BIOM9541 Review

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I. Introduction

Aim:

1) integrate anatomy + mechanics to understand human movement.
2) measure, describe, analyze, evaluate human movements

A. Terminology

Anatomical Position = default pose. standing with arms on the side.

Directional Terms: to define body location precisely.

1) Sagittal, Frontal, Transverse
2) Anteroposterior, Mediolateral, Longitudinal/vertical
3) Left vs Right
4) Medial vs Lateral
5) Superior vs Inferior
6) Anterior (Ventral) vs Posterior (Dorsal)
7) Distal vs Proximal (only with limb segments)

Axes:

1) Longitudinal / Vertical axis
2) Mediolateral axis
3) Anteroposterior axis

Plane:

1) Sagittal
2) Frontal
3) Transverse
4) Oblique - any diagonal section

B. Anatomy

1) Bones
   a) Axial - skull, vertebral column, rib cage
   b) Appendicular - shoulder blades, pelvis, limbs
2) Joints
   a) Structural
      i) Fibrous - connect w/ dense (immovable) fibrous tissues
      ii) Cartilaginous - connect w/ cartilage (don't move much)
      iii) Synovial - joint cavity (liquid)
   b) Functional
      i) Synarthroses - non moving
      ii) Amphiarthroses - partly moving
      iii) Diarthroses - fully moving
   c) Types
      i) Plane
      ii) Hinge
      iii) Condylar
      iv) Ball & Socket
      v) Saddle
      vi) Pivot

Circumduction - (x degree freedom)

C. Forces

- Contact
  - internal vs external
  - tensile (muscles, tendons, ligaments) vs compressive (bones)
  - normal vs tangential forces
  - friction
- gravitational ($9.81m/s^2$)

D. Moments

- Centric (causes linear motion only) and Eccentric (causes rotation and possibly linear motion too) forces
- Torque (rotating & twisting) and Moment (bending)

angular kinetics and momentum link

II. Anthropometry

Definition: concerned with the measurement of the physical characteristics of the human body.

1) Segment length (table II)
2) Lower limb segment length = distance from ASIS to medial malleolus
3) Segment mass
4) Centre of Mass
   - $\bar{x} = \frac{\sum x_i * m_i}{\sum m_i}$
   - (Experimental Method) Anthro balance board
5) Mass Moment of Inertia - resistance of system to rotation
   - Radius of Gyration ($I = mk^2$) - measure of the distribution of its mass about an axis of rotation.
   - Cylinder approximation:

$$I_z = \frac{1}{2}mr^2$$
$$I_x = I_y = \frac{m}{2}(3r^2 + h^2)$$

   - Regression equation from cadaver study
   - Experimental method
   - Parallel Axis Theorem $I = I_0 + md^2$
6) Muscle origin and insertion point
7) Body Density $= 0.69 + 0.9\frac{h}{w^{1/3}}$

See table III.

III. Gait Analysis

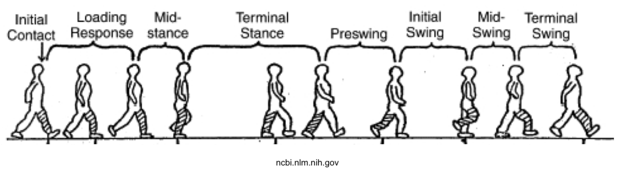


Fig. 1: Phases of Gait

Weight acceptance is for shock absorption, initial limb stability, and preservation of progression. Single Limb Support is for continuation of progression of movement

Gait Parameters

TABLE I: Phases of Gait

Gait Cycle							
Stance (60 %) = Double (20%) + Single (40%)					Swing (40%)		
Weight Acceptance		Single Limb Support			Limb Advancement		
Initial Contact	Loading Response	Mid Stance	Terminal Stance	Pre Swing	Initial Swing	Mid Swing	Terminal Swing
0-2%	2-12%	12-31%	31-50%	50-62%	62-75%	75-87%	87-100%

1) Temporospatial
2) Joint Kinematics
3) Joint Kinetics
4) Energy Expenditure
5) Electromyography

A. Temporospatial

1) stance swing proportion
2) velocity = $cadence * stridelength * 0.5$ (ave: $1.37m/s$)
3) stride length = 2 steps (ave: $1.41m$)
4) step length (m)
5) cadence = steps/minute (ave: $133steps/min$)

B. Joint Kinematics

1) Pelvis - (tilt Y, obliquity X, rotation Z)
2) Hip - (flexion Y, ab/adduction X, rotation Z)
3) Knee - (flexion Y, varus (air between knees) /valgus X, rotation Z)
4) Ankle - (dorsi/plantar (towards ground) Y)
5) Foot progression angle - angle between foot and walk direction (global angle)

See figure 11 for standard joint kinematics.

C. Joint Kinetics

Parameters:

1) Moment
   - external moment can be balanced by (i) muscles (ii) soft tissue structures and (iii) bony structures
   - External moment (*-ing*) = ground reaction force
   - Internal moment (*-or*) = within musculoskeletal system
2) Power
   - work / time or $P = \vec{F} \cdot \vec{v} + \vec{M} \cdot \vec{\omega}$ Watts or J/s or Nm/s
   - (+, muscle puts work into bones) Generation (-) Absorption
   - Muscle power is difficult to measure because it requires measuring muscle force and velocity directly. Instead, Joint power is measured $P_J = \vec{M} \cdot \vec{\omega}$.
   - However, joint power does not account for energy expenditure because of (i) antagonist activities between muscles (only net is known) (ii) elastic and nonelastic internal forces (iii) displacement of muscle relative to skeleton (iv) activation of muscle.
3) Type of Muscle Contractions
   a) Concentric - muscle shortens, generates power
   b) Eccentric - muscle lengthens, absorbs power
   c) Isometric - no change in length
4) Joints - do no generate or absorb mechanical energy, but redistributes/transfers mechanical energy to adjacent segments.

1) Hip - con ext, ecc flex, con flex
2) Knee - ecc ext, con ext, ecc ext, ecc flex
3) Ankle - ecc plantar flex, con plantar flex

See figure 12.

D. Measuring Instruments

1) OpenSim
2) Optical Motion Capture System - based on stereophotogrammetry.
   a) passive markers (e.g., Vicon, Qualisys, Motion Analysis)
   b) active markers (e.g., optotrak, codamotion)
   c) SACR, PSI, ASI, THI, KNE, TIB, ANK, HEE, TOE
3) Force Plates (force center x, y can be derived)
   a) AMTI ($F_x, F_y, F_z, M_x, M_y, M_z$)
   b) Kistler (F_x, F_y, F_z for all four corners)
4) Limitations
   a) theoretical background
   b) instrumental errors
   c) soft tissue artifact
   d) assessment of anatomical landmark misplacement and its effect on joint kinematics

IV. 3D Mathematics

1) Vector:
   - addition
   - unit
   - dot products: $\vec{a} \cdot \vec{b} = |\vec{a}||\vec{b}| \cos\theta$
   - cross product: $\vec{a} \times \vec{a} = |\vec{a}||\vec{b}| \sin\theta$
2) Coordinate Systems: Global (positive: z superior, y left, x anterior) and Local
3) Rotation Matrix:
   - Global CS to Marker CS to Anatomical CS
   - $$R = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \tag{1}$$
   - Euler (start and end with same letter) and Cardan (have X, Y, Z)
   - Active (rotating the vector) vs Passive (rotating the CS) rotations
   - Cardan Angles (usually use YXZ in lower limb dynamics)

$$\theta_x = -\sin^{-1}(k''' \cdot j) \tag{2}$$

$$\theta_y = \sin^{-1}(\frac{k''' \cdot i}{\cos\theta_x}) \tag{3}$$

$$\theta_z = \sin^{-1}(\frac{i''' \cdot j}{\cos\theta_x}) \tag{4}$$

V. 3D Kinematics

A. Joint Centre

1) Hip:

$$\begin{aligned} HJC_x &= C\cos 0.5\cos 0.314 - \\ &\quad (ASISTrocDist + mm)\cos 0.314 \\ HJC_y &= \pm(C\sin 0.5 - aa) \\ HJC_z &= -C\cos 0.5\cos 0.314 - \\ &\quad (ASISTrocDist + mm)\sin 0.314 \\ ASISTrocDist &= 0.128 * LegLength - 48.56 \\ C &= MeanLegLength * 0.115 - 15.3 \\ aa &= 0.5 * InterASISDist \end{aligned} \tag{5}$$

mm is marker radius, usually $14/2mm$. HJC are in Pelvic CS.

2) Knee: Solve for FEP, then use KNE,THI,FEP. See sample problem set.

3) Ankle: Solve for FEO, then use ANK,TIB,FEO. See sample problem set.

B. Anatomical CS

Plugin gait: x front, y left, z up.

1) Pelvis: $y = LASI - RASI$, $b = SACR - RASI$, $z = y \times b$, $x = y \times z$
2) Thigh: $z = LFEP - LFEO$, $b = LKNE - LFEO$, $x = b \times z$, $y = z \times x$
3) Shank: $z = LFEO - LTIO$, $b = LANK - LTIO$, $x = b \times z$, $y = z \times x$
4) Foot: $z = LTIO - LTOE$, $b = y_{SHANK}$, $x = b \times z$, $y = z \times x$

C. Joint Angles

Cardan angles where distal CS = $'''$ and proximal CS = no dash. Pelvis, Thigh, Shank, Foot angles are calculated by using distal CS = laboratory CS and proximal CS = segment CS. See table IV for convention.

$$\theta_x = -\sin^{-1}(k''' \cdot j) \tag{6}$$

$$\theta_y = \sin^{-1}(\frac{k''' \cdot i}{\cos\theta_x}) \tag{7}$$

$$\theta_z = \sin^{-1}(\frac{i''' \cdot j}{\cos\theta_x}) \tag{8}$$

$$v = \frac{\theta_{t+1} - \theta_{t-1}}{2\Delta t} \tag{9}$$

$$a = \frac{\theta_{t+1} - 2\theta_t + \theta_{t-1}}{\Delta t^2} \tag{10}$$

VI. 3D Kinetics

A. Inverse Dynamics

- Calculate *joint reaction forces*, *net muscle moments*, and *KE and PE* using *anthropometric*, *kinematic*, *kinetic* data.
- Assumptions
  1) assume CoM point
  2) fixed CoM position during movement
  3) joints are hinge or ball and socket
  4) constant I and segment length
- Types of Forces:
  1) Gravitational forces
  2) Ground reaction or external forces
  3) Muscle and joint forces
- We overcome static indeterminacy (# of unknowns ¿ # of equations) by just computing net muscle moments. In other words, we simplify the problem.
- Link segment model: proximal forces and moments assume positive convention.
- Solving 2D ID: Equate F_x, F_y, and $\sum M = I\alpha$ and solve for the proximal forces and moments.
- Solving 3D ID:
  1) Calculate reaction forces at proximal end of the segment in GCS.
  2) Express proximal and distal reaction forces, distal moments, segment kinematics into LCS.
  3) Apply Euler's equation of motion in 3D ($\sum \vec{M} = I\vec{\alpha} + \vec{w} \times (I\vec{w})$) to solve for the proximal moment in LCS.
  4) (Optional) Convert proximal moment to GCS and move on to next segment.

B. Work and Energy

1) Work
   - Effort to move an object
   - $\vec{W} = \vec{F} \cdot \vec{s} + \vec{M} \cdot \vec{\theta}$ Joules
2) Energy (**Mechanical**, Thermal, Chemical, Nuclear)
   a) Kinetic
      i) Linear $T_L = \frac{1}{2}mv^2$ J
      ii) Angular $T_A = \frac{1}{2}I\omega^2$ J
   b) Potential
      i) Gravitational $V_g = mgh$ J
      ii) Elastic - associated with deformation of an elastic body
         A) Linear Spring $V_e = \frac{1}{2}k(\Delta x)^2$
         B) Tortional Spring $V_e = \frac{1}{2}k_\theta(\Delta\theta)^2$
3) Work Energy Theorem:
   - $W = \Delta T$ (change in KE)
   - Derived from $\sum F = ma$ where $a = vdv/ds$
4) Modified Work Energy Theorem
   - $W_{NC} = \Delta E = \Delta T + \Delta V_g$
   - Nonconservative (NC) (e.g., friction, ΔT)
   - Conservative (C) = only dependent on initial and final displacement (e.g., ΔV_g).

C. Power

1) $P = \vec{F} \cdot \vec{v} + \vec{M} \cdot \vec{\omega}$
2) $P_{Joint} = \vec{M} \cdot \vec{\omega}$
3) Power Balance: Is $P_{NC} = \frac{dW_{NC}}{dt} = \frac{dE}{dt}$ satisfied?
4) $P_{NC} = \sum \vec{F_i} \cdot \vec{v_i} + \sum \vec{M_i} \cdot om\vec{e}ga_i$ (note: ω = angular velocity of segment, F, v, M = from joint)

D. Efficiency

1) Definition: $\epsilon = \frac{P_{out}}{P_{in}}$
2) Causes of inefficiency (general):
   a) Conversion of metabolic to mechanical energy.
   b) Neurological inefficiency in the control of the mechanical energy.
3) Mechanical Efficiency
   a) $\epsilon_{metabolic} = \frac{mechanicalworkdonebyallmuscles}{metabolicworkofallmuscles}$
   b) $\epsilon_{mechanical} = \frac{mechanicalwork}{metaboliccost - restingmetaboliccost}$
   c) Affected by: conditioning and fatigue of each muscle, diet, metabolic disorder.
4) Causes of Inefficiency (specific):
   a) Cocontraction
   b) Simultaneous positive and negative work
   c) Isometric contractions against gravity

VII. Muscle Mechanics

Focus:

1) understand muscle physiology and how to model it
2) decompose net muscle model to individual muscle forces

A. Muscle Structure

- Types: cardiac (heart), smooth (digestive system), skeletal
- Action: Contract and Relax
- Tendon: connect muscle to bone
- Ligaments: connect bone to bone
- Muscle Fascicles ¿ Muscle Fibers ¿ Myofibrils ¿ Sarcomeres (the one that actually contract and relax) ¿ Myofilaments ¿ Actin and Myosin

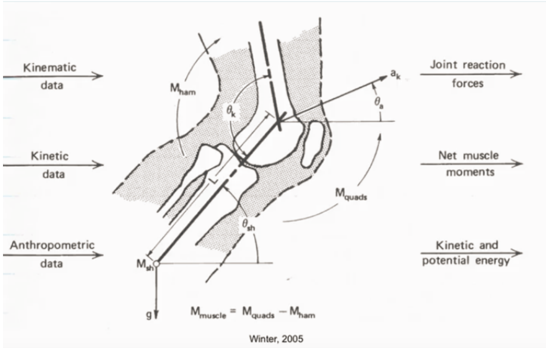


Fig. 2: Muscle Power Moments

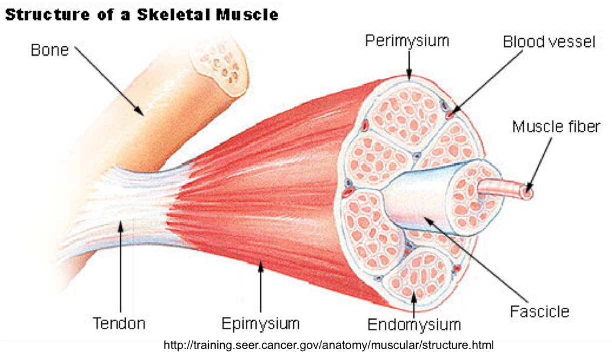


Fig. 3: Muscle Struction

- **Sliding Filament Model**:
  1) Rest: Actin has Tropomyosin and Troponin (insulation), Myosin has ATP and Phosphate (pent up energy), Sarcomere has SR (calcium pump to have gradient outside to inside).
  2) Contract: nerve signal release ¡¿ which distracts Tropomyosin and Troponin, making Myosin "grope" Actin and cause contraction.
  3) Rest: ATP pushes the "groping" of Myosin, back to original state
- Epimysium: surround entire muscle
- Perimysium: group muscle fibres to fascicles
- Endomysium: group tissues to muscle fibres
- Excitability: ability of muscle to respond to stimuli
- Contractility: ability of muscle to contract forcefully when stimulated
- Extensibility: ability of muscle to stretch without being damaged
- Elasticity: ability of muscle to return to original length

B. *Muscle Properties*

1) Types of Forces: **Active** (caused by contractile element) and **Passive** (caused by noncontractile element)
2) Viscoelasticity (like a pump where there is more resistance when you pump quickly but least resistance when you pump slowly)
   a) Creep: The load is kept constant and deformation is monitored. For example, rubber band attached to a constant weight. If the setup is kept, the distance of the weight to the ground will lessen over time.
   b) Stress Relaxation: The deformation is kept constant and stress is monitored.

C. *Hill Muscle Model*

1) Spring and Damper Theory:

Fig. 4: Viscoelasticity

1) Spring: $F = k\Delta x$ where k has unit N/m
2) Dampers $F = b\dot{x}$ where b has unit Ns/m
3) Series: $x = x_1 + x_2 = F * (\frac{1}{k_1} + \frac{1}{k_2})$
4) Parallel: $F = F_1 + F_2 = \Delta x * (k_1 + k_2)$

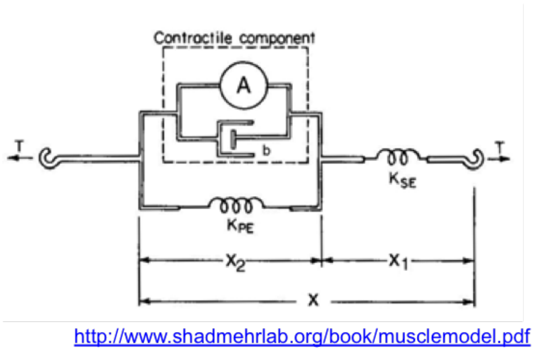
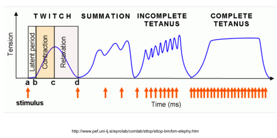


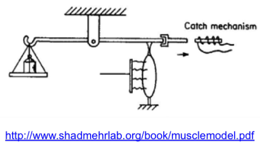
Fig. 5: Hill Muscle Model

2) Definition:

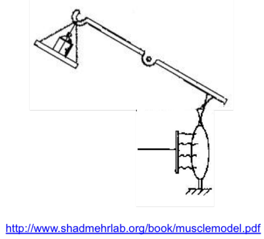
1) Contractile Component (CE): "active" component; converts electrical signal to mechanical output.
2) Parallel Element (PE): represents "fascia" or derived from muscle membranes such as epimysium, perimysium, endomysium and sarcolemma; contributes to passive tension; resists lengthening of muscle.
3) Series Element (SE): passive element that generates force base on elasticity of connected tissues of the muscle; It can come from *cross bridge elasticity* and/or *stretch shortening cycle* (used by ostrich and kangaroos).



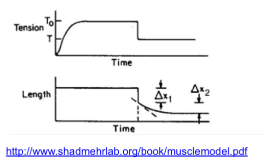
(a) Tetanus



(b) Setup (1)



(c) Setup (2)



(d) Results

3) Hill's Experiment: From these experiments, Hill was able to calculate the constants related to the model.

$$\dot{T} = \frac{k_{SE}}{b}\left[A + b\dot{x} + k_{PE}(x - x^*) - T(1 + \frac{k_{PE}}{k_{SE}})\right] \quad (11)$$

where x is original length, x^* is new length.

- $k_{SE} = \frac{\Delta T}{\Delta x}$ (at yellow line)

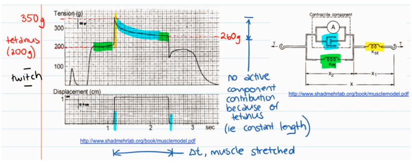


Fig. 7: Constant Calculation

- k_{PE} can be solved by setting up eq. 11 before and after elongation (green line). Note that since $\dot{T}$ and $\dot{x}$ are zero, the equations will be a lot simpler.
- b can be solved by solving for eq. 11 which gives us $T = a_1/a_2 + Ce^{-a_2 t}$. $\frac{k_{SE}}{b}(1 + \frac{k_{PE}}{k_{SE}}) * t = 1$ where t is the time when the decay is around 0.37 of peak/initial value.

4) Furthermore:

1) Benefits
   a) describes approximate behavior of muscles for certain contractile conditions
   b) most frequently used in biomechanics
   c) mathematically simple
2) Limitations
   a) Arbitrary nature of (i) division of force between CE and PE and (ii) separation of elongation between SE and PE.
   b) Only valid for restricted contractile conditions, namely, maximal activation, maximal shortening contraction, at or near optimal length.
3) CE Physical Properties:
   a) Mechanical properties are affected by the ff.:
      i) Stimulation-activation
      ii) Force-activation
      iii) Force-velocity
         - Hill's equation (only good for contraction)
         - $(F+a)(v+b) = (F_0+a)b$ where F is force, v is velocity, a is coefficient of shortening heat, v_0 is maximum velocity (when $F = 0$), $b = av_0/P_0$, F_0 is maximum isometric tension.
      iv) Force-length: force generated by muscle depends on its fibre length. As muscle deviate from optimal length, there are fewer binding sites which means less force.
   b) Power-velocity: For concentric contractions, there is an optimal velocity to generate the most power. Eccentric contractions doesn't have a similar relationship.
   c) Combined Properties

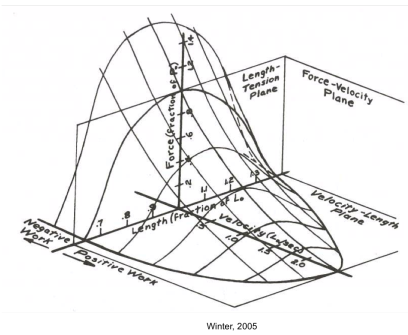


Fig. 8: CE Combined Properties

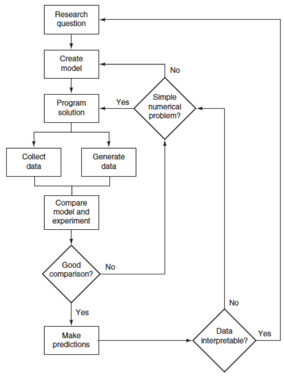


Fig. 9: Forward Simulation Flow

VIII. Musculoskeletal Modelling

Focus: optimization protocols to calculate muscle forces

A. Optimization

- Minimizing cost. Maximizing benefit.
- Static (1 time point) vs Dynamic (multiple time points)
- Cost function J
- PCSA: physiological cross sectional area

1) Linear Functions:

1) Simplex algorithm (Dantzig): minimize or maximize J while satisfying other inequality equations.
2) Mathematical results $! =$ experimental results. *Simple* solutions are not realistic.

2) Nonlinear Functions:

1) Lagrange multiplier method: solve $f(x_1, \ldots, x_n)$ subject to constraints $g_i(x_1, \ldots, x_n)$.

$$\nabla f(x_1, \ldots, x_n) = \sum_{i=1}^{p} \lambda_i \nabla g_i(x_1, \ldots, x_n) \tag{12}$$

$$\nabla f = \frac{df}{dx_1} e_{x_1} + \cdots + \frac{df}{dx_n} e_{x_n} \tag{13}$$

2) Still not good enough to predict experimental results.

B. Opensim

1) Static optimization constrained by one of
   a) Ideal force generators
   b) Force length velocity properties
2) Computed muscle control: compute muscle excitation that will drive the generalised coordinates (e.g., joint angles) towards desired kinematic trajectory. Doing using a combination of proportional-derivative (PD) control and static optimisation.

C. Forward Simulation

Tool to answer "what if" questions.

1) General Procedure:

1) create/draw mechanical model
2) derive model motion equation
3) program numerical solution
4) determine start and end condition for simulation
5) run program
6) interpret model data and compare with experimental data

2) Limitations:

1) numerical imperfections
2) difference of accurately modelling impacts
3) approximation
4) enormous adaptability of human system
5) inevitability of assumptions. you can never account for human or environment.

3) Guidelines:

1) exact magnitude should be treated conservatively
2) analogy should remain loosely
3) discuss model and body separately

IX. Wearable Devices

Why? remote gait monitoring

A. Sensors

1) Accelerometers
2) Gyroscopes
3) Magnetometers
4) GPS
5) Heart rate

B. Coordinate Systems

1) Sensor and device CS
2) Body segment CS
3) Global vertical body centered heading CS
4) Global vertical magnetic heading CS
5) GPS (Earth centred earth fixed) CS

One can calculated distance from acceleration over short time frames ($< 1s$), but over long time frames, the drift increases rapidly.

C. Parameters Captured

1) Step counting:
   - Peak in accelerometer reading = 1 step
   - Cadence = peak / sec * 60 sec / min
   - Older people walk with reduced walking speed, cadence, acceleration variance, all correlated to a reduction in vigour and increased frailty.
2) Harmonic ratio: FFT of acceleration data obtained while walking. Non faller tend to have clearer peaks.
3) Jerk Ratio:
   - derivative of acceleration
   - distance ¿ velocity ¿ acceleration ¿ jerk ¿ snap ¿ crackle ¿ pop
   - older people has less vertical jerk and more lateral jerk
4) Gender differences in gait: alpha male ”monkey” gait and ”cat” like gait with little ML
5) Step time variability $s = sqrt\frac{\sum(x-\bar{x})^2}{n-1}$: used wearable devices to assess the effect of drugs

D. Types of Motion Capture Systems

data quality vs compliance (acceptance)

E. Sensor Fusion

F. Analysis of daily life walking patterns

1) Activity recognition
   a) Detecting when the device is worn
   b) Detecting walking patterns
   c) Machine learning (over-fitting and over training)
2) Laboratory vs free-living walk:

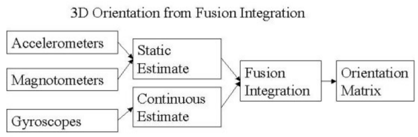


Fig. 10: Sensor Fusion

   a) they are different because of the ”white coat” effect
   b) lab cadence $\approx$ max daily cadence
   c) step variability in daily life much greater than in lab
   d) laboratory walk reflects person’s best performance, which is correlated to their free-living walk. Therefore, laboratory walk is enough for assessing current health status. However, for predicting future health, using free-living walk is better.
3) Remote assessments of walk lengths, variability, adaptability and biomodal cadence in daily life
   a) Walking is good for us
   b) Quality of walking is just as important as quantity of walking.
   c) (i) Longer stride (more closer to log-normal distribution), (ii) high step time variability (bimodal graph or high Ashman’s $D = |\mu_1 - \mu_2|/sqrt(\sigma_1^2 + \sigma_2^2)/2)$, (iii) larger spread of walk adaptability (slow and fast walk) is better (power law, more likely to complete longer walks)
4) Multidimentional analysis of walking patterns and fall risk: there is no simple answer. it’s always ”it depends”.

G. Argus App

X. OpenSim

A. Scaling

B. Inverse Kinematics

C. Inverse Dynamics

D. Residual Reduction Analysis (RRA)

The purpose of residual reduction is to minimize the effects of modeling and marker data processing errors that aggregate and lead to large nonphysical compensatory forces called residuals. Specifically, residual reduction alters the torso mass center of a subject-specific model and permits the kinematics of the model from Inverse Kinematics to vary in order to be more dynamically consistent with the ground reaction force data.

E. Computed Muscle Control (CMC)

The purpose of Computed Muscle Control (CMC) is to compute a set of muscle excitations (or, more generally, actuator controls) that will drive a dynamic musculoskeletal model to track a set of desired kinematics in the presence of applied external forces (if applicable).

F. Forward Dynamics

G. Medical Devices

XI. Appendix

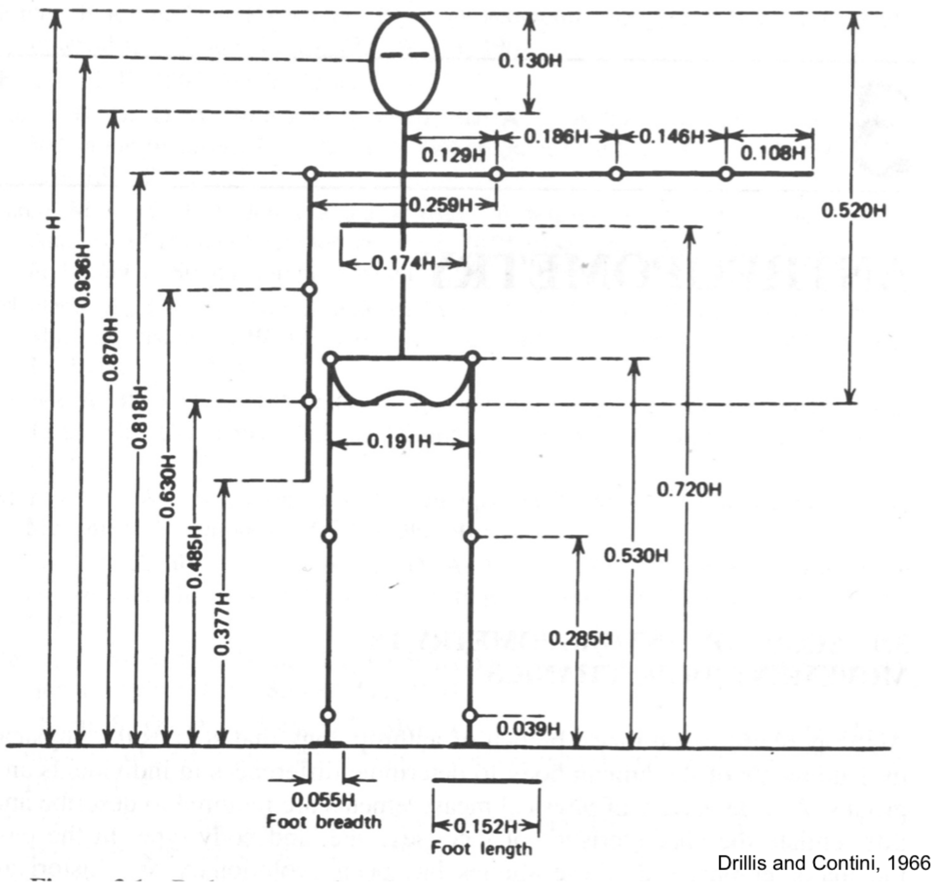


TABLE II: Segment Lengths

Anthropometric Parameters from Winter, D. A. (1992) Biomechanics and Motor Control of Human Movements, 2nd ed. University of Waterloo Press, Waterloo, Canada.

Segment	Definition	Segment Wt/ Total Body Wt	Centre of Mass / Segment length	Centre of Mass / Segment length	Radius of Gyration / Segment length	Radius of Gyration / Segment length	Radius of Gyration / Segment length
			Proximal	*Distal*	*C of G*	*Proximal*	*Distal*
Hand	wrist / knuckle II digit 3	0.006	0.506	0.494	0.297	0.587	0.577
Forearm	elbow / ulnar styloid	0.016	0.430	0.570	0.303	0.526	0.647
Upper arm	G.H jt / elbow	0.028	0.436	0.564	0.322	0.542	0.645
F'arm+hand	elbow / ulnar styloid	0.022	0.682	0.318	0.468	0.827	0.565
Upper limb	G.H jt / ulnar styloid	0.050	0.530	0.470	0.368	0.645	0.569
Foot	Lat. mall / hd. MT2	0.0145	0.50	0.50	0.475	0.690	0.690
Shank	Fem.cond. / med. mall	0.0465	0.433	0.567	0.302	0.528	0.643
Thigh	Gr.troch / fem. cond.	0.100	0.433	0.567	0.323	0.540	0.653
Foot+shank	fem. cond. / med. mall.	0.061	0.606	0.394	0.416	0.735	0.572
Lower Limb	Gr.troch / med. mall.	0.161	0.447	0.553	0.326	0.560	0.650
Head, neck, trunk	Gr troch / G.H joint	0.578	0.66	0.34	0.503	0.830	0.607
Head, neck, arms, trunk	Gr troch / G.H joint	0.678	0.626	0.374	0.496	0.798	0.621
Head and neck	[C7-T1 and 1st rib] / ear canal	0.081	1.000	0.000	0.495	1.116	-

TABLE III: Anthropometric Parameters

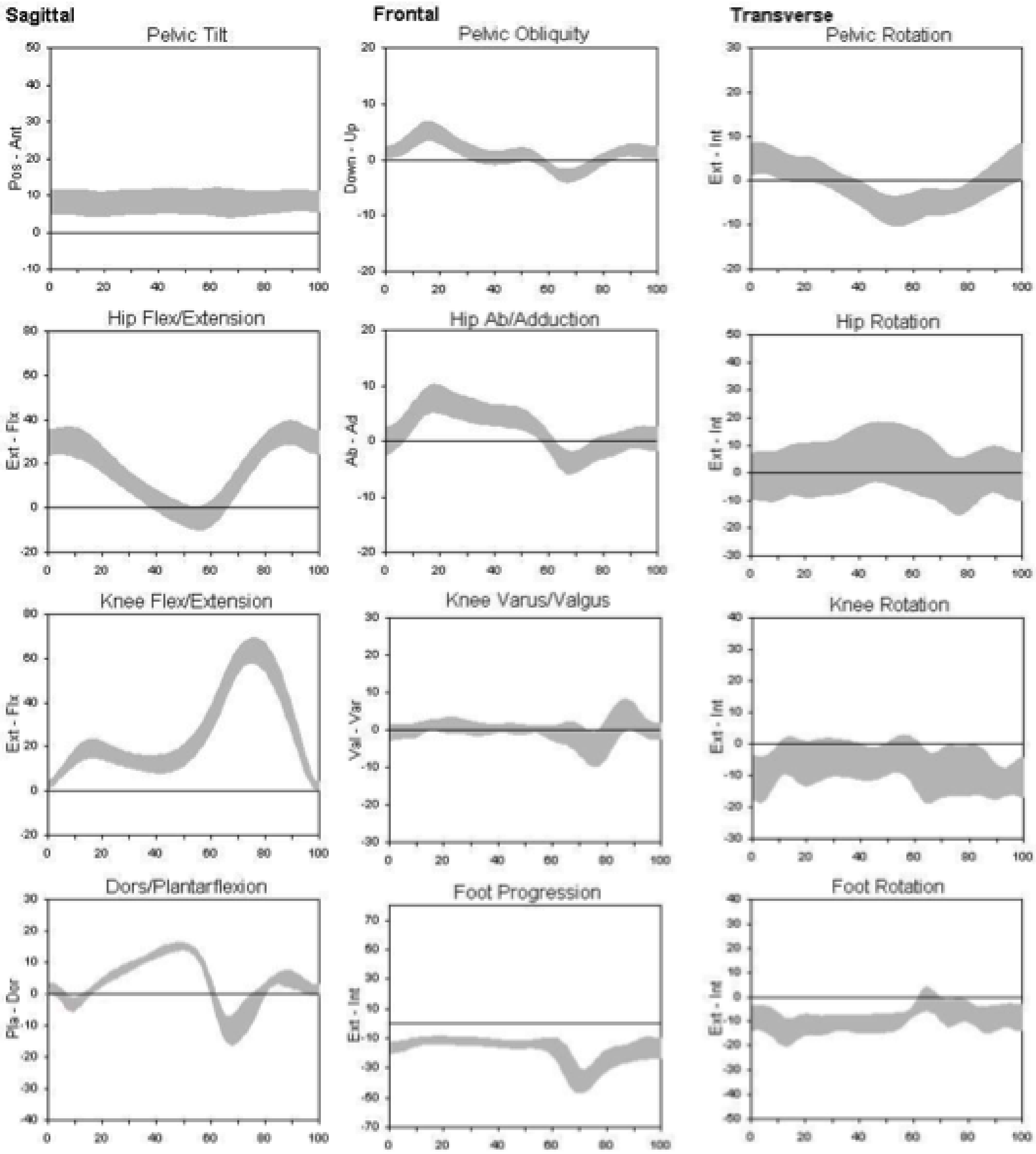


Fig. 11: Standard Joint Kinematics

Angle	Type	Proximal Coordinate System	Distal Coordinate Segment	Axis	Anatomical Naming	Clinical Convention	Mathematical Convention
Pelvic	Global	Laboratory	Pelvis	ML	Tilt	Anterior +ve	Both: Anterior +ve
				AP	Obliquity	Up +ve	Left: Up +ve Right: Down +ve
				Long	Rotation	Internal +ve	Left: External +ve Right: Internal +ve
Hip	Local	Pelvis	Thigh	ML	Flexion/extension	Flexion +ve	Both: Extension +ve
				AP	Adduction/abduction	Adduction +ve	Left: Abduction +ve Right: Adduction +ve
				Long	Rotation	Internal +ve	Left: External +ve Right: Internal +ve
Knee	Local	Thigh	Shank	ML	Flexion/extension	Flexion +ve	Both: Flexion +ve
				AP	Varus/valgus	Varus +ve	Left: Valgus +ve Right: Varus +ve
				Long	Rotation	Internal +ve	Left: External +ve Right: Internal +ve
Ankle	Local	Shank	Foot	ML	Plantarflexion/ dorsiflexion	Dorsiflexion +ve	Both: Plantarflex +ve
Foot Progression Angle	Global	Foot	Laboratory	Long	Rotation	Internal +ve	Left: External +ve Right: Internal +ve

TABLE IV: Joint Angle Convention

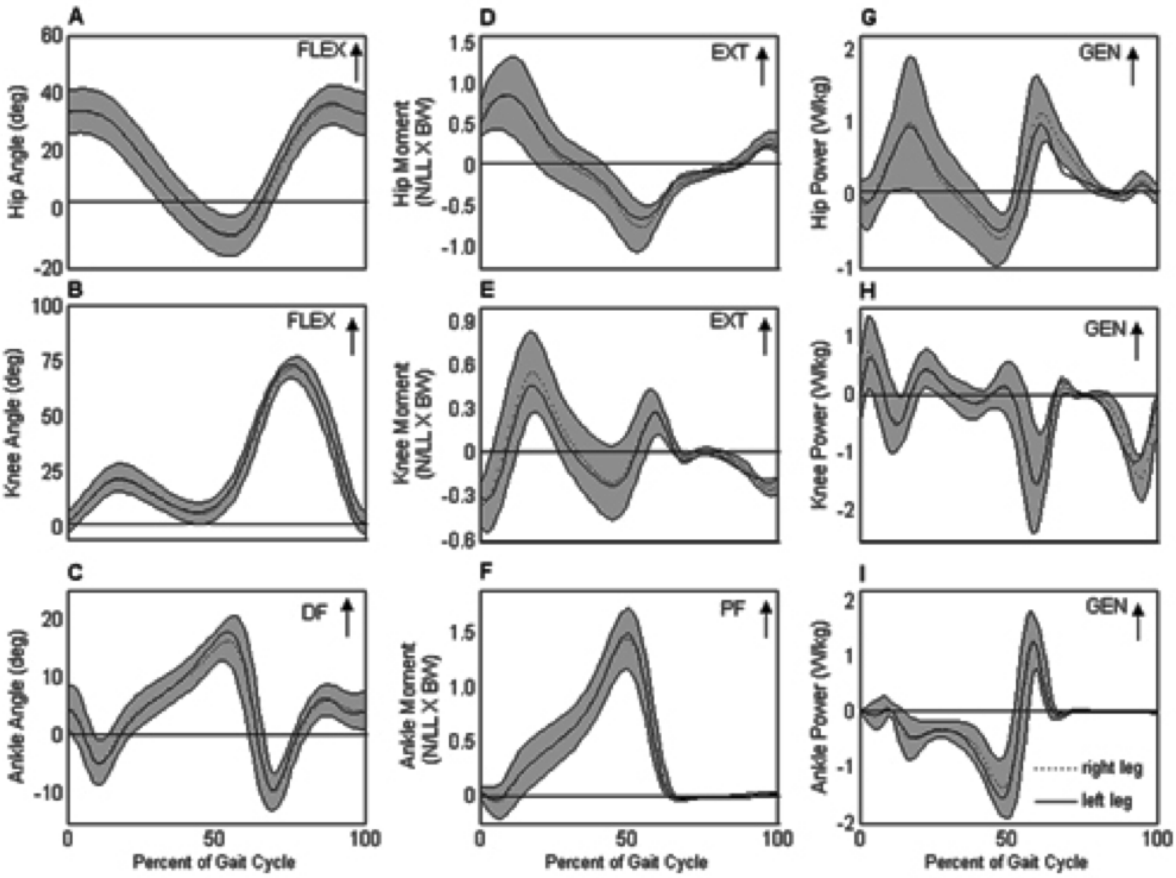


Fig. 12: Standard Joint Kinetics