Musculoskeletal Biomechanics
BIOEN 520 | ME 527

Session 5A
Imaging in Biomechanics
Review: Session 4A and 4B

- Kinematics and kinetics from the RGS
- Kinematics highlights
  - Position vectors and rotation matrices
  - Marker-based coordinate systems
  - Anatomic vs. technical coordinate systems
  - Description of rigid body kinematics
- Kinematics and kinetics of gait analysis
- Mini-Lab #2: Grant writing
- Final project
- Homework 1
- Tour and lab at ABL
Session 5A and 5B Overview...

- Review sessions 4A and 4B
- Imaging in Biomechanics
- Biplane fluoroscopy
- Histology and Biochemistry
Imaging in Biomechanics

• Bone scans
• Bone density scans
• Others:
  ▪ fMRI
  ▪ PET scan
Bone scans

Very small amount of radioactive dye to help diagnose problems with your bone metabolism – abnormal bone growth – due to fracture, infection, cancer, arthritis, trauma, etc.
Bone density scans

DEXA (Dual X-ray Absorptiometry Test)
Scan lumbar vertebrae, upper femur, forearm, wrist
Information used to generated a T-score
-1.0 = healthy; -1.0 to -2.5 = at risk; < -2.5 osteoporotic
FOUR MODALITIES
## The Matrix

<table>
<thead>
<tr>
<th></th>
<th>CT</th>
<th>Ultrasound</th>
<th>X-ray</th>
<th>MRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>$: buy ($M)/use ($1000)</td>
<td>1-2/0.3-0.5</td>
<td>0.1-0.3/0.1-0.3</td>
<td>0.5-1.5/0.1-0.5</td>
<td>2-3/0.3-0.5</td>
</tr>
<tr>
<td>Risks</td>
<td>X-ray effects</td>
<td>None</td>
<td>X-ray effects</td>
<td>None</td>
</tr>
<tr>
<td>Temporal resolution</td>
<td>Low (1 minute)</td>
<td>High (to 30 msec)</td>
<td>High (to 10 msec)</td>
<td>Low (3D), 1-2 sec (2D), gating</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>Medium (to 500 microns)</td>
<td>Medium to high (to 100 microns)</td>
<td>High (to 150 microns)</td>
<td>Medium (0.5-1 mm 3D)</td>
</tr>
<tr>
<td>What is seen</td>
<td>Bones, soft tissues, fat</td>
<td>Soft tissue boundaries</td>
<td>Bones, markers</td>
<td>Everything</td>
</tr>
<tr>
<td>2D/3D</td>
<td>3D</td>
<td>2D (slow 3D)</td>
<td>2D (projection)</td>
<td>2D or 3D</td>
</tr>
<tr>
<td>Limitations</td>
<td>Poor soft tissue discrimination</td>
<td>Soft tissue only, blocked by bone</td>
<td>Bones only</td>
<td>Physically constrained</td>
</tr>
<tr>
<td>Applications</td>
<td>3D morphology, esp. for bones</td>
<td>Soft tissue motion, elastography</td>
<td>Bone/marker motion, dynamic studies, weight-bearing</td>
<td>3D morphology, muscle use and structure, quasistatic studies, elastography</td>
</tr>
</tbody>
</table>
- X Ray and Fluoroscopy (1895)
- Ultrasound (1917)
- MRI (1946)
- Computerized Tomography (1970s) x-ray based
X-ray dosage

• Many factors to consider – spectrum, directions, sensitivity of body parts, age, rate...
• Lower extremities least radiosensitive
• Additional risk of cancer = .004%/mSv
• Average background dose in US = 3.1 mSv
• Annual dose in US = 6.2 mSv
• CT scan (foot) = 0.2 mSv
• 30 secs of fluoroscopy (foot) = 0.08 mSv
• 4 X-rays (foot) = 0.02 mSv
X-ray dosage

I. Computed tomography (CT)

- Images generated by detecting shadow in X-ray photons
- X-rays photons – same photons as visible light, just a higher energy, able to pass through soft tissue, absorbed by bone
- Patient lies on table, which moves through the CT scanner
- X-ray tube and detectors mounted on ring that rotates around table
- X-ray energy varied depending on tissue that is being scanned
Hounsfield unit (HU) scale
- linear transformation of the attenuation
- radiodensity of distilled water is defined as 0 HU
- radiodensity of air at STP is defined as -1000 HU
- radiodensity of cortical bone defined as 1000 HU
Sir Godfrey Newbold Hounsfield
Multi-detector CT

Key innovations:
- Slip rings
- Spiral scanning
- Multi-detector arrays
- Beam configurations
Axial multi-detector CT of foot

Three scans through ankle, subtalar joint, and metatarsals. Cortical and trabecular detail well seen; soft tissues only distinguishable when separated by fat.
CT scans -- reformatted

We can take advantage of the near-isotropic resolution of multidetector CT scans (~0.5mm) to produce reformatted views in any plane. These are thin slices, but we could also produce simulated X-rays (digital reconstructed radiographs or DRRs). Note the tibial fracture.
What can we do with CT scans of the foot?

- Relatively easy to segment into separate bones
- Make submillimeter-accurate patient-specific 3D models of bones and their relative positions
- Collect data for active shape models
- Skin thickness, some muscle cross-sections
- Limited weight-bearing can be simulated
- No motion studies!
Metal artifact
Metal artifact reduction

Gemstone Spectral Imaging (GSI): low (70 kV) and high (140 kV), interpolate in between

Metal Artifact Reduction Sequence (MARS): estimate intensity with no metal
Computer Tomography (CT)

Ledoux WR, et al., J Orthop Research, 24, 2006
An Elaborate Data Set Characterizing the Mechanical Response of the Foot

Ahmet Erdemir\textsuperscript{1,2}, Pavana A. Sirimamilla\textsuperscript{1,3}, Jason P. Halloran\textsuperscript{1}, and Antonie J. van den Bogert\textsuperscript{1}
II. Ultrasound

- Images generated by generation of longitudinal pressure waves (1-50 MHz), and detection of reflections
- Half-λ thickness piezoelectric transducer functions as wave generator/sensor for reflected wave
- Reflection occurs at interfaces where acoustic impedance changes, with total reflection at interfaces with air/bone
- Axial resolution (0.3mm at 10MHz) typically better than lateral
- Real time (2D) or near-real-time (3D)
- Correlation-based speckle noise tracking for tissue motion, elastography
Generation of the ultrasound signal

A: transmitted pulse and reflected echoes
B: conversion of echoes to one line in the image
C: buildup of whole image
Synovial imaging in RA

A: cartilage thinning over MC head
B: normal MC
C: synovial proliferation
D: bony erosion
Speckle generation

Left, specular reflection from a flat, perpendicular interface. Center, reflection from an oblique interface, with weaker return signal. Right, reflection from small scatterers (<0.1 $\lambda$) producing isotropic reflection.
Speckle tracking

Correlation-based matching can be used either to find motion of corresponding points on images or in raw signal, yielding tissue motion and strain.
In ultrasound elastography, gentle compression is applied by the operator, and strain is measured throughout the image. Abnormal tissues (here, breast cancer) are frequently stiffer than normal tissues. Note that only the external stress is known.
Ultrasound elastography

A stiff, nondeforming lesion inside normal breast tissue.
A second example. Here the lesion has both soft and hard components.
Ultrasound applications in foot biomechanics

- Plantar soft tissue stiffness
- Bone motion
- Tendon and muscle motion
- Moment arms (angular deviation vs. tendon motion)
- Surgical adhesions
- Distribution of strains in superficial tissues
Inverse FEM of heel pad stiffness

Axisymmetric model. Measured layer thickness only. Diabetics and normals not significantly different, but wide range of individual variation.

Erdemir et al., J Biomech 2006
Validation of MRI loading device
Validation of MRI loading device
Tracking motions of the gastrocnemius and soleus with ankle motion

Muscle markers were used in this study rather than the musculotendinous junction.

Loram et al, J Appl Phys 2006
Results with active flexion/extension

Note phase difference between gastrocnemius and soleus in C, and differential recruitment of the gastrocnemius over time. Method is capable of subpixel resolution (<20 microns) corresponding to very small motions (<0.1 degree of passive motion) because of signal averaging performed in the cross-correlation measurement.

Loram et al, J Appl Phys 2006
III. X-ray imaging (fluoroscopy)

- Images generated by detecting shadow in X-ray photons
- X-rays photons – same photons as visible light, just a higher energy, able to pass through soft tissue, absorbed by bone
- Area of interest of patient is placed between X-ray tank (source) and image intensifier (II); often this is done was the patient is on a table, but that is not required
- X-ray energy varied depending on tissue that is being scanned
- Fluoroscopy rooms used for bypass surgery
- Portable machines (i.e., C-arms) often used for orthopaedics
X-ray measures of foot type

- Faxitron X-ray cabinet and digital scanner
- All specimens loaded to 25% body weight and standard clinical X-rays taken

Hindfoot Alignment
Anterior-Posterior (AP)
X-ray measure of foot type

- Lateral view
  - Lateral talometatarsal angle (LTMA) (Sangeorzan et al, Foot & Ankle, 1993)
  - Calcaneal pitch angle (CPA) (Sangeoran et al, Foot & Ankle, 1993)
  - Navicular height (Ellis et al., JBJS, 2000)
X-ray measure of foot type

- **AP view**
  - Talonavicular coverage angle (TNCA) (Sangeorzan et al, Foot & Ankle, 1993)

- **Hindfoot alignment view**
  - Calcaneal eversion distance (CED) (Saltzman and el-Khoury, FAI, 1995)

Clinical foot and ankle X-rays with cadaveric specimens, Roush et al., in review FAI
X-ray imaging

Wilhelm Roentgen

Modern C-arm, image intensifier at top
Distortion arises from the influence of external magnetic fields on the paths that electrons follow inside the II.
Image intensifiers produce position-dependent image distortion

Predistortion images (summed over multiple positions) demonstrates distortion and variability with position. After a separate correction is applied at each position, appearance of the grid no longer demonstrates distortion or variability.
Two independent calibration steps

• Correct 2D distortion (repeat if system moved)
• Using a phantom, determine the focal length (distance between X-ray source and image plane), pixel dimensions (more stable) and intrinsic parameters of the camera
• Validate by comparing computed images of 3D phantom to actual images
Flat-panel detectors

- Array of elements that generate signals directly
- Three layers – scintillator, photodiode, transistor array
- No distortion, wide dynamic range, linear response, better efficiency
- Current generation has long lag time, limiting frame rate to 30/s
Three biplane systems

VA Puget Sound

U. Pittsburgh

Brown
Biplane imaging – now what?

Schematic of single frame pair from a calibrated and distortion-corrected biplane system. (note that one projection is suboptimal).

How to localize each of the separate bones in space?

If we know that a particular point on each of the two images corresponds to the same point in the object, we can localize that point in 3D.
IV. Magnetic Resonance Imaging (MRI)

- Takes advantage of body’s natural magnetic properties
- Hydrogen protons = little bar magnetics, randomly aligned
- In a strong magnetic field (1.5 T or 3T), they line up
- Add a source of energy (radio waves, RF), hydrogen resonates
- Strength magnetic field altered with gradient coils
- Altering the local magnetic field by these small increments, different slices of the body will resonate as different frequencies are applied
Magnetic Resonance Imaging (MRI)

- RF source turned off, magnetic alignment returns, RF signal emitted – this signal is used to create the images
- Receiver coils around body sense the RF signal, intensity if plotted in grey scale
- Multiple RF pulses can be used in sequence for different tissues, which relax at different rates
- $T_1 =$ longitudinal relaxation
- $T_2 =$ transverse relaxation
- Proton density = Measures the signal strength from different tissues based only on the relative densities of hydrogen atoms
Peter Mansfield and Paul Lauterbur

MRI Scanner Cutaway

- Radio Frequency Coil
- Patient
- Gradient Coils
- Magnet
- Scanner

Diagram showing MRI components and flowchart.
An MR pulse sequence is a program for each of the approximately half-dozen independent functional units in the scanner. Gradients are used for spatial localization and motion/diffusion sensitization. By manipulating TR, TE, sensitivity to $T_1$ and $T_2$ is changed.
MR pulse sequence

Spin-echo Pulse Sequence
Single Echo T1-weighted

Spin-echo Pulse Sequence
Dual Echo T2-weighted

$T_1$-weighted and $T_2$-weighted
MRI and tissue properties

- \( T_1, T_2, \) proton density – tissue contrast
- Elastography
- Diffusion tensor imaging – coherent microstructure
- \( T_2 \) exercise effect

- 2D/3D – make motion studies possible
- Loading devices can (imperfectly) simulate weight-bearing
- \( \text{SNR} \propto (\text{field})(\text{voxel volume})(\text{imaging time})^{0.5} \)
Different tissue contrasts result from different sequences

1) Sagittal T$_1$-weighted, 2) fat-suppressed T$_2$-weighted, and 3) fat-suppressed SPGR images (for cartilage) of the ankle.
Longitudinal shear waves are produced; their wavelength in the transverse direction increases with tissue stiffness. The actual motion amplitude is measured in microns.

Muthupillai et al., Science 1995
MRE to measure liver stiffness

Normal liver, top; cirrhotic liver, bottom. Scarring increases stiffness.