Kinematics and Kinetics of Foot and Ankle during Gait

- foot during weight bearing does 4 things (Perry and Burnefield):

1) upright stability despite an everchanging posture
2) progression is generated by interaction of selective postures, muscle forces & soft-tissue elasticity
3) floor impact at onset of each stride is minimized
4) energy is conserved, minimizing muscular energy, use efficient patterns

- foot is principle contact
- stance phase foot and ankle creates rotation through more proximal structures
- 7 biomechanical phases in gait total
- foot & ankle, 3 "rockers" of gait
- strike to midstance = first and second rocker

+ use flexibility of structure to absorb force in dynamic terrain

+ terminal → swing: 3rd rocker, stiffer structures for force generation

Overview of Relevant Anatomy

- 2 joints: talocrural (tibiotalar) & subtalar

+ talocrural

* trochlea of talus fits in mortise of tib/fib
* loadbearing occurs between tib and domelike superior surface of talus
* No muscle into talus, constrained by medial/lateral malleoli + ligaments/tendons
* prominently hinge with aspects of stability

x e.g. talar width increases anteriorly supporting dorsiflexion

* however, rotated 19° (15°-25°) externally, meaning more motion than just hinge.

+ subtalar

* stability and motion during locomotion
* oblique axis + inability to observe motion study difficult outside cadaver & bone pin (Inman + Mann
* mitered hinge. 1st-2nd rocker, leg IRs
* Leg IR = calcane ER + plantar flexion + talus IR

* creates supple foot for force absorption
* 2-3 rocker, leg ER = calcaneal IR, dorsiflexion, talus ER
* foot becomes rigid lever for power and support.

- calcaneocuboid + talonavicular joint = transverse tarsal

+ level ambulation, transverse tarsal opposes subtalar movement
* when calcaneocuboid + talonavicula are parallel on axes, more mobility is unlocked in midfoot, adding suppleness and keeping 5th metatarsal head in joint.
* 2nd -> 3rd rocker, opposite happens, locking transverse tarsal joint,
+ 1st MTP works mostly on extension.
* Late stance + pushoff, "windlass effect" further tensions plantar fascia for power

Overview of kinetic & kinematic modeling

- quantitative gait analysis for pathology
+ 3 noncollinear foot markers on foot
+ When not focused on foot, single revolute joint + single rigid body
* still has been useful across fields when questions are proximal to intricate design

- one approach: markers on lateral shaft of tib, lateral malleolus, midpoint of 2nd/3rd metatarsals

+ static callibration for virtual knee/joint centers for anthropometric diffs.

* identify segments in 3D space, links markers to anatomy

+ calculated talocrural joint to 2nd/3rd metatarsal marker is foot vector

* transverse plane, plantar surface is sagittal alignme

+ 2D motion, most rocker movement through sagittal

- 1st → 2nd rocker: posterior GRF creates internal dorsiflexion moment

+ anterior COM travel 2nd rocker ↑ internal plantarflexion moment.

- 3rd rocker, rigid PF propulsion → swing

+ 30° sagittal ROM
  - minimal transverse motion (6°)
  + relative to global coords, 5-20°
  + change from external. ot. moment to internal moment

Healthy and Impaired Feet

- assumption: deviations in kinematic/kinetic/EMG from healthy = less efficient gait

+ CP: energy expenditure increased due to ankle motion deficiencies

+ PTTD with tendon substitution + medial displacement calcaneal osteotomy

* 5 camera pre/post operative measures

* Despite finding reductions in cadence, step length, velocity, ankle push off power, overly simplified model wasn't enough

+ Similar issues in study of ankle arthrodesis

* 1st/5th metatarsal head represents forefoot in neutral

* found reduced ROM, but no positional differences

- proof that single rigid body model doesn't work for pathology

+ combines talocrural and subtalar, looses midfoot load adaptation

× e.g.: model assumes excessive dorsiflexion from ankle instead of flat footed issues of arch

- Multi Segment foot models

+ 26 bones, 33 articulations

+ clinical groupings
  - hindfoot: talus, calcaneus + talocrural & subtalar joints
  - midfoot: navicular, cuboid, cuneiforms + talonavicular, calcaneocuboid joints and interarticulatio
  - forefoot: metatarsals, phalanges, + cuboid / cuneiform articulations
  - hallux individually modeled due to pathology importance

+ problems:
  - size of bones (small), can't affix markers
  - can't palpate / no visible access
  - oblique positioning awkward to represent
  - ligaments + articulations violate rigid body assumption

+ fundamental definition to all models is ZERO position

* measure of distal in relation to proximal must be zero in all planes

+ easy at thigh → pelvis, error with SIMPLE foot assumption

+ IN COMPLEX, one of 3 neutral or "ZERO" used:

1. comfortable standing
2 imposed position (neutral subtalar OR vertical tibia)
3. reference orientation of underlying bony anatomy

+ 5 current models:

1. DuPont
2. Heidelberg
3. Oxford Child
4. Leardini (RIZZOLI)
5. Utah

Differences
1. marker and transformations
2. angular calculations
3. Definition of ZERO

+ Definition of ZERO big difference

* would require lab-specific or normative values for clinical interpretation

Chart Notes

- Leardini: highest plantar/dorsiflexion variability
- Utah: highest forefoot ab/adduction variability
- most had high variability in swing, low during stance phase

+ alternative: bony landmarks beneath

* Lundberg et al: radio opaque markers implanted + passive motion solidifies understanding of kinematics (like rotation at talocrural through bimalleolar axis midpoint)

* invasive, can't be done clinically

+ Milwaukee Foot Model (MFM)

* use weightbearing radiographs for precise bone segment measures

* use weightbearing trials + motion capture to record bone axis system measures.

* hard to use, but excellent standard

+ all models agree on sagittal hindfoot flexion, extension, forefoot loading and extension and toe off shifts in coronal/transverse plane

Future Research

- Biplane Fluoroscopy

+ current observability based metrics lead to 2.7-14.9 mm errors

+ use 2 x-ray sources to combine internal bony tracking with landmarks to create new kinematic models

+ continuous exposure to radiation is problematic

* try weightbearing cone beam CT scans + MRI

* still no consensus in local coordinate axes in neutral, ongoing

- Modeling

+ Kinematics advancements studied from multisegment models

+ joint kinetics limited: need joint centers, stiffness inertial properties, etc.

+ force plates provide GRF, too big don't isolate foot?.

+ Early work Scott & Winter: separate talocrural & subtalar

* monocentric DOF joints, 7 nonlinear spring + damper in parallel for plantar fascia

* collected data from different parts of foot GRF in walk cycles (high variability)

+ √ Pedobarography plantar pressure study to isolate GRF vectors across foot aligned with walk cycle.

* assumption of proportionality used to distribute mediolateral + anteroposterior shearing forces in question

+ Biomechanical modeling (SIMM, OPENSIM, ANYBODY) add MTU's and reasons about faults from bottom up