In Vitro Analysis of Foot and Ankle Kinematics:

Robotic Gait Simulation

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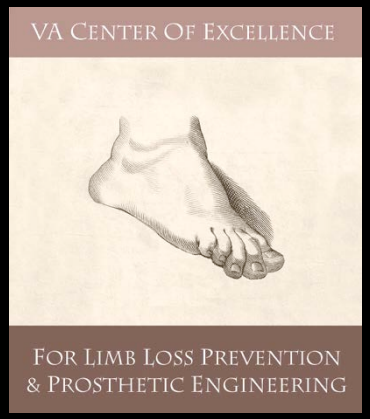
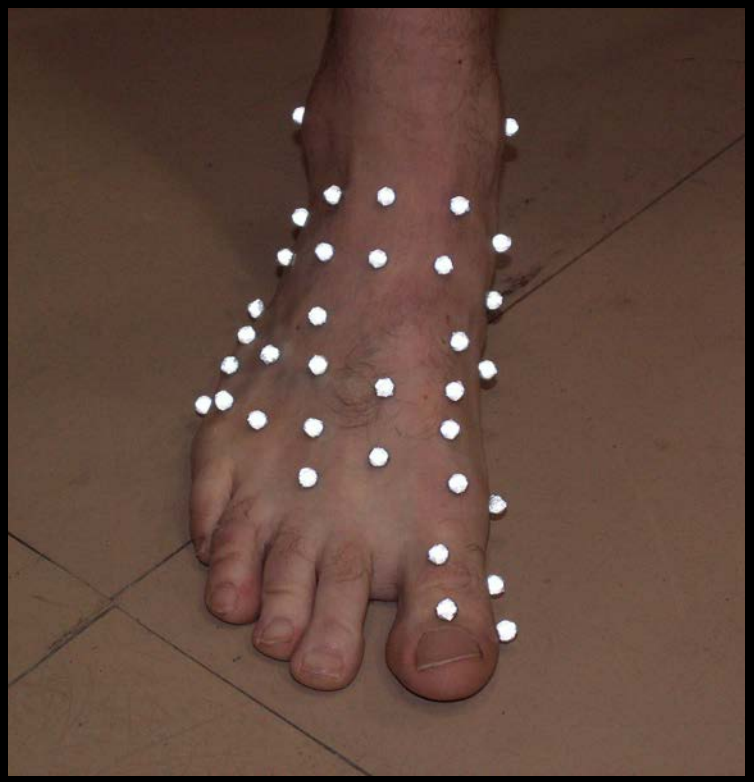
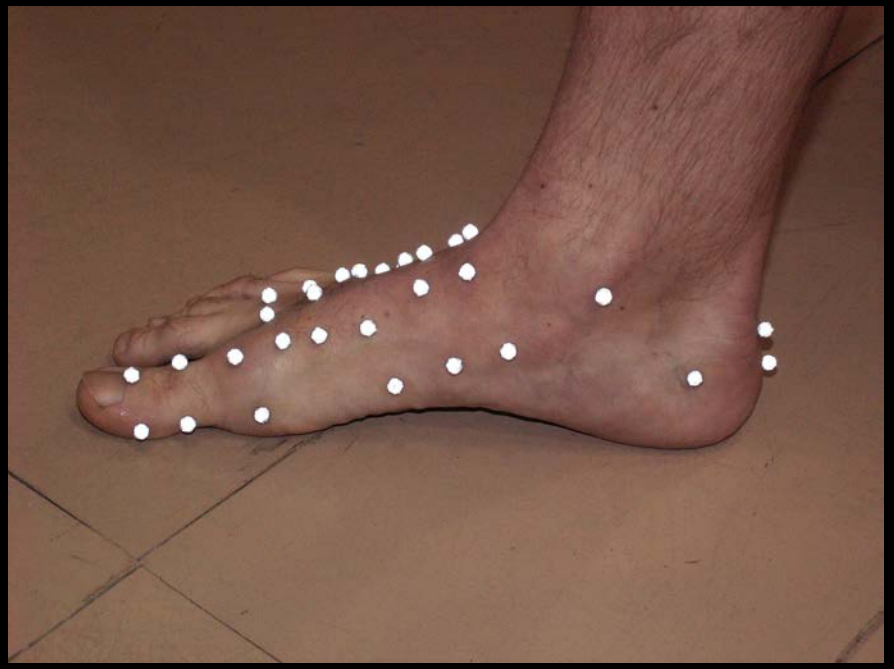


Retro-reflective markers





Numerous authors and groups

Strengths: dynamic; link foot to rest of the body; capture hindfoot motion

Weaknesses: number of markers; rigid body assumption; skin motion artifact

High speed video

Not typically published in research studies

Strengths: high level of detail

Weaknesses: qualitative

X-ray stereophotogrammetry

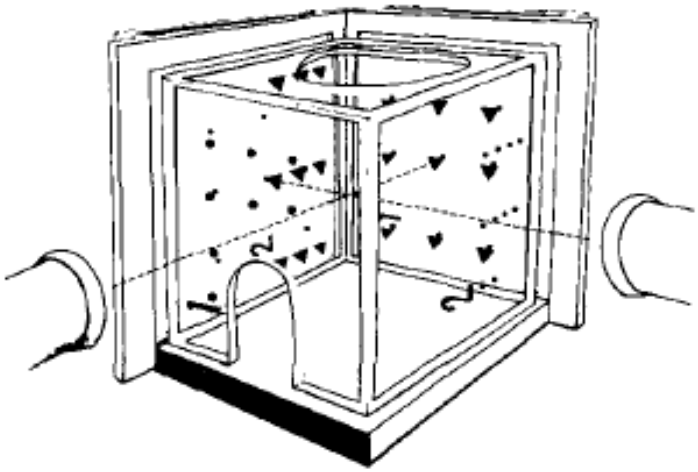


Figure 3. Calibration setup.

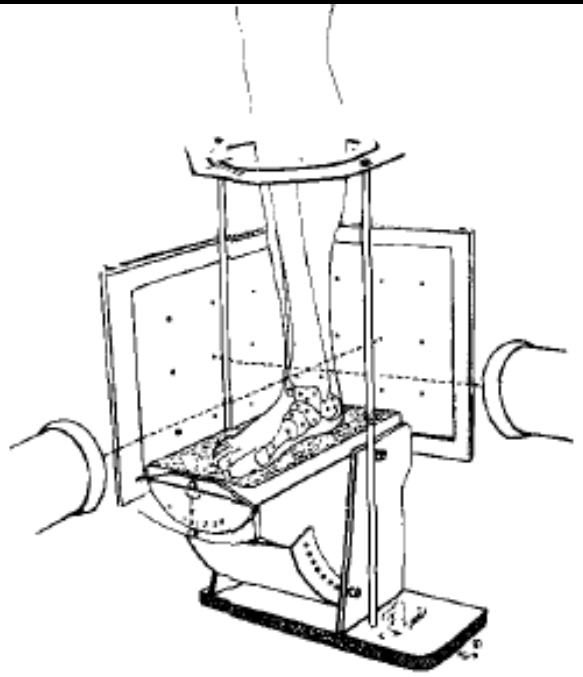


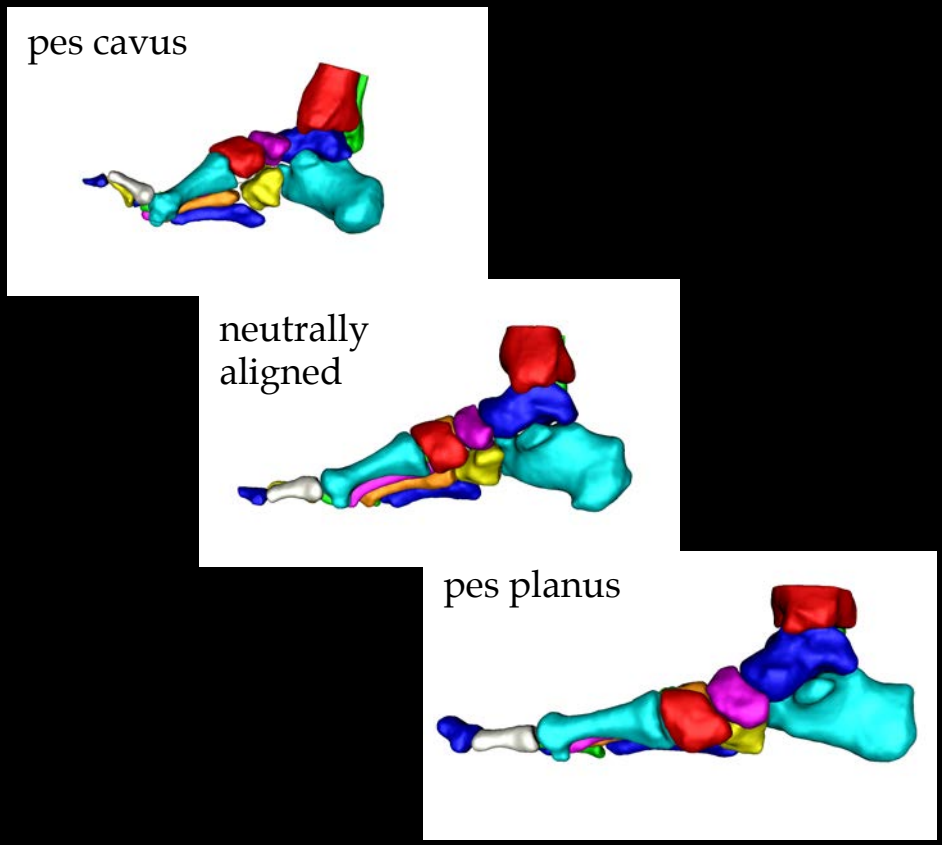
Figure 4. Experimental setup.

Lundberg A, et al., Foot and Ankle, 9, 1989

Strengths: very accurate and precise; multiple bones

Weaknesses: invasive; static; exposure to radiation; cardinal plane motion

Computer Tomography (CT)

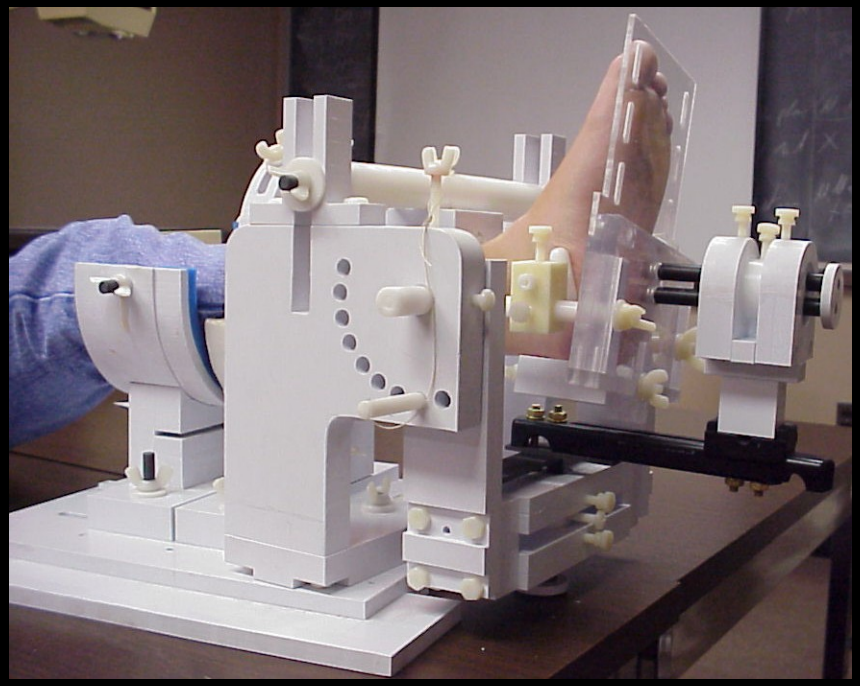


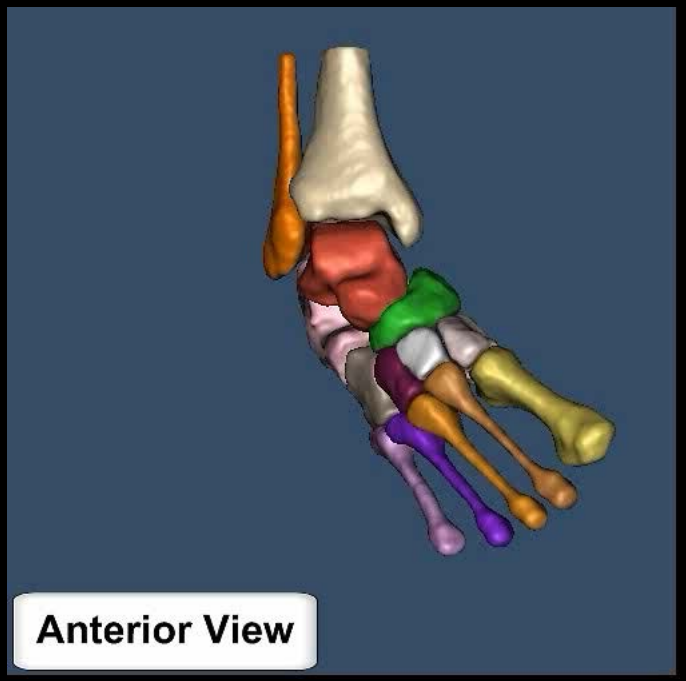
Ledoux WR, et al., J Orthop Research, 24, 2006

Strengths: partially weight bearing; multiple bones; foot type

Weaknesses: single static position; exposure to radiation; inertial based cs

Magnetic Resonance Imaging (MRI)





Fassbind MJ, et al., Journal of Biomechanical Engineering, 133, 2011

Siegler S, et al., Journal of Biomechanics, 38, 2005

Strengths: multiple scanning positions; multiple bones; no radiation

Weaknesses: not dynamic; time consuming data collection

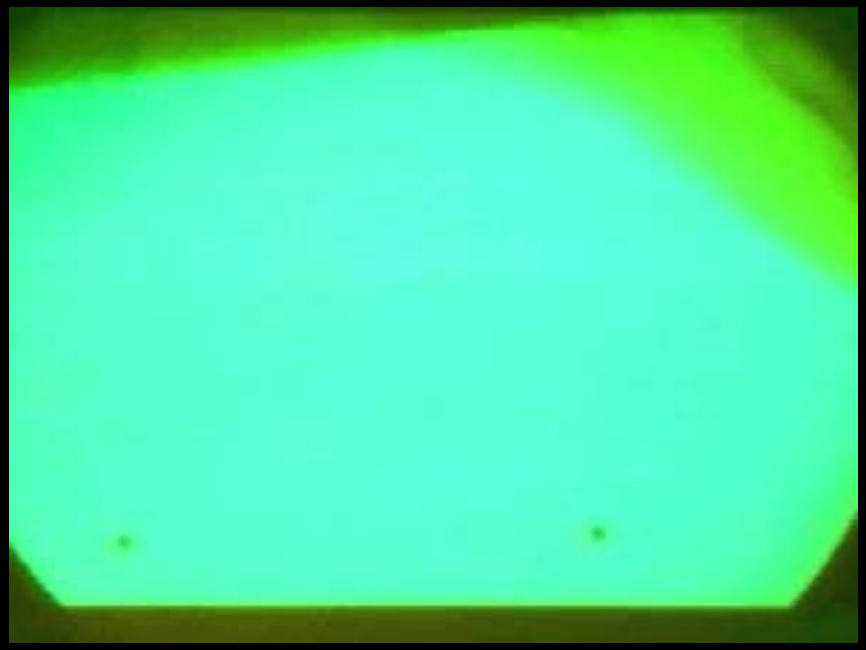
Bone pins

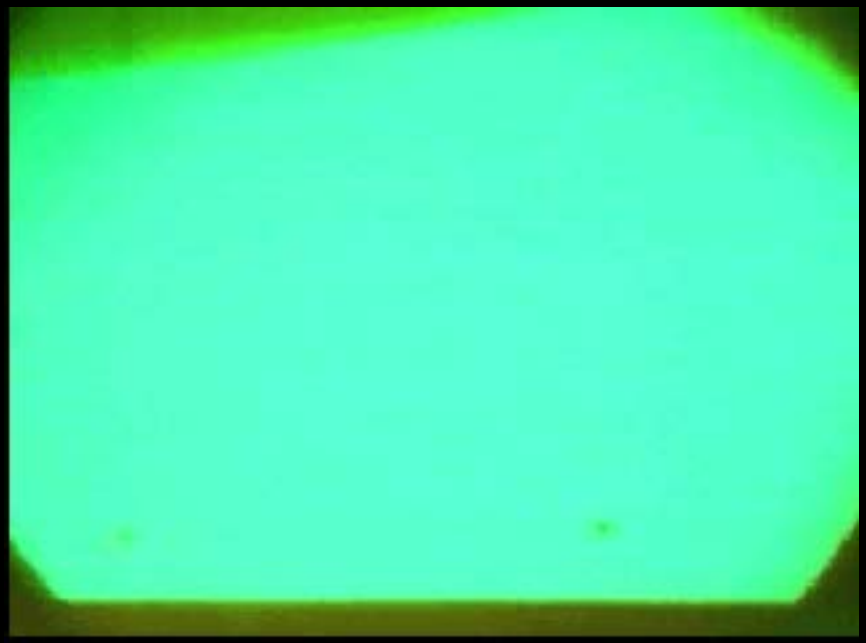
Arndt A, et al., Journal of Biomechanics, 40, 2007

Strengths: dynamic; multiple bones; gold standard

Weaknesses: invasive; not be used in routine clinical care

Fluoroscopy systems





De Clercq D, et al., Journal of Biomechanics, 27, 1994

Strengths: dynamic; multiple bones

Weaknesses: single plane; exposure to radiation

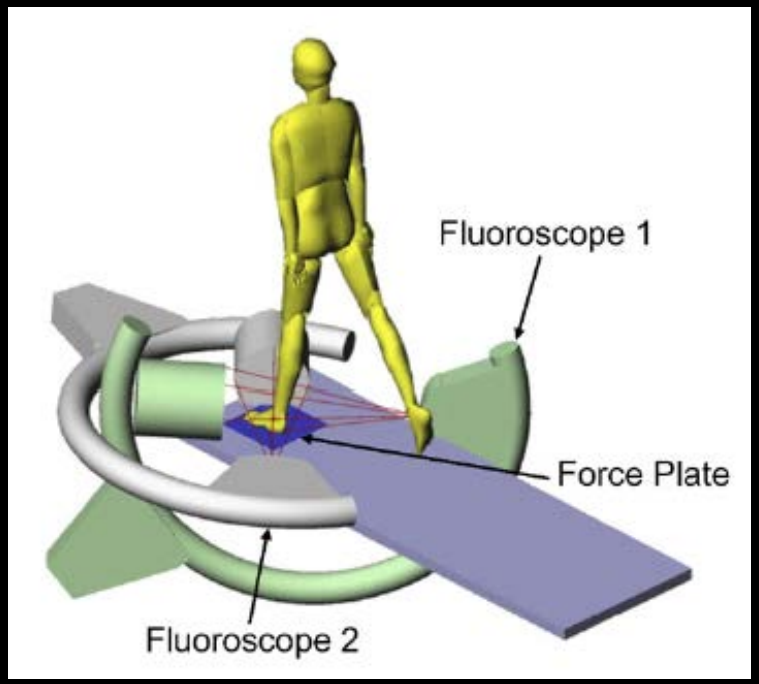
Fluoroscopy systems

Yamaguchi S, et al., Foot and Ankle International, 30, 2009

Strengths: dynamic; multiple bones; 3D-2D model registration

Weaknesses: slower frequency; hindfoot only; exposure to radiation; 3D-2D

Fluoroscopy systems



Li G, et al., Journal of Biomechanics, 41, 2008

Caputo A, et al., American Journal of Sports Medicine, 37, 2009

Strengths: dynamic; multiple bones

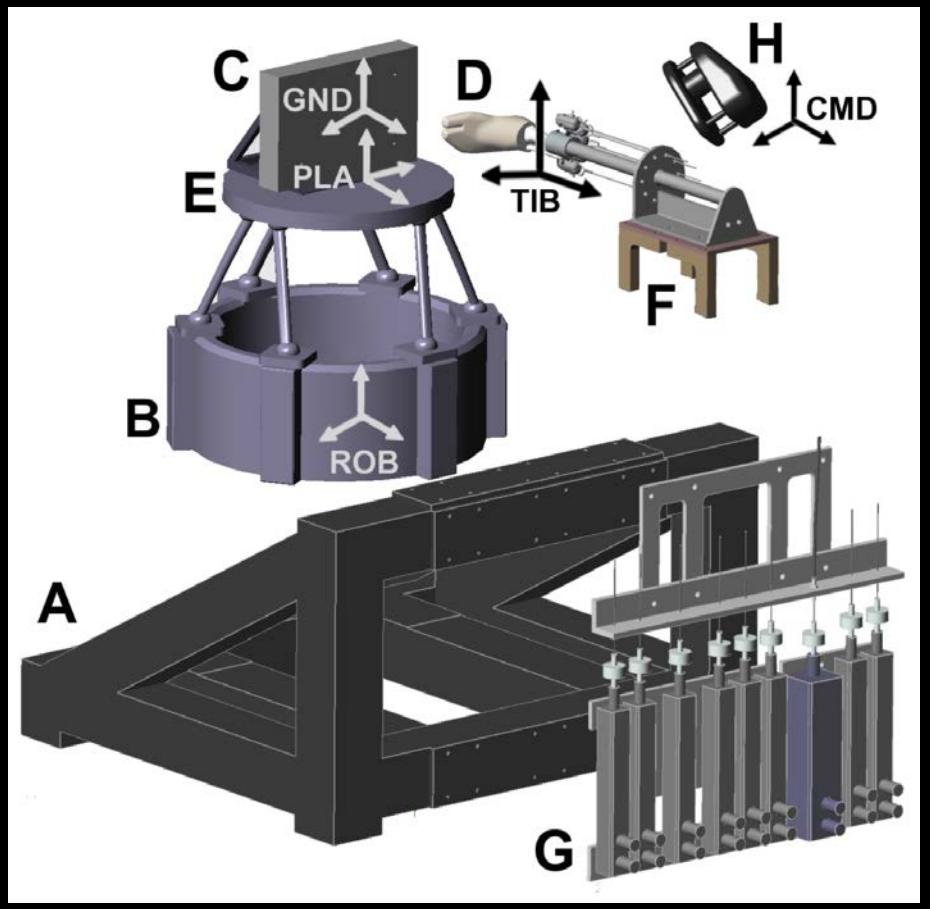
Weaknesses: portion of stance; no oblique images; exposure to radiation

Summary of existing methods

- Skin mounted markers, high speed video, X-ray stereophotogrammetry, CT, MRI, bone pins, fluoroscopy
- Rigid body assumptions, skin motion artifact, static only, invasive and/or exposure to radiation, technology not fully developed

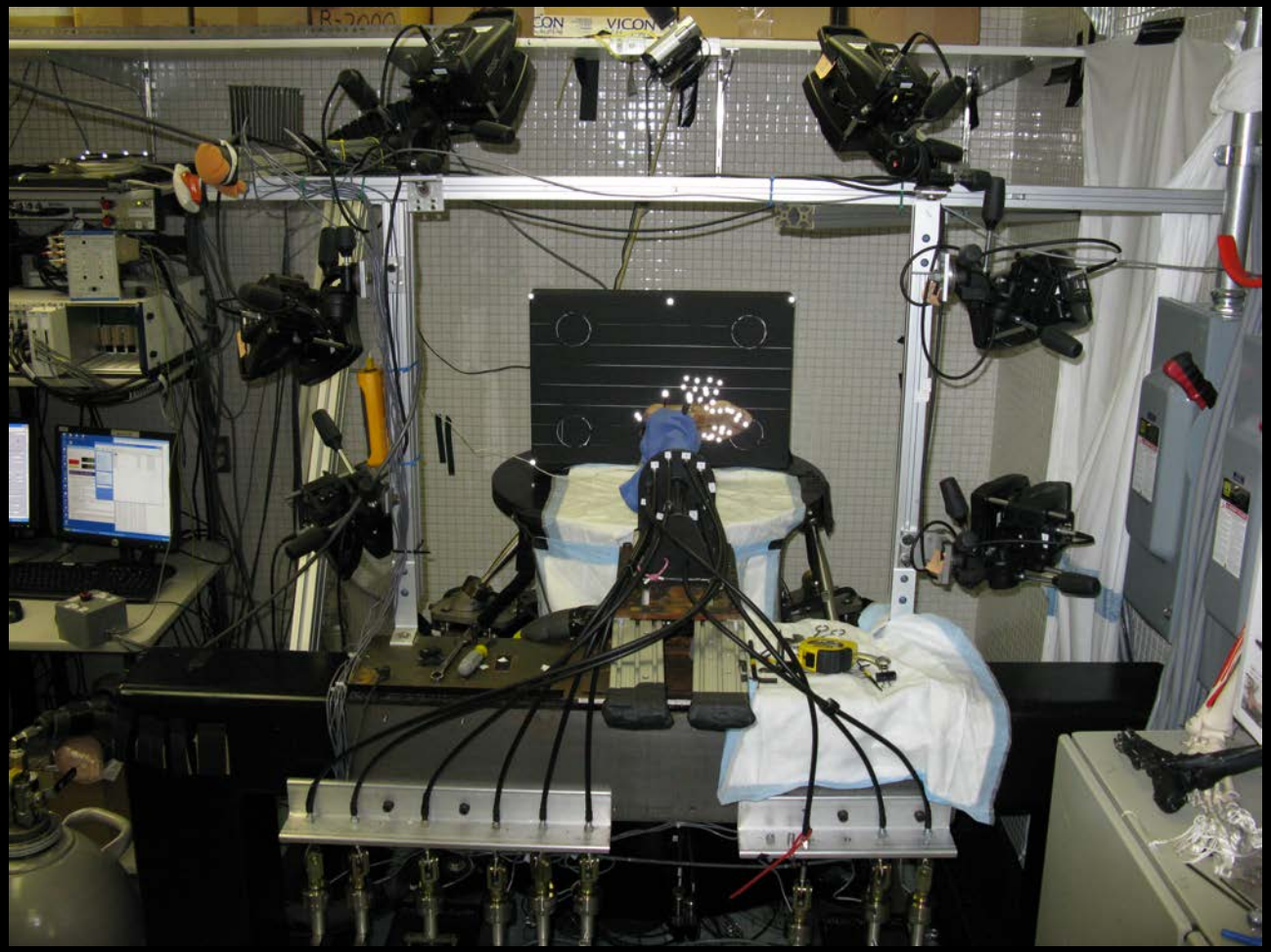
Robotic Gait Simulator (RGS)

- R2000 parallel robot
- Force/pressure plate (C)
- Cadaveric foot (D)
- Tibia mounting frame (F)
- Steel frame (A)
- Tendon actuation (G)
  - 9 brushless DC motors
  - Series load cells
- 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

Robotic Gait Simulator (RGS)



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RGS v5

2010

fast dynamic cadaveric gait simulation (2.7s)

R2000

Kistler force plate

tendon actuators

Vicon motion analysis

fuzzy logic controller v2.0

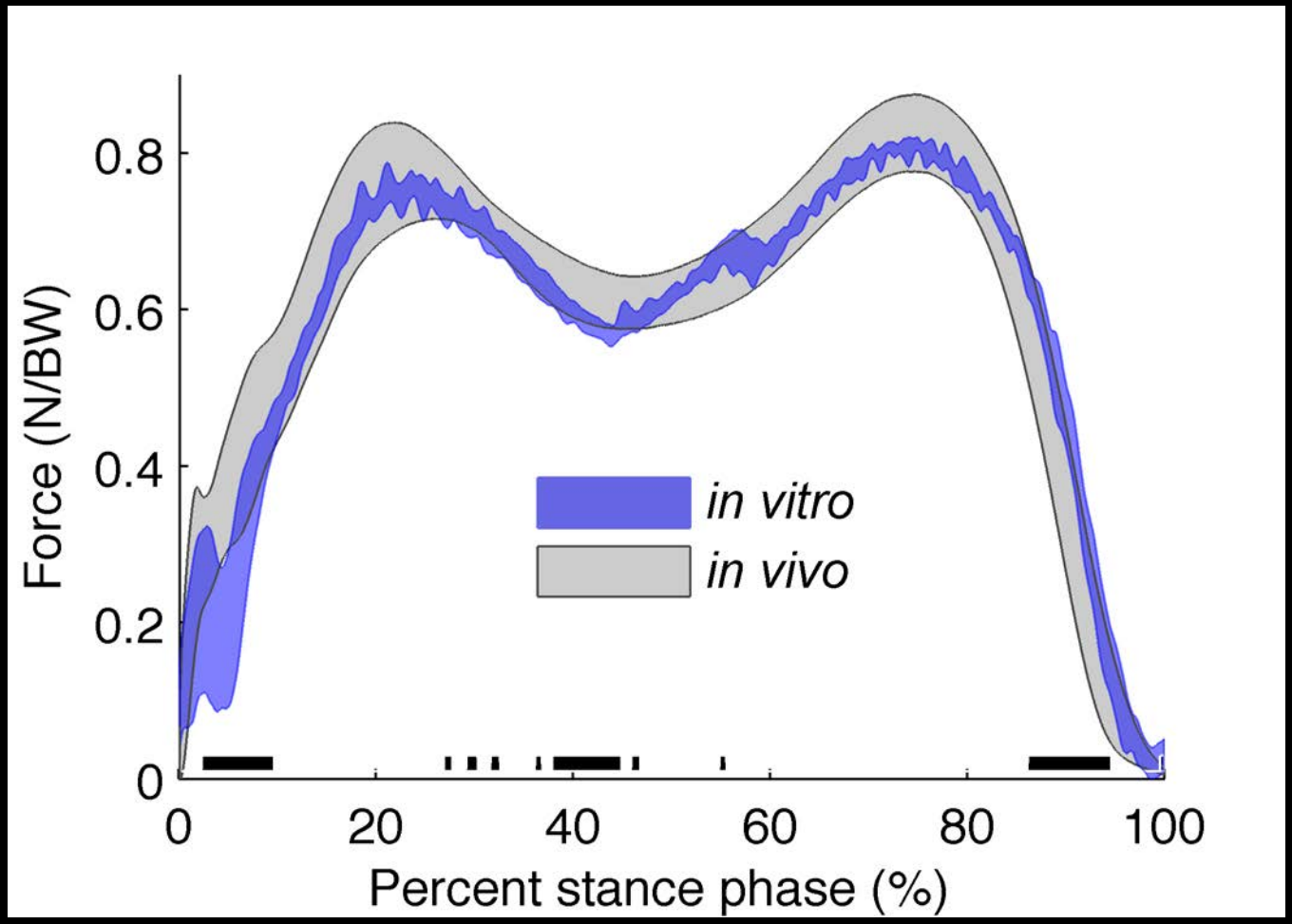
40 marker kinematic foot model

Aubin PM, et al., 2012, IEEE Trans on Robotics, RGS with FLC

Whittaker EC, et al., 2011, Gait & Posture, Foot bone kinematics

RGS v5: GRF

3 learning cycles, 5.6% BW RMS tracking error

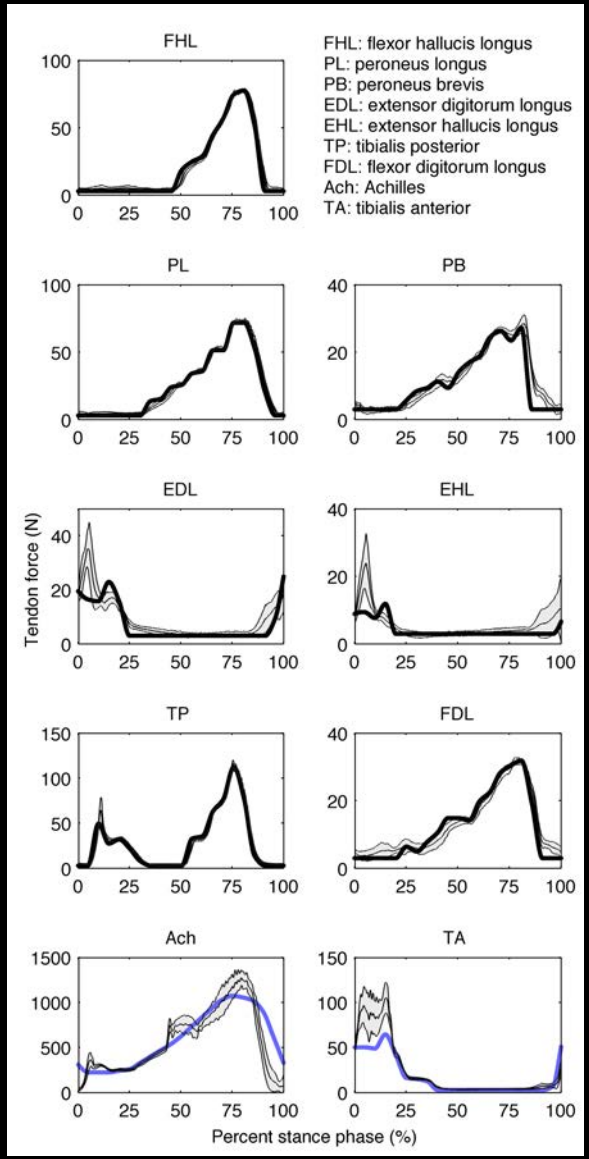


RGS v5: Tendon forces

RMS tracking error for extrinsic tendons ranged from 2.6N for FDL to 5.6N for TP

mean value of 3.9N across all 18 final trials

TA and Achilles were adjusted by controller



RGS v5: Ten-segment model

Anatomical coordinate systems constructed using two methods:

Direct placement on bony landmarks (6 bones):

tibia / fibula

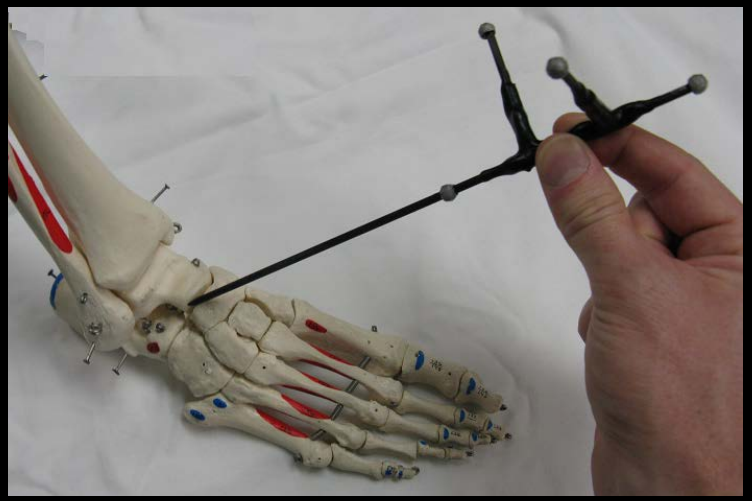
calcaneus

first metatarsal

third metatarsal

fifth metatarsal

proximal phalanx



Arbitrary cluster placement with digitized bony landmarks (4 bones):

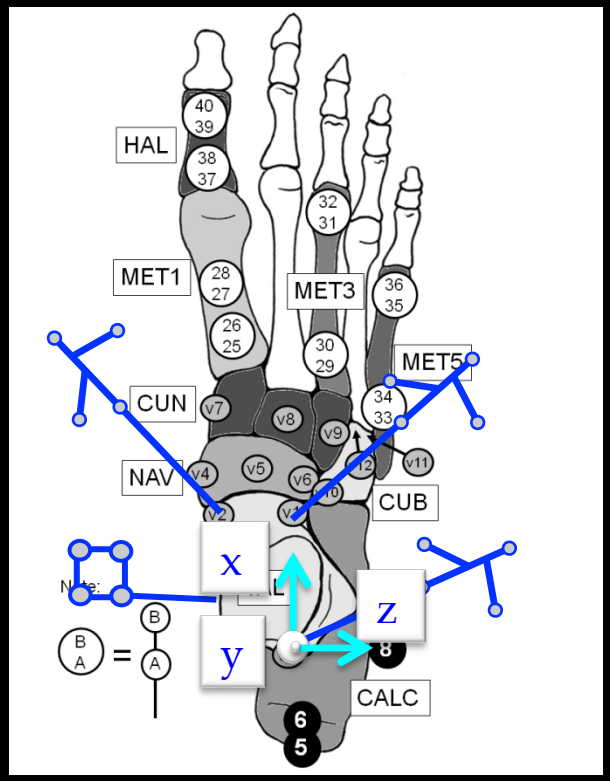
talus

navicular

cuboid

medial cuneiform

Ten-segment foot model



+Z axis: Lateral for right, Medial for left (sagittal plane)

+X axis: Anterior (coronal)

+Y axis: Superior (transverse)