the Y direction is given by

$$\bar{v}_Y = \frac{\Delta y}{\Delta t}$$

and the instantaneous velocity in the Y direction is given by

$$v_Y = \lim_{\Delta t \to 0} \frac{\Delta y}{\Delta t} = \frac{dy}{dt} = \dot{y}$$

Velocity



Whereas the position vector to point P was given by

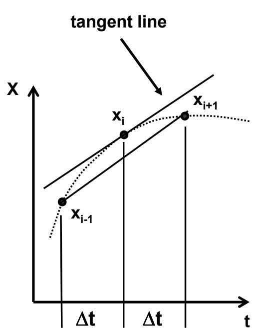
$r = x\,i + y\,j$

the vector representation of the velocity of point P is written as

$v = \dot{r} = \dot{x}\,i + \dot{y}\,j$

The velocity vector v will always be *tangent* to the path followed by point P

Velocity



When data are expressed in digital form, a true instantaneous velocity can not be calculated

It can be approximated, however, using finite difference techniques

$$v_{X(i)} = \dot{x} \approx \frac{x_{i+1} - x_{i-1}}{2\Delta t}$$

As Δt gets smaller, the approximation gets better

Velocity

The equation $v_{X(i)} = (x_{i+1} - x_{i-1}) / 2\Delta t$

is a *first-order*, *central difference* equation, and can be applied to all data points except the first and last

To estimate the velocity for the first point use a *second-order, forward difference* equation

$$v_{X(1)} = \frac{-3x_1 + 4x_2 - x_3}{2\Delta t}$$

and for the last point use a *second-order, backward difference* equation

$$v_{X(n)} = \frac{x_{n-2} - 4x_{n-1} + 3x_n}{2\Delta t}$$

Velocity

Given the following position data for the Y coordinate of a marker on the ankle joint, calculate the velocity

Frame	Time (s)	X coord (m)	X vel (m/s)
1	0.0000	0.1175	?
2	0.0167	0.1182	?
3	0.0334	0.1190	?
4	0.0501	0.1193	?
5	0.0668	0.1185	?

First point, use forward difference

$v_{X(1)} = (-3 \times 0.1175 + 4 \times 0.1182 - 0.1190) / (2 \times 0.0167) = 0.04$

Velocity

Given the following position data for the Y coordinate of a marker on the ankle joint, calculate the velocity

Frame	Time (s)	X coord (m)	X vel (m/s)
1	0.0000	0.1175	0.04
2	0.0167	0.1182	?
3	0.0334	0.1190	?
4	0.0501	0.1193	?
5	0.0668	0.1185	?

Points 2 - 4, use central difference

$v_{X(2)} = (0.1190 - 0.1175) / (2 \times 0.0167) = 0.04$
$v_{X(3)} = (0.1193 - 0.1182) / (2 \times 0.0167) = 0.03$
$v_{X(4)} = (0.1185 - 0.1190) / (2 \times 0.0167) = -0.01$

Velocity

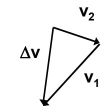
Given the following position data for the Y coordinate of a marker on the ankle joint, calculate the velocity

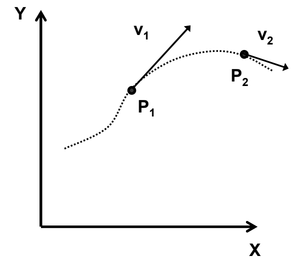
Frame	Time (s)	X coord (m)	X vel (m/s)
1	0.0000	0.1175	0.04
2	0.0167	0.1182	0.04
3	0.0334	0.1190	0.03
4	0.0501	0.1193	-0.01
5	0.0668	0.1185	?

Last point, use backward difference

$v_{X(5)} = (0.1190 - 4\times0.1193 + 3\times0.1185) / (2\times0.0167) = -0.08$

Acceleration

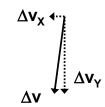




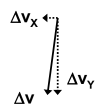
The vector change in velocity (Δv) is given by

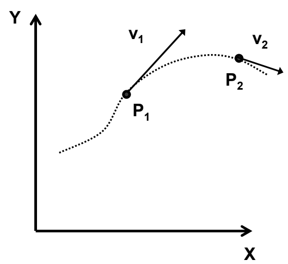
$\Delta v = v_2 - v_1$

It can be represented in terms of the change of velocity in the X and Y directions



Acceleration





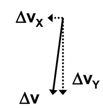
The average acceleration in the X direction is given by

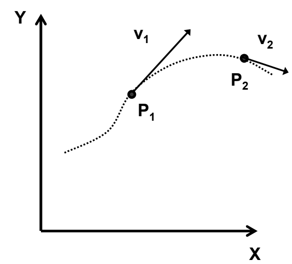
$$\bar{a}_X = \frac{\Delta v_X}{\Delta t}$$

and the instantaneous acceleration in the X direction is given by

$$a_X = \lim_{\Delta t \to 0} \frac{\Delta v_X}{\Delta t} = \frac{dv_X}{dt} = \dot{v}_X$$

Acceleration





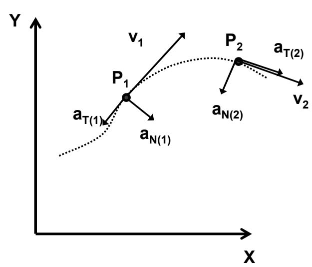
The average acceleration in the Y direction is given by

$$\bar{a}_Y = \frac{\Delta v_Y}{\Delta t}$$

and the instantaneous acceleration in the Y direction is given by

$$a_Y = \lim_{\Delta t \to 0} \frac{\Delta v_Y}{\Delta t} = \frac{dv_Y}{dt} = \dot{v}_Y$$

Acceleration



Whereas the velocity vector of point P was given by

$v = \dot{r} = \dot{x}\, i + \dot{y}\, j$

the vector representation of the acceleration of point P is written as

$a = \dot{v} = \ddot{r} = \ddot{x}\, i + \ddot{y}\, j$

The acceleration vector, *a*, will have two components, *tangent* to and *normal* to the path followed by point P

Acceleration

A similar finite difference approach as for velocity can be used to estimate acceleration

A *first-order*, *central difference* equation for acceleration, written in terms of position data, is

$$a_{X(i)} = \frac{x_{i+1} - 2x_i + x_{i-1}}{\Delta t^2}$$

The *second-order, forward and backward difference* equations for the first and last points are

$$a_{X(1)} = \frac{2x_1 - 5x_2 + 4x_3 - x_4}{\Delta t^2} \qquad a_{X(n)} = \frac{-x_{n-3} + 4x_{n-2} - 5x_{n-1} + 2x_n}{\Delta t^2}$$

Acceleration

Given the following position data for the Y coordinate of a marker on the ankle joint, calculate the acceleration

Frame	Time (s)	X coord (m)	X vel (m/s)	X accel (m/s²)
1	0.0000	0.1175	0.04	?
2	0.0167	0.1182	0.04	?
3	0.0334	0.1190	0.03	?
4	0.0501	0.1193	-0.01	?
5	0.0668	0.1185	-0.08	?

First point, use forward difference

$a_{X(1)} = (2\times0.1175 - 5\times0.1182 + 4\times0.1190 - 0.1193) / (0.0167)^2$

$a_{X(1)} = 2.51$

Acceleration

Given the following position data for the Y coordinate of a marker on the ankle joint, calculate the acceleration

Frame	Time (s)	X coord (m)	X vel (m/s)	X accel (m/s²)
1	0.0000	0.1175	0.04	2.51
2	0.0167	0.1182	0.04	?
3	0.0334	0.1190	0.03	?
4	0.0501	0.1193	-0.01	?
5	0.0668	0.1185	-0.08	?

Points 2 - 4, use central difference

$a_{X(2)} = (0.1190 - 2\times0.1182 + 0.1175) / (0.0167)^2 = 0.36$
$a_{X(3)} = (0.1193 - 2\times0.1190 + 0.1182) / (0.0167)^2 = -1.79$
$a_{X(4)} = (0.1185 - 2\times0.1193 + 0.1190) / (0.0167)^2 = -3.94$

Acceleration

Given the following position data for the Y coordinate of a marker on the ankle joint, calculate the acceleration

Frame	Time (s)	X coord (m)	X vel (m/s)	X accel (m/s²)
1	0.0000	0.1175	0.04	2.51
2	0.0167	0.1182	0.04	0.36
3	0.0334	0.1190	0.03	-1.79
4	0.0501	0.1193	-0.01	-3.94
5	0.0668	0.1185	-0.08	?

Last point, use backward difference

$a_{X(5)} = (-0.1182 + 4\times0.1190 - 5\times0.1193 + 2\times0.1185) / (0.0167)^2$

$a_{X(5)} = -6.10$

Velocity & Acceleration

Note that if global polynomials or spline function were used to fit and/or smooth the data, then velocity and acceleration can be determined analytically

Example:

$x(t) = 3 + 7t - 4t^2 + 8t^3 + 5t^4 - 2t^5$

$v(t) = \frac{dx}{dt} = \dot{x} = 7 - 8t + 24t^2 + 20t^3 - 10t^4$

$a(t) = \frac{dv}{dt} = \dot{v} = -8 + 48t + 60t^2 - 40t^3$

High Frequency Noise

Why do we need to be sure we minimize the amount of high frequency noise in our data?

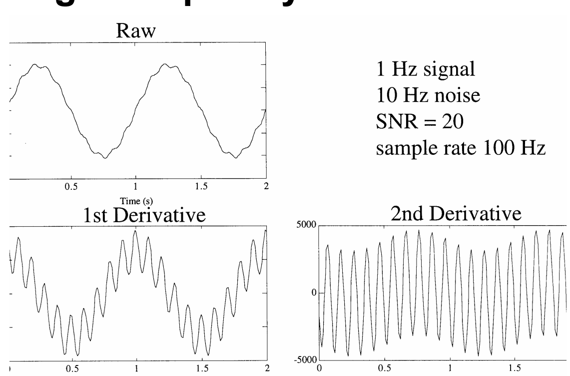
Differentiation amplifies high-frequency noise.

- consider a 1Hz signal contaminated with 10Hz noise, with a signal-to-noise (SNR) ratio of 20 (26 dB):

$x(t) = 20\sin(6.28t) + \sin(62.8t);\quad \text{SNR} = 20$
$x'(t) = 125\cos(6.28t) + 62.8\cos(62.8t);\quad \text{SNR} = 2$
$x''(t) = -785\sin(6.28t) - 3944\sin(62.8t);\quad \text{SNR} = 0.2$

- The 2nd derivative of the noise is 5 times larger than the 2nd derivative of the signal!

High Frequency Noise



1 Hz signal
10 Hz noise
SNR = 20
sample rate 100 Hz

High Frequency Noise

- In the 1st derivative (velocity) signal amplitude increases proportional to frequency
- In the 2nd derivative (acceleration) signal amplitude increases proportional to frequency squared
- This is why it is so important to eliminate sources of high frequency noise before data collection, and suppress the remaining high frequency noise through low-pass filtering

Angular Kinematic Variables

The following is applicable to rigid bodies in planar motion (3-D is more complicated)

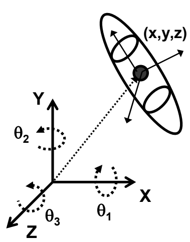
- <u>Angular Position</u> - angle at a given time
- <u>Angular Displacement</u> - change in angular position over a period of time
- <u>Angular Velocity</u> - rate of change in angular position with respect to time
- <u>Angular Acceleration</u> - rate of change in angular velocity with respect to time

*Only angular velocity and acceleration are vector quantities, because angular rotations are not commutative

Angular Position (Orientation)

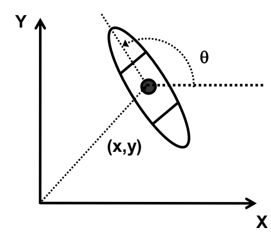
<u>Degrees of freedom</u> - a rigid body in 3-D space requires six quantities to completely describe its position and orientation

Could use the x, y, and z coordinate of the center of mass, plus the angular rotations relative to the global reference frame (other coordinate sets are also possible)



Angular Position (Orientation)

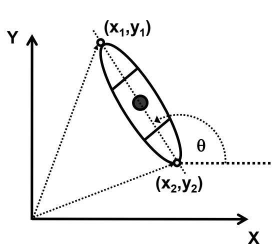
In two-dimensional analysis, only two linear coordinates (x, y) and one angle (θ) are needed to completely describe the position and orientation of a rigid body



So in planar analyses, you must know the x and y coordinates of at least one point on each body, plus the angle relative to some fixed reference

Angular Position (Orientation)

Segment angles, relative to the right horizontal, can be calculated using the coordinates of markers at the ends of the segment

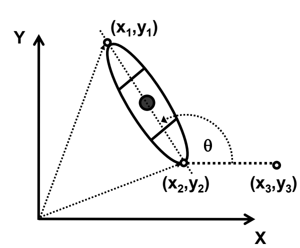


The segment angle can be calculated anywhere in the first two quadrants using the law of cosines:

$$a^2 = b^2 + c^2 - 2bc \times \cos\theta$$

$$\theta = \cos^{-1}\left(\frac{b^2 + c^2 - a^2}{2bc}\right)$$

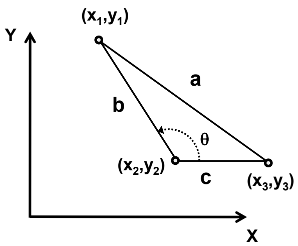
Angular Position (Orientation)



First, create a third, imaginary point, to the right along the x-axis

The value of y_3 is the same as y_2, the value of x_3 simply needs to be larger than x_2

Angular Position (Orientation)



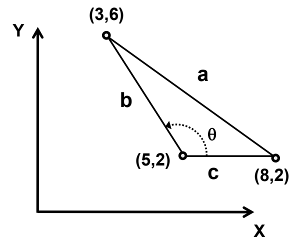
Label the sides a, b, and c as shown, and solve the equation for θ

$$\theta = \cos^{-1}\left(\frac{b^2 + c^2 - a^2}{2bc}\right)$$

where

$$a = \sqrt{(x_3 - x_1)^2 + (y_3 - y_1)^2}$$
$$b = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$
$$c = \sqrt{(x_3 - x_2)^2 + (y_3 - y_2)^2}$$

Angular Position (Orientation)



With point 1 (3,6), point 2 (5,2), and point 3 (8,2)

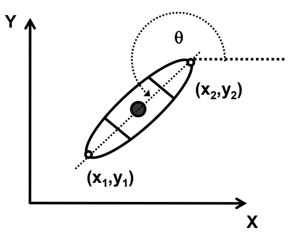
$$a = \sqrt{(8-3)^2 + (2-6)^2} = 6.4$$
$$b = \sqrt{(5-3)^2 + (2-6)^2} = 4.5$$
$$c = \sqrt{(8-5)^2 + (2-2)^2} = 3.0$$

$$\theta = \cos^{-1}\left(\frac{4.5^2 + 3.0^2 - 6.4^2}{2(4.5)(3.0)}\right)$$

$\theta = 115.7°$

Angular Position (Orientation)

If the motion you are studying might cause a segment to be in the third or fourth quadrants, simply add a check to see which quadrant you are in before performing your angle calculation



e.g., check to see if

$x_1 > x_2$ (1st or 2nd quad)

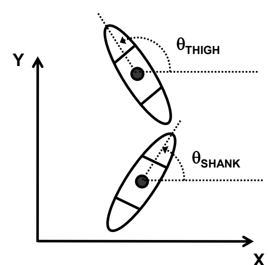
or

$x_1 < x_2$ (3rd or 4th quad)

before trying to calculate angle θ

Angular Position (Orientation)

Once segment angles are known, relative joint angles can be easily calculated



Joint angles are typically calculated as the angle of the proximal segment minus the angle of the distal segment

$$\theta_{KNEE} = \theta_{THIGH} - \theta_{SHANK}$$

This would make knee angle 0 at full extension, pos for flexion, and neg for hyperextension

Angular Kinematics

- For planar (2-D) motion, the relationships between angular displacement, angular velocity, and angular acceleration are perfectly analogous to linear displacement, linear velocity, and linear acceleration
- Once segment or joint angles are known, angular velocities and angular accelerations can be calculated using the same finite difference approach as we used for linear velocity and linear acceleration

Kinematic Measurement Systems

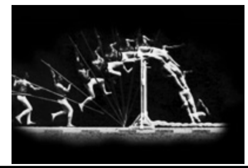
- Single exposure photography
- Multiple exposure photography
- Cinematography
- Videography
- Optoelectronic systems
- Electromagnetic tracking
- Electrogoniometers
- Accelerometers

Single exposure photography

Advantages
- Inexpensive
- Applicable to static analysis (e.g., frontal area, body segment volume, assessment of static postures)

Disadvantages
- Very limited application to dynamic activities

Multiple exposure photography

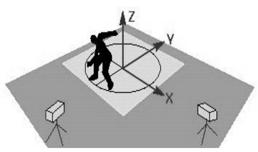


Advantages
- Simple, inexpensive
- An early solution to motion capture

Disadvantages
- Concerns about image clarity
- Movement must occur in a completely dark environment
- Problems with image overlap

Cinematography

Advantages
- Permanent record of the movement
- With proper calibration, accuracy can be very high
- Wide range of sampling rates (e.g., 0-500 Hz for Locam)
- Highly flexible applications (indoor, outdoor)



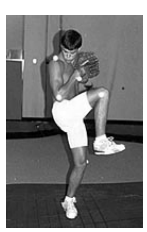
Cinematography

Disadvantages
- Careful attention to film sensitivity/light exposure
- High, recurring costs (film plus developing)
- No immediate feedback about image quality
- Requires manual digitization (marker coordinate generation)

Locam

Vendors
- Redlake Corp. (Lowcam, Highcam)

Videography



Advantages
- Low cost medium (videotapes)
- Immediate image quality feedback
- Less sensitive to lighting conditions than film
- Highly flexible applications
- Many competing vendors
- Modern systems provide real-time 3D coordinate data (bypassing the tape stage)

Videography

Disadvantages
- Early problems; low & fixed sampling rate, long & fixed exposure time
- Sampling rates > 60 Hz come at a price
- Automatic, 3D coordinate acquisition comes at a price

Vendors
- Motion Analysis Corp.
- Peak Performance Technologies
- Oxford Metrics (Vicon)
- Qualisys (MacReflex)
- Ariel Dynamics
- BTS (Elite Motion Analyzer)

Still one of the most cost-effective, flexible approaches to motion data capture

Optoelectronics

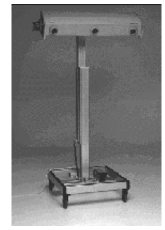
Advantages

- Automatic marker coordinate data generation
- Immediate review of collected coordinate data
- 3D coordinates available immediately after data collection
- Flexible sampling rates
- Comprehensive collection, processing, and reviewing packages

Optoelectronics

Disadvantages

- Reflections, reflections, reflections
- No visual record other than stick figure
- Identifying special events difficult due to no visual record
- System is tied to the laboratory, not portable
- Active markers require tethering subject to system



Vendors

–Northern Digital (Optotrak)
–Selcom (Selspot)

Electromagnetic tracking

Advantages

- Automatically generates 3D marker coordinate data
- Provides linear *and* angular position data
- No "lost" or hidden markers
- Immediate review of collected coordinate data

Electromagnetic tracking

Disadvantages

- Low sampling rates (but improving)
- Interference from nearby metals distorts signals
- Markers relatively large and obtrusive
- Active markers require tethering subject (telemetry may become available)
- No visual record of the movement

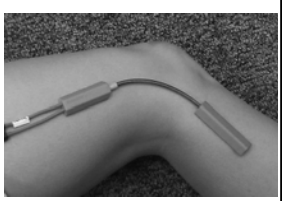
Vendors

–Polhemus (Fastrak)
–Ascension Tech (Flock of Birds)

Electrogoniometers

Advantages

- Fairly inexpensive
- Output signal immediately available
- Provides relative joint angles



Disadvantages

- Only provides relative joint angles
- Can shift relative to joint during data collection

Vendors

–Penny & Giles
–Biometrics Limited

Accelerometers

Advantages

- Provides clean acceleration signal
- Output signal immediately available

Disadvantages

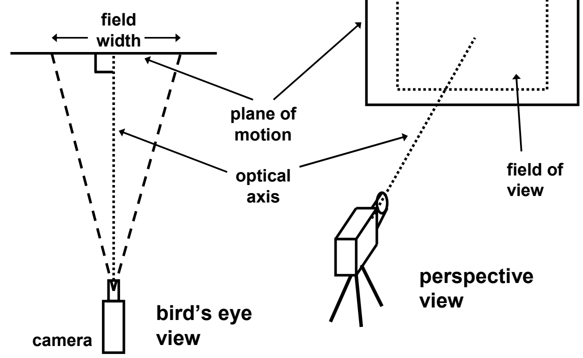
- Difficulty determining global components of the acceleration
- Use of multiple, triaxial, accelerometers is costly
- May interfere with natural movement of the subject

Vendors

–Kistler
–Sensotec
–IC Sensors

Basics of Two-Dimensional Video Motion Capture

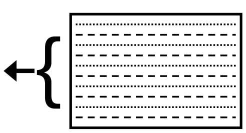
Typical Set-up



Video basics

What information can be obtained from video?

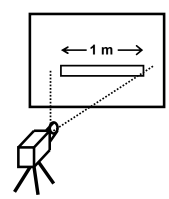
- Timing information
  - Standard video cameras operate at 30 (29.97) Hz
  - Separating (de-interlacing) odd and even scan lines yields 60 (59.94) Hz
  - 200-500 Hz camera are now common, some cameras go up to 100k Hz but image quality suffers



Video basics

What information can be obtained from video?

- Position information
  - Requires one to perform a spatial calibration
  - Subject to digitizing errors
  - In 2-D, subject to perspective errors



Video basics

Image quality is affected by many factors

- Lighting
- Contrast
- Camera resolution
  - Video (250-1200 horizontal lines)
  - 16 mm film (~20,000 horizontal lines)
- Exposure time
  - Video - electronic shutter
  - Film - mechanical shutter

Video basics

Exposure time - duration in seconds that film or video element is exposed to light

- Determined by sampling rate and shutter factor
- A shutter factor of 2 means the shutter is open 1/2 the time; a shutter factor of 6 is open 1/6 the time
- Example - sampling at 100 Hz with shutter factor of 3; exposure time is given by:

$$\frac{1}{100\ \text{s}} \times \frac{1}{3} = \frac{1}{300\ \text{s}} = 0.00333\ \text{s}$$

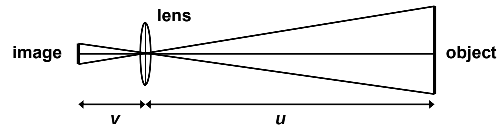
Video basics

Exposure time

- Manipulating exposure time allows you to:
  - avoid blurring of markers
  - control light intensity
- Video cameras typically have selectable exposure times of:

open, $\frac{1}{100}$ s, $\frac{1}{250}$ s, $\frac{1}{500}$ s, $\frac{1}{1000}$ s, $\frac{1}{2000}$ s, $\frac{1}{4000}$ s

Basic Lens Optics



Basic geometric relationship governing lenses

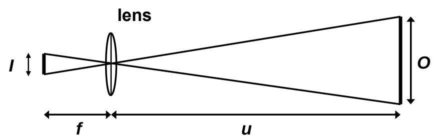
$$\frac{1}{f} = \frac{1}{v} + \frac{1}{u}$$

where ***f* is the focal length** of the lens, ***v* is the lens to image distance**, and ***u* is the lens to object distance**

When lens to object distance is large, the focal length (f) is approximately equal to v

Basic Lens Optics

Effect of focal length on image size

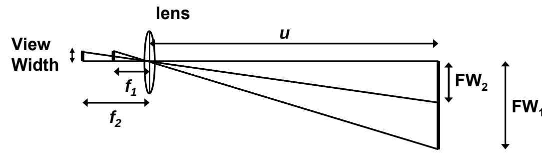


$$\frac{I}{O} = \frac{f}{u} \quad \text{thus,} \quad I = \frac{O\,f}{u}$$

So, you can maximize image size by decreasing u (but you don't want to do this!) or by increasing f (zooming in)

Basic Lens Optics

Effect of focal length on field width (FW)



$$\frac{VW}{f} = \frac{FW}{u} \quad \text{thus,} \quad FW = \frac{u\,VW}{f}$$

So, the longer the focal length (f) the less of the plane of motion you will be able to see

Basic Lens Optics

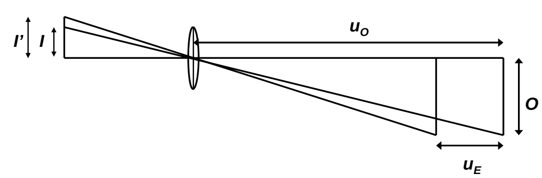
- **Perspective Error**: misrepresentation of the position of a marker due to the subject being out of the intended plane: a problem for 2-D analysis only
- If camera to subject distance is large, and the subject is only a little out of the plane, then the fractional error (ε) is approximately:

$$\varepsilon = \frac{u_E}{u_O - u_E}$$ (see next slide)

Basic Lens Optics

$\varepsilon = u_E / (u_O - u_E)$

u_O – object to lens distance
u_E – distance out of plane



So for the same absolute "out-of-planeness", fractional perspective error will be smaller when the camera is farther from the intended plane of motion

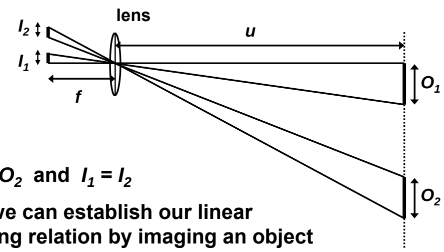
Basic Lens Optics

Back to Focal Length

- Lenses can have a fixed focal length or a variable focal length (i.e., a zoom lens)
- A small focal length will produce a wide field of view, but objects will look small (this is a wide angle lens)
- A large focal length will cause objects to appear larger, but will result in a narrow field of view (this is a telephoto lens)
- If the camera is moved back to minimize perspective error, a large focal length is required to maintain adequate image size

Basic Lens Optics

Constancy of object-image relations in the plane



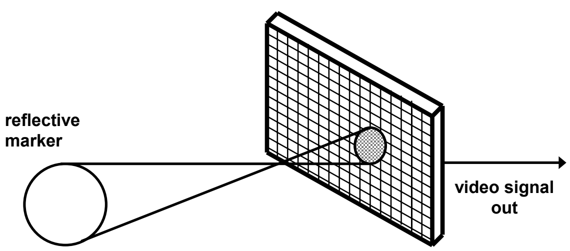
$O_1 = O_2$ and $I_1 = I_2$

So, we can establish our linear scaling relation by imaging an object of known length and this will allow us to convert from pixels to real-life units (m, cm)

Video Data Capture

Intensity of incoming light is sensed by a CCD (charge coupled device) element inside the camera

The intensity of light on each pixel of the CCD is encoded as an electrical signal



Video Data Capture

- The resulting video signal is typically saved on analog tape for later analysis
  - This requires a VCR and frame-grabber or video input card to get the video images into the computer for digitization
- The video signal from the camera can also be digitized directly into a computer as it is being collected using a specialized ADC
  - This allows for the possibility of real-time or near real-time marker identification

Guidelines for 2-D Data Capture

- The subject should move in a plane that is at a right angle to the optical axis of the camera
- The camera should be as far away from the subject as possible to minimize perspective error
- The camera should be mounted on a stable tripod, or other mounting, and leveled

Guidelines for 2-D Data Capture

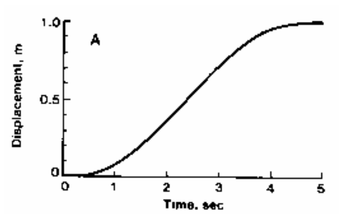
- As long a focal length as possible should be used to maximize subject image size (subject should be at least half the frame height)
- Background should be uncluttered and provide good contrast with the subject
- Anatomical landmarks should be marked to aid in location during digitization

Guidelines for 2-D Data Capture

- Lighting should be adequate; a focused light source behind the camera is helpful
- A scaling rod of known length should be imaged before (or after) data capture to allow conversion to real-life units
- A light in view of the camera, or some other means, should be used if synchronizing video with other data (force, EMG, etc) is required

Interpretation of Human Kinematic Data

Human Motion Graphs

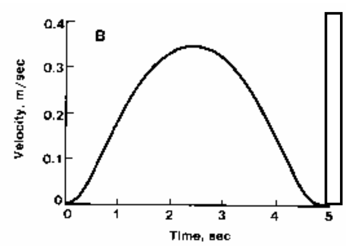


Displacement

Many human movements begin at rest, end at rest, and involve a ballistic movement in between

A plot of displacement vs time will be similar to the graph at left

Human Motion Graphs

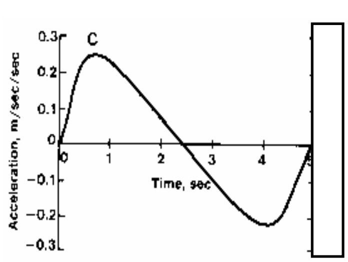


Velocity

Ballistic, point-to-point movements will produce a characteristic bell-shaped velocity curve

At any point in time, the magnitude of the velocity will be equal to the slope of the displacement curve

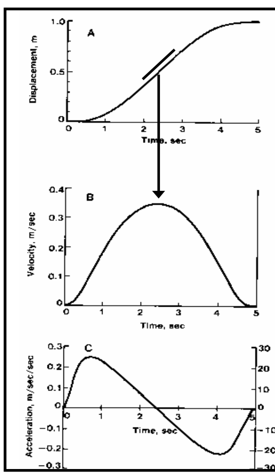
Human Motion Graphs



Acceleration

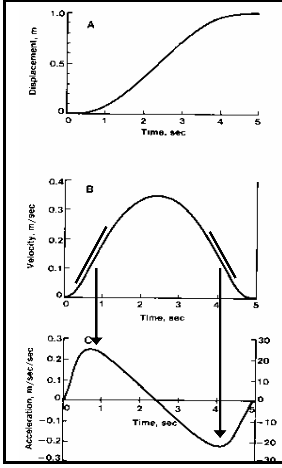
Ballistic, point-to-point movements will produce a characteristic biphasic acceleration curve

At any point in time, the magnitude of the acceleration will be equal to the slope of the velocity curve



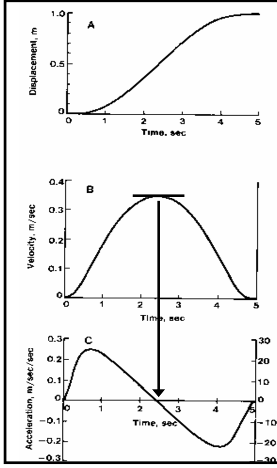
Human Motion Graphs

Notice that when the slope of the displacement curve is steep, velocity is high



Human Motion Graphs

Also notice, when the slope of the velocity curve is steep, acceleration is high (in an absolute sense)

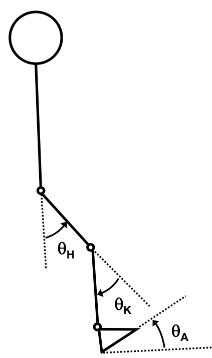


Human Motion Graphs

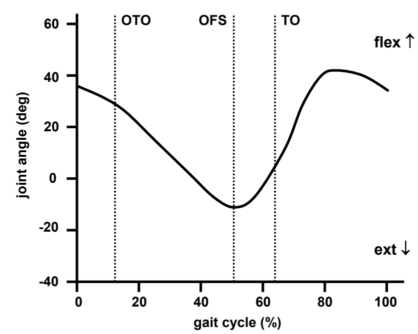
Conversely, when the velocity curve is flat (tangent line is horizontal), acceleration is zero

If acceleration remained at zero, what would happen to the velocity?

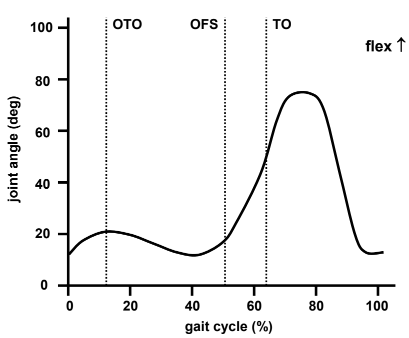
Kinematics of Human Walking



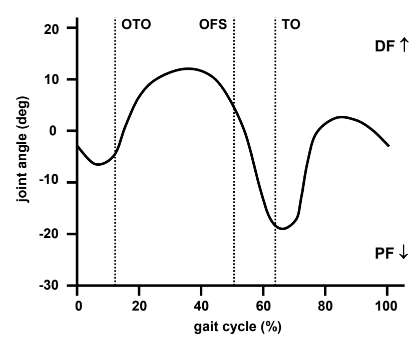
Walking - Sagittal Plane Hip Joint Angle



Walking - Sagittal Plane Knee Joint Angle

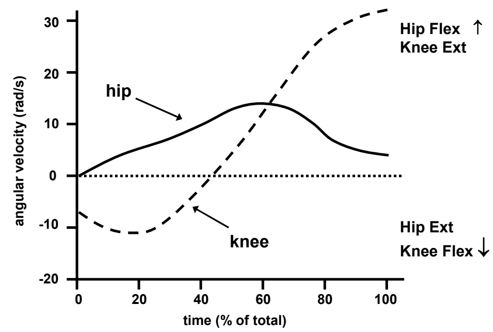


Walking - Sagittal Plane Ankle Joint Angle

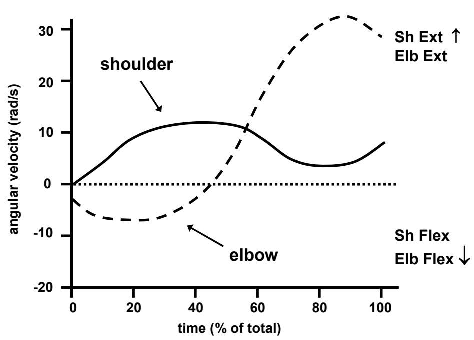


Proximal-to-Distal Sequence of Joint Actions in Rapid Limb Motions

Kicking - Sagittal Plane Hip & Knee Joint Angular Velocities



Throwing - Sagittal Plane Shoulder & Elbow Joint Angular Velocities



Introduction to 3-D kinematics

The need for 3-D

Human motion is inherently three dimensional in nature

- Some activities can be studied safely in a single plane of motion (2-D analysis)
  - Examples?
- Other activities require 3-D data to be collected to adequately capture the motion
  - Examples?

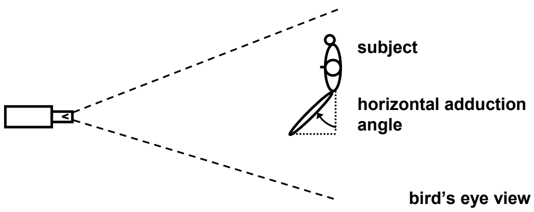
3-D data acquisition

- 2-D coordinates (X and Y) can be determined using a single camera, after a simple calibration has been performed
- To determine 3-D coordinates (X, Y, and Z) a more involved calibration is required
  - Current techniques require that all points of interest been seen by at least 2 different cameras at all points in time
  - Two cameras are required, but using more than 2 generally gives more accurate results

Early 3-D Approaches

Using a single camera

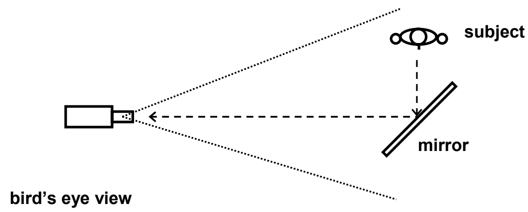
Based on ratio of the apparent length of a segment to the true length of the segment



Early 3-D Approaches

Using a single camera

Place a mirror at 45° to the optical axis of the camera, in the field of view of the camera

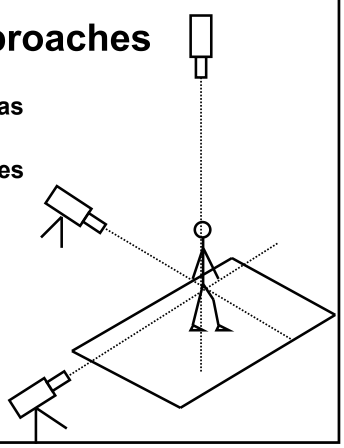


Early 3-D Approaches

Using multiple cameras

2 or 3 cameras are placed at right angles to each other

(camera placement becomes critical)

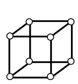
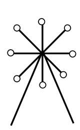


3-D data acquisition

- What information is necessary to accurately reconstruct 3-D coordinates from 2 (or more) 2-D camera views?
- Need to know certain internal and external camera parameters:
  - Positions and orientations of cameras
  - Camera focal lengths
  - Camera principal points
- These can be measured (costly and labor intensive), or determined mathematically

3-D data acquisition

- The Direct Linear Transformation
  - Abdel-Aziz & Karara (1971)
  - Shapiro (1978), Walton (1981)
- The current standard in 3-D motion analysis
- Camera parameters are determined mathematically by imaging an object with known point locations (a "calibration object")

3-D data acquisition

The DLT equations:

$$x_i + L_1X_i + L_2Y_i + L_3Z_i + L_4 + L_9x_iX_i + L_{10}x_iY_i + L_{11}x_iZ_i = 0$$
$$y_i + L_5X_i + L_6Y_i + L_7Z_i + L_8 + L_9y_iX_i + L_{10}y_iY_i + L_{11}y_iZ_i = 0$$

where:

x_i, y_i, are 2-D video coordinates of point i
X_i, Y_i, Z_i are real 3-D coordinate of point i
$L_1,\ldots,L_{11}$ are the DLT parameter (camera constant)

For each point on the calibration object you can generate 2 equations, but there are 11 unknowns

3-D data acquisition

The basic DLT procedure:

- Record images with two (or more) cameras of 6 (or more) points on a calibration object
- Each point results in two unique DLT equations (12 equations total)
- Solve the simultaneous system of equations for the 11 unknown DLT parameters ($L_1,\ldots,L_{11}$)
- Once $L_1,\ldots,L_{11}$ are known, the same DLT equations can be used to solve for real 3-D coordinates, given digitized 2-D video coordinates from 2 (or more) cameras

3-D data acquisition

Newer techniques

- Several newer techniques exist that use nonlinear optimization to determine the internal and external camera parameters
- The wand technique we use is a good example
- The main advantage is that you do not need to maintain a (typically) large calibration object with known marker locations
- The size of the calibration space can also be varied quite easily

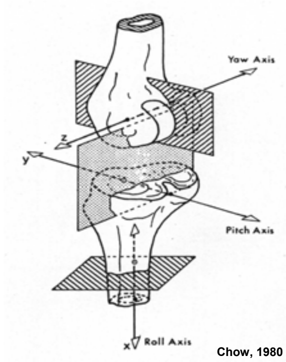
3-D angular kinematics

- Segment and joint angles in 2-D are very easy to calculate and interpret
- Spatial (3-D) segment and joint angles are much more difficult to calculate, and can be more challenging to interpret (different standards exist)
- 3-D joint angle calculations suffer from:
  - Rotation order effects
  - Mathematical singularities

Joint Coordinate System

Joint coordinate system
- Chow (1980)
- Grood & Suntay (1983)

- Most common 3-D joint angle standard in use
- The 3 joint angles are clinically relevant
- Axis system is not orthogonal
- Difficult to use for the shoulder joint



Chow, 1980

Up Next…

Data Processing & Signal Analysis