The Neglected Midfoot: New Research Guiding Clinical Exam and Intervention

American Physical Therapy Association Combined Sections Meeting
February 17-20, 2016 Anaheim, CA  Orthopaedic Section  Foot and Ankle Special Interest Group

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The authors have no affiliations with any organization/ entity with a financial or non-financial interest in the material presented
Course Learning Objectives:

1. Review current evidence on normal midfoot kinematics and kinetics that occur during daily activities
2. Recognize the signs of failure of key muscles and/or ligaments that are needed to support the midfoot
3. Identify the key predictors of a disruption in medial column alignment and foot function
4. Identify the different potential effects of external supports on changing midfoot mechanics
5. Recognize limitations of weight-bearing clinical tests when midfoot function is impaired
How is midfoot function studied?
In-vivo Surface Markers
Some concern with directly tracking all of the midfoot bones (Nester et al., 2007b)

Three (or more) segment modeling
  Tibia
  Rearfoot (calcaneus/talus)
  Forefoot (metatarsals)

Multi-segment Biomechanics
  Rearfoot to Tibia Motion and Power

Multi-segment Biomechanics
  Forefoot to Rearfoot Motion and Power
  Allows for inference of midfoot biomechanics

We Will Review…..
  Kinematics during walking
    Forefoot with respect to Rearfoot (ROM°)
  Kinetics during walking and stair ascent
    Midfoot peak power

Study Design & Sample
  Observational Cohort Study
Kinematic and Kinetic Foot Model

Kinematic Model
- 5 Segments: Tibia, calcaneus, metatarsals (1st, 3rd and 5th)
- Angular displacement (ROM)
  - Forefoot with respect to Rearfoot

Kinetic Model
- 3 Segments: Forefoot, Rearfoot, Tibia
- Midfoot Power
  - Rate of torque production

Results:
- Sagittal Plane Kinematics (DF / PF ROM°)
- Transverse Plane Kinematics (ADD / ABD ROM°)
- Midfoot Power Across Activity

Review and Summary
- Muscle performance at the midfoot contributes power for push off
- Increases with increases in demand of activity

For normal midfoot function we need....
- Extensibility and strength of non-contractile tissues (Jennings et al., 2008; Carvaggi et al., 2010)
  - Joint capsules, ligaments, tendons
- Mobility of joint surfaces (Blackwood et al., 2005; Nester et al., 2007a; Okita et al., 2014)
  - Tarsal and tarsometatarsal joints
- Muscle performance (Nikki et al., 2001; Kelly et al., 2014; Kelly et al., 2015)
  - Intrinsic and extrinsic muscles

What happens when mechanisms behind midfoot function are compromised?
What can we do about it?

References


How Diabetes Mellitus affects multi-segment foot motion and midfoot power

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Diabetes Mellitus
Poor Blood Glucose Control
Peripheral Neuropathy
Reduced or Variable Activity
Elevated Plantar Pressure

Peripheral Neuropathy and Foot Biomechanics
Peripheral neuropathy
Decreases tissue extensibility → Decreased functional ROM
Atrophied and fatty muscles → Decreased muscle performance
…Deformity

Purpose: In people with Diabetes and Peripheral Neuropathy….
Assess individual metatarsal and forefoot ROM during terminal stance
Assess ankle and midfoot muscle performance
Power (Rate of torque production)
Relate midfoot power to plantar pressure

Study Design & Sample
Case (DMPN) – Control (MC)
DMPN group without history of ulceration
Kinematic and Kinetic Foot Model

Kinematic Model
5 Segments: Tibia, calcaneus, metatarsals (1st, 3rd and 5th)
Angular displacement and velocity
   Forefoot and metatarsals

Kinetic Model
3 Segments: Forefoot, Rearfoot, Tibia
Power and Total Power: Rearfoot and Midfoot

Kinetic Measurements
Power
   Negative = power absorption    eccentric muscle activity
   Positive = power generation    concentric muscle activity

Pressure Measurements
   Forefoot mask (55-80%)
   Pressure Time Integral
      Peak pressure across time

Results –

Sagittal Plane Kinematics  (Total DF / PF ROM°)

Transverse Plane Kinematics  (Total Abd / Add ROM°)

Rearfoot Power

Midfoot Power

Negative Total Power Ratio

Pressure and Power
Discussion

People with DMPN without deformity or ulceration history

Limited ROM at multiple metatarsals
   Likely related to tissue extensibility and muscle control

Abnormal power profile at both the RF and MF
   Likely related to muscle contractility and activation

Abnormal power profile at both the RF and MF

Decreased + power   Impaired concentric contraction
Excessive – power    Poor eccentric control
Increased – TP Ratio  Increased loading on MF passive structures
   ....Deformity?
Increased forefoot pressure
   ....Tissue Breakdown?

Future Research

DM vs. DMPN vs. DMPN + ulcer history

Evaluate:
   Decline of kinetic function
   MF negative total power

Determine the appropriate time point for clinical intervention....
   What structures and mechanisms should we be targeting?
Acknowledgements

Jill Quinn RN, PhD
Din Chen PhD
Jeff Houck PT, PhD
Josh Tome, MS
Judy Baumhauer MD, MPH
Deborah Nawoczenski PT, PhD

University of Rochester Medical Center - Strong Health Network
    Orthopaedic Foot and Ankle Institute
    Highland Family Medicine and Diabetes Health Source
    Rochester Internal Medicine Associates

University of Rochester
    School of Nursing and Department of Orthopaedics

Funding Source
    University of Rochester, School of Nursing Dean’s Fellowship
    University of Rochester, Department of Orthopaedics, Louis A. Goldstein Award
Predictors of Midfoot Deformity in People with Diabetes Mellitus

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Funding Sources
• National Institutes of Health:
  • K12 HD055931: Comprehensive Opportunities for Rehabilitation Research and Training
  • KL2 TR000450 and UL1 TR000448: Postdoctoral Program
• Washington University Program in Physical Therapy, St. Louis, MO USA

Prevalence of Diabetes

Foot Deformity Cascade

Medial Column Deformity in Diabetes
• Thought to be
  • Confined to a Charcot event
  • Driven by bone deterioration
  • Once treated stable over time
• However
  • Medial column deformity progressed over time
  • Indication of progression in uninvolved foot too
Factors that Impact Medial Column Alignment and Function

- Intrinsic Foot Muscle
- Plantar fascia
- Extrinsic foot muscle/tendon

Participant Characteristics

- DMPN (DMPN, n=23)
  - Diabetes mellitus
  - Peripheral neuropathy
    - unable to feel 5.07 Semmes-Weinstein monofilament on at least one plantar location
  - Spectrum of medial column foot alignment

- Controls (n=12)
  - No Diabetes or peripheral neuropathy
  - No medial column foot deformity
  - Age and weight matched

Purpose

- To determine the ability of measures of foot and leg muscle, tendon, fascial integrity and function to predict Medial column alignment and Medial column function...

Methods: Medial Column Function

- Plantarflexion excursion of the forefoot relative to the hindfoot
  - Kinematics of the single-limb heel rise
  - Segments
    - Hindfoot
    - Forefoot
  - 4 sets of 5 reps
  - Averaged 3 with highest plantarflexor torque
Methods: Intrinsic Foot Muscle
• Magnetic Resonance Images
  • Intrinsic foot muscle and fat
    • Total volumes from talonavicular to tarsometatarsal
      (Cheuy 2013a, Cheuy 2013b)
• MR specifics
  • Transverse
  • 0.36 mm x 0.36 mm x 3.5 mm, no inter-slice gap
  • T1 weighted
  • Pulse repetition time=5360 msec
  • Echo Time=38 msec
  • Image Matrix 384 x 384

Methods: Plantar Fascia Function
Change in Meary’s Angle
• Toe flat to toe extended position-60°
  (Hastings 2011, Gelber 2014)

Methods: Extrinsic Foot Muscle/Tendon
• MRI: Tendon volumes
  • Posterior tibialis
  • Flexor digitorum longus
  • Ratio: Posterior Tibialis/Flexor digitorum longus
  • Total: 9 slices proximal to talocrural joint
• MR specifics
  • Transverse
  • 0.36 mm x 0.36 mm x 3.5 mm, no inter-slice gap
  • T1 weighted
  • Pulse repetition time=5050 msec, Echo Time=38 msec
  • Image Matrix 256 x 256

Methods: Extrinsic Foot Muscle/Tendon
• Plantarflexor Torque
  • Biodex
    • 60°/sec
    • Warm up
• 3 trials
  • Average 2 highest trials

Data Analysis:
• Group Differences
  • Chi-square
  • T-test
• Correlations
  • Predictor variables for model
• Multiple Regression
  • Predicting
  • Foot alignment-Meary’s
  • Foot function-Forefoot relative to hindfoot plantarflexion excursion

Results: Demographics
• Participants
  • Around 60 yo, more male than female, and obese class II

Results: Variables to be Predicted
• Meary’s Angle
  • Large range of angles
• Forefoot on hindfoot plantarflexion excursion
  • DMPN group has limited ability to plantarflex the forefoot on the hindfoot

Results: Intrinsic Foot Volumes
• DMPN have decreased muscle volume and increased fat compared to controls

Results: Tendon and Fascial Volumes
• No difference in tendon or plantar fascia volume between those with DMPN and controls

Results: Plantarflexor Torque (Nm)
• DMPN have reduced plantarflexor torque
Alignment Predictors in DMPN
• Meary’s Predictors
  • Ratio Posterior tibialis/Flexor digitorum longus Tendon Volume (18%)
  • Intrinsic muscle volume (16%)
  • Total variance explained=44%

Function Predictors in DMPN
• Forefoot on hindfoot excursion predictors
  • Plantarflexor Peak Torque (24%)
  • Intrinsic Fat Volume (19%)
  • Total variance explained=44%
• Plantar fascia function
  • correlation with function (r=.34)
  • Not a significant predictor

Conclusions
• DMPN
  • Leg and foot muscle/tendon function deterioration
• Muscle and tendon deterioration associated with
  • Deformity
  • Function

Limitations...leading to future research
• Small sample size for a big question
• Cross sectional study for a longitudinal/progressive question
• Incomplete model: bone shape, ligament integrity
• Can neuropathic muscle be strengthened?
References1-22:


Midfoot Arthritis: Impairments to Intervention

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**Background**
- Arthritis: One of the leading causes of disability *(MWWR, 2006)*
- Midfoot Arthritis: High potential for chronic secondary disability

**Incidence and Prevalence**
- Athletic population
- Minor twisting injuries
- Motor vehicle trauma
- Chronic overload – high heels

**Operative Management**
- Surgical management - challenging
- Complications following surgery
  - Non-union, broken screws and wound problems
  - May necessitate further surgery involving revision, arthrodesis, hardware removal

**Non-operative Management**
- Primary aim of Treatment
  - Provide pain relief
- Steel shanked shoes
- Poor compliance
- Custom-molded three-quarter insert (3Q)
  - Most common recommendation
- Patients continue to report pain
  Alternative
**Purpose**
- Assess impairments contributing to symptoms
  - Segmental foot motion
  - Regional loading
- Assess the effect of 4 week intervention using the FL on symptoms
  - Segmental foot motion
  - Regional loading

**Subjects**
- Clinical:
  - Pain on dorsum, localized to TMT region
  - Aggravated by walking
  - Stair descent
- Radiographic:
  - Joint space reduction
  - Osteophytes
  - ‘Dorsal bossing’

**Functional Outcomes**
- Foot Function Index – Revised (FFI-R)
  - Pain
  - Stiffness
  - Disability
  - Activity Limitation
  - Psychosocial Issues

  *(Budiman-Mak, E et al, 2006)*
- Psychometric properties
  - Reliability, Convergent validity, Criterion validity
  - Responsiveness

  *(SooHoo et al. 2006, Budiman-Mak, E et al, 2006)*

**Results:** Foot Function Index – Revised *(Rao et al. J Biomech 2009)*
Kinematics: Data Acquisition
- 5 segment kinematic foot model.
- Sensors placed over respective segments
- Secured with skin tape
- Anatomically based local co-ordinate systems for each segment
- Reference trial: Subtalar Neutral
  *(Tome et al. 2004, Houck et al. 2008)*

Kinematics: Results
New Insights: Group x Activity Interaction
- 1st metatarsal plantarflexion ROM  \( p = 0.02 \)
- Calcaneal eversion ROM \( p < 0.01 \)
- At baseline, patients with MFA show a *stiffening strategy*.
- *Instability*, evident only in high demand activities.

Plantar Loading: Data acquisition
- Data Acquisition
  - Barefoot
  - EMED™
- Data Analysis
  - 6 “masks”
  - Heel, Medial and Lateral Midfoot, Medial and Lateral Forefoot, Great Toe
  - Dependent Variables: Average Pressure - mean of the highest pressures sustained within each mask and expressed in kilopascals (kPa).

Plantar Loading: Results
New Insights: Cluster Analysis – Adequacy Index and Bivariate Scatter plot
- K-means clustering identified two subgroups:
  - *Cluster 1*  
    (higher medial midfoot average pressure \( n=20 \))
  - *Cluster 2*  
    (lower medial midfoot average \( n=10 \))
Conclusions:
• Independently or in combination, these patterns of loading and motion may contribute to articular stress and thus provoke symptoms.

Mechanisms underlying Pain Relief

Results – Baseline to 4 weeks
Significant symptomatic improvement after 4 week intervention with the FL (Rao et al, APMR 2009)

Kinematic results: FL compared to Shoe

In Shoe Plantar Loading Changes
Decreased midfoot loading with FL, compared to 3Q. No difference between FL and shoe. (Rao S. et al., J Orthop Sports Phys Ther 2009)

Mechanisms underlying Symptomatic Relief
• Accompanied by decreased 1st MTP ROM (compared to shoe), decreased medial midfoot loading, (compared to 3Q) (Rao S, et al. Arch Phys Med Rehab, 2010)

Limitations and Caveats
• Larger sample sizes, longer term follow-up and clinical trial design indicated
• Homogenous sample = interesting, in and of itself, but may not be generalizable to men (different BMI range) and activity demands.
Current Interests:

- Cumulative Stress in Individuals with Foot Pain  
  \textit{(Rao et al Arthritis Care and Research (accepted))}
- Pain mechanisms in Individuals with Foot Pain
  - Widespread mechanical hyperalgesia
  - Efficacy of soft tissue mobilization
  - Reduction of hyperalgesia
  - Restoration of plantar load distribution and muscle activation during walking

Acknowledgements

Rheumatology Research Foundation
AOFAS Research Grant
Arthritis Foundation
Chapter Grant and Post-doctoral Fellowship

Deborah A Nawoczenski, PT, PhD
Judith F Baumhauer, MD, MPH
Jeff Houck, PT, PhD
Josh Tome, MS
Howard Hillstrom, PhD
Kenneth Mroczek, MD
Loss of dynamic midfoot support from Tibialis Posterior Tendon Dysfunction: Biomechanical effects and treatment options

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Midfoot Support…
  Tibialis Posterior Tendinopathy
  Role of Tibialis Posterior
  Spring Ligament and Sagittal Plane Collapse

• Correction of flatfoot deformity unloads soft tissue structures (spring ligament)

Flatfoot Deformity Walking

Flatfoot Deformity during Heel rise

Tibialis Posterior Tendinopathy

Clinical Strength Measure

Lower Arch

EMG:

• Self-Adhesive (Ag/AgCl) electrodes were placed on the skin overlying the belly of the PL

• Indwelling fine-wire electrode were placed into the TP muscle under ultrasound guidance

• Stimulation (Grass - square pulse stimulator) with intensities to produce a strong contraction
Purpose

To determine the effect of a longer foot plate design and ankle articulation on foot kinematics and ankle power in subjects with stage II PTTD.

Methods:

Sample

Kinematic Model

Ankle Kinetics

Analysis:

• Repeated Measures ANOVA Model
  • Condition (5 levels)
    • Off-the-shelf
    • Custom standard
    • Custom articulated
    • Custom extended
    • Shoe Only
  • Phase (4 levels)
    • LR, MS, TS, PS
  • Model repeated for each DV (MLA, FF Abd/ Add, HF Ev/Inv, Ankle Power)

Results…

  Frontal Plane Hindfoot Motion

  Ankle Power
Discussion….

Summary Kinematics

- Custom Devices are achieving control of flatfoot deformity with:
  - hindfoot inversion
    - ankle articulation design – may facilitate muscle control
  - forefoot plantarflexion (raising MLA)
  - forefoot adduction (standard design and extended design with extended showing promise of greater control)
- Does correction of flatfoot kinematics relate to improved function?

Summary Kinetics

- Articulated Ankle Design
  - Preserves Push-off power at the end of stance
- Solid Ankle Design
  - Limits ankle power with no greater control of kinematics
Impact of midfoot motion on clinical tests: Single limb heel rise & Lunge test

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Why the midfoot?
• Clinical tests of rearfoot strength (e.g. single limb heel rise) and flexibility (e.g. lunge test)
• Impact of midfoot…
  — How can “rearfoot clinical tests” be used to assess midfoot function?
  — How could the midfoot mask and/or exacerbate clinical findings at the rearfoot?
  — How would midfoot pathology alter your treatment strategy?

Current use of Heel Rise Test
■ Assess plantar flexor strength and endurance
■ Part of diagnostic criteria for establishing stage of posterior tibial tendon dysfunction (PTTD) (Johnson & Strom, 1989; Gluck, Heckman, Parekh, 2010)

Purpose
■ Examine kinematics of a unilateral heel rise between:
  • Stage II PTTD
  • Older Controls
  • Younger Controls
Hypotheses

• People with PTTD compared to controls (young and old) will demonstrate:
  ■ ↓ Heel rise height
  ■ ↓ Ankle plantar flexion
  ■ ↓ 1st Metatarsal plantar flexion
  ■ ↓ Rearfoot inversion

Participants

Laboratory Performance Measures

**Normalized Heel Height**

■ Change in vertical position of calcaneal marker as a % of truncated foot length

**Forefoot**

■ 1st Met PF with relation to the Calcaneus

**Rearfoot**

■ Calcaneal PF with relation to the tibia
■ Calcaneal INV with relation to the tibia

Heel Rise Height

• Significant differences in heel rise height between all groups

Forefoot and Rearfoot ROM

Clinical Implications for Rearfoot

• Single limb heel rise performance (height, forefoot & rearfoot excursions) is affected by age and PTTD
Heel Rise Height

- PTTD = 7.7 ± 1.9 cm
- Old = 10.5 ± 1.6 cm
- Young = 12.0 ± 1.6 cm

Clinical Implications for Midfoot

- Successful performance of the single limb heel rise depends on forefoot and rearfoot excursion
- Restore medial column and rearfoot plantar flexion during functional tasks, e.g. walking and stair climbing
- Patients with PTTD have the potential to raise the medial longitudinal arch under lower load
  - 50% achieved 1st metatarsal PF during bilateral heel rise (Houck, Neville, Tome, Flemister, 2009)
  - 30% achieved 1st metatarsal PF during unilateral heel rise

Lunge test in patients with insertional achilles tendinopathy

Current use of the Lunge test

- Limited ankle dorsiflexion commonly targeted in rehabilitation

Advantages of the lunge test:
  - Weight-bearing test indicative of function
  - Time efficient
  - Minimal equipment
  - Reliable (Bennell et al, 1998; Chisholm et al, 2012; Jones, 2005; Munteanu et al, 2009)
• Limitations of the lunge test:
  — Assumes foot is a rigid structure
    • Calcaneal plantar flexion (Chizewski & Chiu, 2012)
    • Lowering of medial longitudinal arch (Jung et al, 2009)
  — May be less valid for persons with foot pathology

• Insertional achilles tendinopathy (IAT)
  — 5% of general population has had achilles tendinopathy (Kujala, Sarna, & Kaprio, 2005)
  — 1/3 cases at insertion (Karjalainen et al, 1999)

• Lunge used for
  — Assessment of DF (lunge test)
  — Intervention (weight-bearing calf stretch)

• Unknown
  — Contributions of forefoot vs rearfoot
  — Effect of rearfoot pathology

Purposes
• Compare single-segment (representing a clinical lunge test measure) versus multi-segment contributions to lunge test dorsiflexion
• Determine if differences are present in patients with chronic insertional achilles tendinopathy
Discussion

Lunge test represents:
- Rearfoot DF (Single-segment model ~5°>than calcaneal DF)
- Rearfoot eversion \( \rightarrow \) Consider medial rearfoot posting
- 1st metatarsal DF

IAT group had limited DF compared to controls
- Impairment detected by single-segment and multi-segment models
- Midfoot motion strongly correlated with single-segment DF in IAT

For examination and interventions support arch/medial side of foot

Why the midfoot?
- Midfoot function is needed for rearfoot function
  - Weakness with single limb heel rise may be exaggerated
  - Limited ankle dorsiflexion with lunge test may be masked
- Single limb heel rise and lunge position can load (strengthen or stretch) the plantar flexors
- But may also be overload the midfoot and passive support structures
Acknowledgements

• University of Rochester Medical Center
  — Jeff Houck, PT, PhD
  — Debbie Nawoczenski, PT, PhD
  — A. Samuel Flemister, MD
  — Sproull Fellowship

• Faculty and students at Ithaca College
  — Josh Tome, MS
  — Annmarie Forenza, DPT
  — Elizabeth Previte, DPT
  — Cody Hillin, MS, MD
  — Amy Smith, PT
  — Caitlin Pautz, PT

• Funding from Foundation for Physical Therapy
References


Clinical Implications

Examination

Deformity assessment:
• Clinical measures of alignment
  • Navicular height
  • medial longitudinal arch angle
    …well correlated with radiographic measures

Foot and calf muscle function
• Single limb heel rise

Ankle and midfoot range of motion
• Lunge test

Interventions for active structures

Intrinsic muscles

Extrinsic muscles

Interventions for passive structures

Orthotics

Bracing

Panel discussion

Challenges/ Opportunities