Introduction to Biomechanics, Part II

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Bioengineering Applications in Sports Medicine
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Inverse Dynamics

Kinematics + Kinetics = Konfusion

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Inverse Dynamics

- Combine motion and force plate measurements to estimate forces acting at joints of body
- Combine them with Newton's laws of motion
- Assume body is a connected set of rigid links

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Inverse Dynamics

- Applied use of Newton's Second Law
- Free body diagram, equations of motion
- Using forces/moments at distal joint, can calculate forces/moments at proximal joint
  - Work way up the body this way

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Inverse Dynamics Example

- Subject walking across force plate
- Foot contacts only force plate
- Know:
  - Motions of foot, leg, thigh
  - Forces/moments acting on foot
  - Point of application of forces on foot
    - Must map from force plate coordinate system to camera coordinate system

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Big Assumptions

- Body segments are completely rigid links
- We know mass, moment of inertia of body segments
  - Can measure with MRI, CT scan
    - Expensive, time-consuming
  - Cadaveric studies
    - Look up in a table: a 38-year-old man has a 2-kg foot
    - Regression: a foot should be 2.5% of body weight

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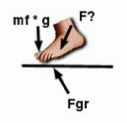
Start With Forces at the Foot...

- $\sum \mathbf{F}_f = m_f \mathbf{a}_f$
- Ground reaction force $\mathbf{F}_{gr}$: known
- Weight of foot $m_f g$: known
- Ankle joint reaction force $\mathbf{F}_?$: dunno
- $m_f \mathbf{a}_f = \mathbf{F}_{gr} + m_f g + \mathbf{F}_?$
- $\mathbf{F}_? = m_f \mathbf{a}_f - \mathbf{F}_{gr} - m_f g$
- Note: **bold** indicates vectors!



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Moments are Messier...

- $\sum \boldsymbol{\tau} = \mathbf{I}\,\boldsymbol{\alpha}$
- $\mathbf{M}_? + \mathbf{M}_{gr} + \mathbf{r}_{gr} \mathbf{x} \mathbf{F}_{gr} + \mathbf{r}_{ank} \mathbf{x} \mathbf{F}_{ank} = I_f \boldsymbol{\alpha}_f$
- $\mathbf{M}_? = I_f \boldsymbol{\alpha}_f - \mathbf{M}_{gr} - \mathbf{r}_{gr} \mathbf{x} \mathbf{F}_{gr} - \mathbf{r}_{ank} \mathbf{x} \mathbf{F}_{ank}$
  - $\mathbf{r}_{gr}$: dist from center of pressure on force plate [i.e., point of application of force] to center of mass of foot
  - $\mathbf{r}_{ank}$: dist from ankle to center of mass of foot
- Note **vector** quantities!

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Now We Know the Ankle...

- Repeat process...
  - Ankle is distal joint, know forces/moments
  - Know kinematics of leg
  - Compute forces/moments at knee
  - And then onto the hip...

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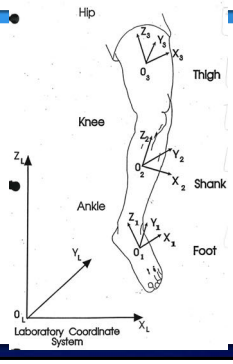
Go Up the Body…



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It Doesn't Have to be a Force Plate

- Pitching:
  - Measure acceleration of ball as it leaves hand
  - Know mass of ball
  - Know forces ball exerts on hand
  - Perform inverse dynamics:
    - Ball → Wrist → Elbow → Shoulder

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Inverse Dynamics Are Powerful

- Non-invasively estimate forces/moments seen by joints
- Predict pathology?
  - Andriacchi's work with arthritis, knee adduction moment

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Inverse Dynamics Suck

- Extremely accurate force measurements
- Extremely accurate motion measurements
- Waaaaaay inaccurate estimates of inertial properties of body
- Error gets bigger as we go farther from force plate

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Inverse Dynamics Caveats

- *Estimate* of joint forces/torques
- *Net* force/torque about a joint
  - Doesn't tell what a particular muscle may be doing
  - Can *qualitatively* relate EMG to inverse dynamics results if enough/correct muscles monitored

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One Great Inverse Dynamics F*ck Up

- "Quad avoidance" gait post-ACL injury
  - Gait adaptations by patients who have a deficient anterior cruciate ligament.
    - Berchuck M, Andriacchi TP, Bach BR, Reider B
    - *J Bone Joint Surg Am.* 1990 Jul;72(6):871-7.
  - Reduced [external] knee flexion moment during gait with ACL injury
    - Less quad activity?
    - More hamstring activity?
  - No EMG measurements

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The Holy Grail

- Record:
  - Kinetics
  - Kinematics
  - EMG
- Relate forces/moments at joint to EMG activity
  - How much force is each muscle generating?
- Difficult/impossible
  - Need very good muscle model
  - Measure *all* muscles that may contribute
    - Agonist/antagonist
    - Deep muscles

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Why Not Have a Motion Lab?

- Large space needed
- Equipment expensive
  - Force plates ~$20-$50K
  - Camera system $75-$300K
  - Electromagnetic system $20-$125K
  - EMG system $5-25K
  - Additional software expensive as well
  - Don't forget the expertise to use the equipment

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Useful References

- Winter, DA. *Biomechanics and Motor Control of Human Movement*. New York: John Wiley and Sons, Inc., 2nd ed. 1990.
- Enoka, RM. *Neuromechanics of Human Movement*. Champaign, IL: Human Kinetics, 3rd ed. 2002.
- Nigg BM, Herzog W. *Biomechanics of the Musculoskeletal System*. New York: John Wiley and Sons, Inc., 2nd ed. 1999.

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Gait Analysis

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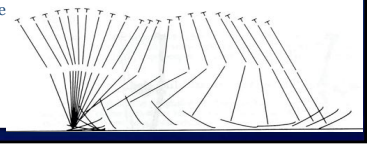
Gait

- Repetitious sequence of limb motions to move body forward
  - One limb is mobile source of support
  - Other limb advances to new support site
  - Limbs reverse roles
- Single sequence by one limb called gait cycle
  - Defined by initial contact with ground
    - Normally heel strike



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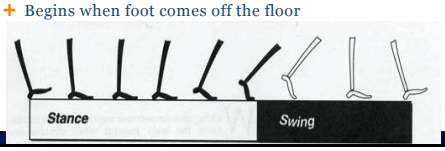
Gait Cycle

- Defined as initial contact to next initial contact
  - Normally, heel strike-heel strike
- Stance phase
  - Foot on ground
- Swing phase
  - Foot in air
  - Begins when foot comes off the floor



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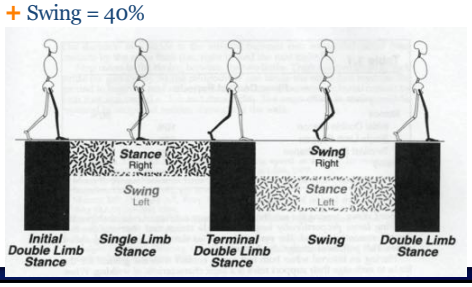
Gait Cycle Subdivisions

- Grossly speaking:
  - Stance = 60%
  - Swing = 40%



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Stance Phase

- Initial double stance
  - Both feet on floor after initial contact
  - 10%
- Single-limb support
  - Opposite foot lifted
    - Swing
  - Duration is good indicator of limb's support capability
  - 40%
- Terminal double stance
  - Contralateral initial contact
  - 10%

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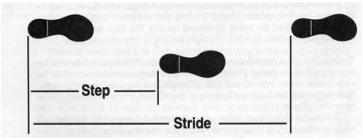
Stride vs Step

- Stride
  - Interval between sequential heel strikes by same limb
  - One stride = one gait cycle
- Step
  - Timing between two limbs
  - Interval between initial contact by each foot



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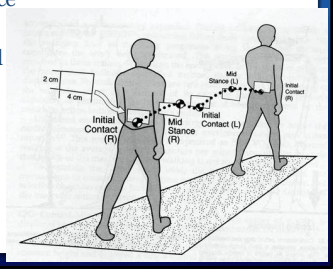
Motion of Center of Mass

- Efficient gait will minimize COM motion
  - Knee flexion in stance
  - Pelvic tilt
  - Heel rise in terminal stance



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Efficiency in Gait

- Minimize center of mass vertical displacement
- Energy storage in elastic elements
  - Tendons
- Use passive momentum of body
  - "Falling" forward during stance
  - Marey [remember him?] called running "controlled falling"
- Measure using metabolic cart
  - Indirect calorimetry
  - Oxygen consumption
    - VO_{2max}
    - Metabolic cost of a given speed

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Gait Measurements

- Joint angles
  - Ankle
  - Knee
  - Hip
- Joint forces/moments/powers
  - Inverse dynamics
- Rates of change of all these
  - Joint angular velocities/accelerations
  - Loading rates
- Muscle activation
  - Timing
  - Amount
  - Frequency?

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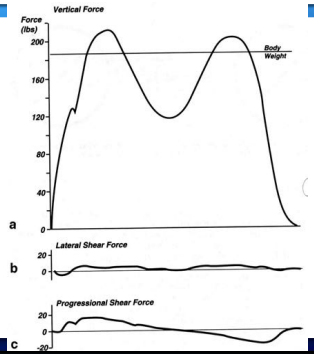
Ground Reaction Forces



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Vertical Ground Reaction Forces

- F1
  - Onset of mid-stance
  - Loading response peak
- F2
  - Mid-stance valley
  - Rise of body center of gravity as body rolls over stance foot
- F3
  - Terminal stance
  - Lowering of center of gravity
  - Preparing to push off
- F1, F3 ~ 110% BW, F2 80% BW
  - Lower speed, lower force
- Impact peak prior to F1

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Shear (Horizontal) Forces

- Medial-lateral (ML)
  - Should be very small
    - < 10% BW
  - Indicative of shift in body weight from one limb to the other
- Anterior-posterior (AP)
  - < 25% BW
  - Initially, breaking force
  - Later, propulsive force
    - Can use to break stance into breaking and propulsive phases

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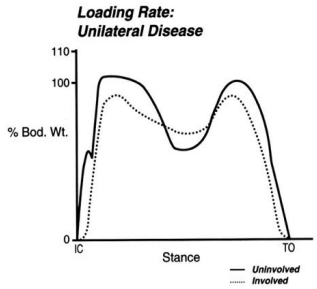
Example: Abnormal GRF



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Running?

- No double support
- Flight phase
  - Both feet off ground
- Single peak in vertical ground reaction force (vGRF)
- Often presence of impact peak which can be greater than "normal" peak

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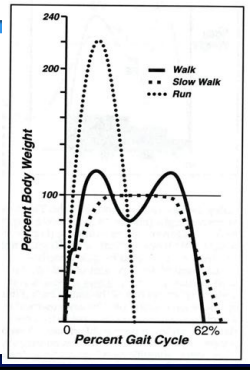
vGRF for Different Speeds of Locomotion



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What About that Barefoot Running Thing?

- Started by popularity of book "Born to Run" [Christopher McDougall]
- Barefoot [or wearing minimalist shoes] tends to land on forefoot
- Normal running shoes [padding] tend to land on heel/rearfoot
- Fore-/midfoot landing allows ankle to assist in absorption of shock
- Tends to get rid of impact peak

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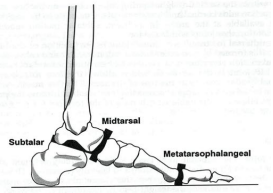
Ankle Simplifications

- Foot/ankle is more complex than a single joint
- Really (at least) three joints within the foot
  - Load/fulcrum moves among them during gait cycle



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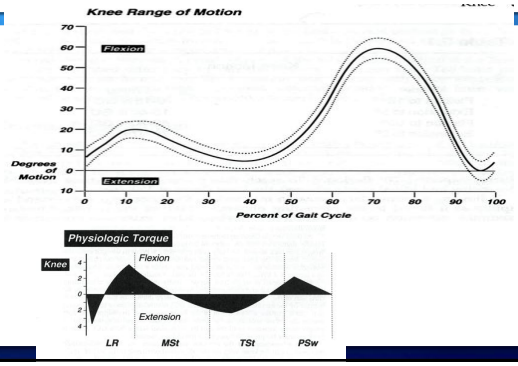
Sagittal Plane Knee Angle and Moment



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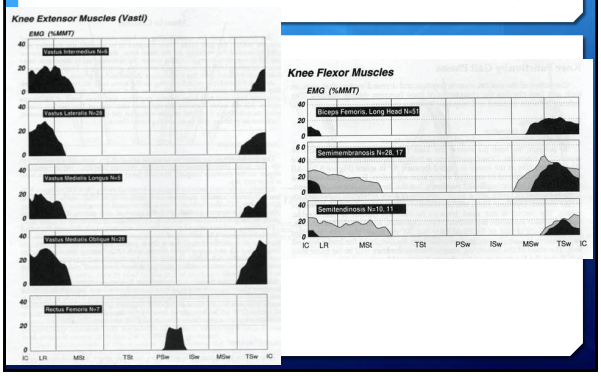
Knee Extensor and Flexor Activity



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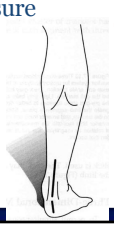
Other Measurements

- Stride/step
  - Length
  - Time
- Center of pressure progression
- Rearfoot angle



- Foot switches
- Pressure-sensitive insoles
- Instrumented walkway

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The Book

- Gait Analysis: Normal and Pathological Function, 2nd ed
  - Jacquelin Perry
  - SLACK, Inc. 2010

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