VA Center of Excellence for Limb Loss Prevention and Prosthetic Engineering

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Limb Loss Prevention

• Functional limb loss
  – Relevant pathologies:
    • Ankle OA (arthrodesis vs. arthroplasty)
    • Foot type (high arch v. neutral v. flatfoot)
  – Dr. Ledoux’s research thrusts:
    • Robotic gait simulation
    • Biplane fluoroscopy
Functional limb loss

- Ankle osteoarthritis:
  - Affects ~6% of the population, $370M per year
  - Veterans have a higher incidence of ankle OA

- Foot types:
  - Veterans have a higher incidence of flatfoot
  - 308M Americans (2010), 21.8M Veterans, 9M older 65 years
  - Foot pathologies are more prevalent in older populations
Limb Loss Prevention

• Anatomical limb loss
  – Relevant pathologies:
    • Diabetes
  – Dr. Ledoux’s research thrusts:
    • Cadaveric tissue testing (diabetic v. non-diabetic)
    • MRI-compatible loading device
    • Patient-specific computational modeling
Limb Loss Prevention

• Anatomical limb loss
  – Despite declining amputation rates among diabetic subjects and Veterans, amputations are still an important problem
    • Li 2012, Tseng 2011
  – In 2010, 8% of population has diabetes, but had over 60% of non-traumatic amputations. Over 65,000 amputations in 2006.
    • CDCP 2011
  – Veterans have 2x to 3x incidence of diabetes
    • VHA 2004

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Robotic Gait Simulator (RGS)

We have developed a device that allows us to simulate the motion and forces of the foot relative to the ground.

- R2000 parallel robot (B and E)
- Force/pressure plate (C)
- Cadaveric foot (D)
- Tibia mounting frame (F)
- Steel frame (A)
- Tendon actuation (G)
- 3D motion tracking system (H)

Basic idea: invert tibial kinematics, force plate relative to foot, keep rotations the same, and adjust translations (plate position) and tendon forces to match GRF.

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Robotic Gait Simulator (RGS)
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- The device accurately generates the forces between the foot and the ground during gait.
- We are exploring the difference between ankle fusion and ankle joint replacement for end-stage ankle osteoarthritis.
- Misalignments of both surgical procedures is being studied.

Biplane fluoroscopy

We have developed a dual X-ray device that allows for the tracking of the motion of the bones of the foot.
Biplane fluoroscopy

- By X-raying in two planes and matching to an a-priori CT scan, the motion of each bone can be determined.
- We are using the system to explore various surgical corrections for high arched or flat feet.
Plantar soft tissue compression: Diabetic vs. normal

- Diabetic tissue is rate dependant (faster = stiffer).
- Diabetic tissue is stiffer, across all rates and tissue locations.

Pai and Ledoux, J Biomechanics, 2010
Plantar soft tissue shear: Diabetic vs. normal

- In shear, the tissue has a characteristic shaped curve.

Pai and Ledoux, J Biomechanics, 2012
Compressive vs. Shear Properties

- J- vs. S-shaped curves
- Final modulus of 1147 kPa (c) vs. 60 kPa (s) for diabetic specimens and 593 kPa (c) vs. 41 kPa (s) for non-diabetic specimens
MRI-compatible loading device

- Gated MRI sequence conducted for multiple 3D data sets.
- Used to determine patient-specific material properties.
MRI-compatible loading device

- We will study normal vs. diabetic feet (stiffer tissue).
- We will study normal vs. clawed toes (higher strains).
Computational foot model

- 27 bones
- 7 pairs of manual segmented cartilage
- 19 joint contacts
- 8 extrinsic muscle tendons
- 107 ligaments
- Plantar fascia
- Plantar fat (6 volumes)
- Encapsulated soft tissue

Isvilanonda, et al., Clinical Biomechanics, 2012
Computational foot model
Clawed hallux simulation

- Clawed hallux deformity and correction procedures
  - Modified Jones procedure (extensor hallucis longus - EHL)
  - Flexor hallucis longus (FHL) tendon transfer procedure
4th Gen FE foot model

- Generated from live subject, unloaded foot
- Include intrinsic muscle volume and skin
  - Eliminate manual segmentation
Inverse FEA analysis

- Force vs. deformation data obtained from MRI
- Determine patient-specific material properties
- Change in internal stresses due to diabetes and claw toes
Prosthetic Engineering

• **Vision:** Enhance the quality of life & functional status of lower limb amputees
  - Determine the efficacy of current clinical practices
  - Investigate novel approaches that offer breakthrough advances to the standard-of-care
Dr. Klute’s Research Thrusts

Mobility Enhancement
- Activities & Levels
- Restore Lost Function
- Balance & Confidence

Injury Prevention
- Socket Fit
- Tissue O₂

Patient Comfort
- Skin Temperatures
- Thermal Conductivity
- Thermoregulation
- Moisture Management
Long-term Goal: Enhance Mobility

- Observe & Record Activities
- Restore Lost Motor Function
- Improve Balance & Balance Confidence
- Mobility
- Injury Prevention
- Comfort

Comfort
Prosthetic knee-ankle-foot system with biomechatronic sensing, control, and power generation

- Energy harvesting knee (MIT)
- CESR foot (Univ. of Michigan)
- Activity monitoring (VAPSHCS)
- EMG Control (Univ. of Oregon)
• Activity monitoring VAPSHCS
  – Develop a pylon-embedded instrument
  – Observe & record activities
• EMG Control Univ. of Oregon
  – Robustly record residual limb EMG
  – Identify locomotion mode, gait cycle phase, and user intent
• Can we improve mobility by optimizing prosthetic foot-ankle stiffness?
  – Klute & Neptune
  – Hahn & Kuo
  – Morgenroth
• Improve Balance & Balance Confidence
  – Disturbance Response in Amputee Gait
  – Unexpected Uneven Ground
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• Improve Balance & Balance Confidence
  – Disturbance Response in Amputee Gait
  – Unexpected Uneven Ground
  – Develop interventions to enhance stability
Long-term Goal: Prevent Injuries
• Tissue Oxygenation during Amputee Gait
  – How does socket shape and suspension type influence tissue $O_2$?
  – How does vacuum level influence tissue $O_2$?
Long-term Goal: Enhance Comfort

- Skin Temperatures
- Thermal Conductivity
- Thermal Regulation & Perception
- Moisture Management
Thermoregulation & Perception

- Can we improve thermal comfort?
  - Control temperature, measure perception, & physiological response
  - Thermal manequin
Thermoregulation & Perception

• Can we improve thermal comfort?
  – Control temperature, measure perception, & physiological response
  – Thermal mannequin
Dynamic Air Exchange Prosthesis

Solenoid: air in

Pump: air & sweat out while maintaining suspension
• Dynamic Air Exchange Prosthesis (n=3)