A new look at the dynamic measurement of foot arch stiffness during gait

Zachary Katzman[1], **Robert Yoho**[1], **& Vassilios Vardaxis**[2,3]
[1]College of Podiatric Medicine and Surgery, [2]Department of Physical Therapy, & [3]Human Performance Laboratory
Des Moines University, West Des Moines, IA

DES MOINES UNIVERSITY
MEDICINE & HEALTH SCIENCES

Introduction

- Foot arch stiffness has been studied in relation to overuse injuries[10], athletic performance[17], exercise-associated incontinence[14], control of balance and postural sway[15], and child development[13].
- It is possible to increase arch stiffness through exercises like jump-roping[7] and to either increase or decrease its stiffness surgically via plantar fasciotomy[16] or the modified Kidner procedure[12], respectively.
- Several static measures of arch stiffness have been proposed that rely on either arch height[18] or plantar contact area[4], however these static measures are not fully representative of dynamic arch behavior[3].
- Dynamic arch stiffness can be measured using plantar contact area, but the use of a surrogate variable in this method creates uncertainty about how well it characterizes arch stiffness[8].
- Changes in arch height and vertical ground reaction force (vGRF) from touch-down to mid-stance have also been used to quantify dynamic arch stiffness[9], yet the peak arch deformation and the peak vGRF both occur well after mid-stance[1], during the third rocker **(Figure 1)** and just before the windlass mechanism is engaged.
- We argue that the point of maximal arch deformation is a more clinically relevant timepoint, which consistently occurs during the third rocker across different speeds, as opposed to mid-stance, which may occur during the second or third rocker **(Figure 1)**.
- Additionally, to match how stiffness is measured in the joints of the lower extremity[6], we propose that the medial longitudinal arch angle (MLAA), rather than arch height, be incorporated into the measurement of stiffness in a metric that we are defining as medial longitudinal arch stiffness (MLAS).
- There is currently only indirect evidence that higher walking speed is associated with increased arch stiffness[2], so **the purposes of this study were to determine: (1) the test-retest reliability of MLAS and (2) the effect of walking speed on MLAS.**

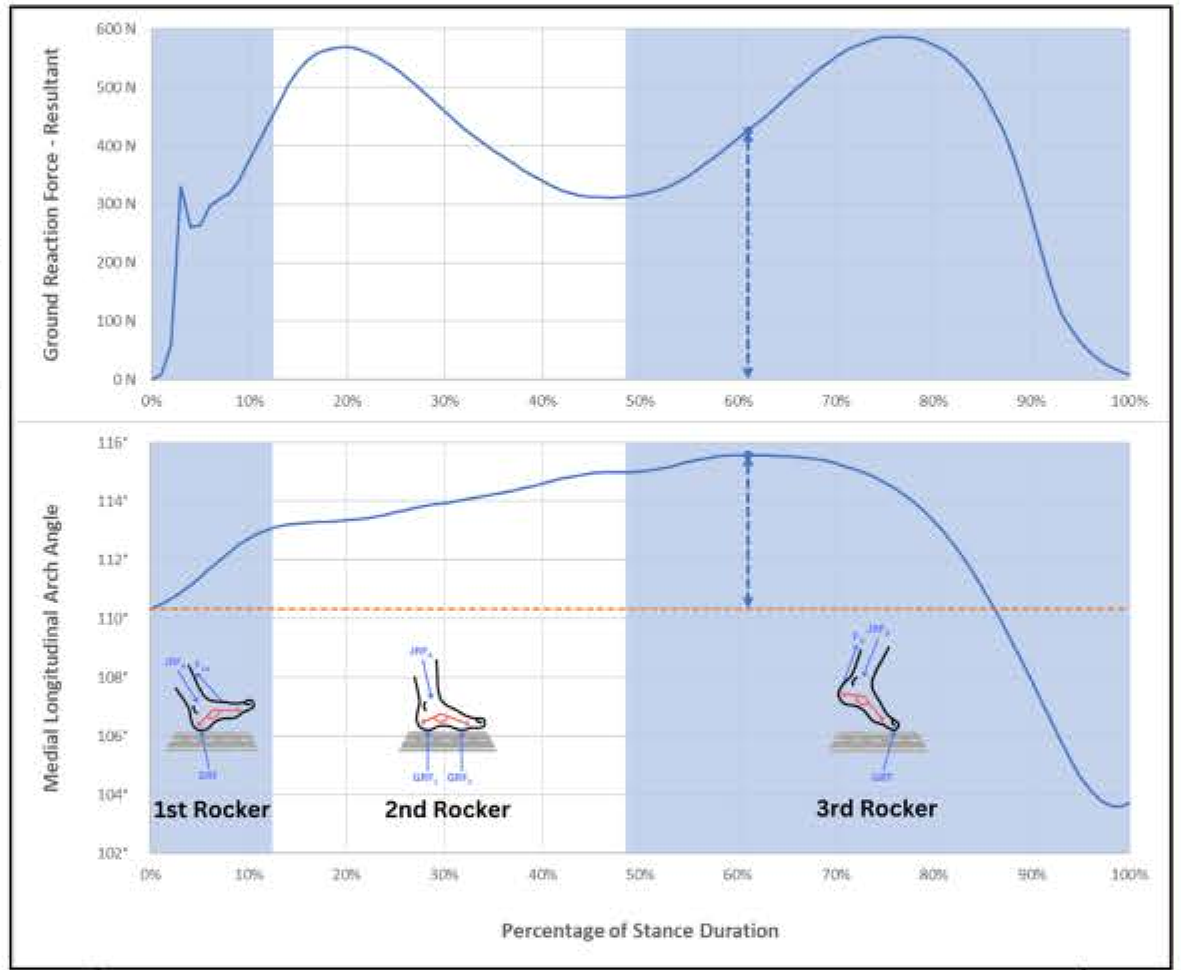

Figure 1. Example stance illustrating the rGRF (*top*) and ΔMLAA (*bottom*) values that were used in the calculation of MLAS. Free body diagrams of the three rocker phases of gait with their approximate durations highlighted and the MLAA shown in red. Ankle joint reaction force (JRF_A), ground reaction force (GRF / GRF_1 / GRF_2), and force of the tibialis anterior or gastrocnemius muscles (F_{TA} / F_G).

Results

- On average and at a typical walking speed:
  - tMLAAmax was 71.0 ±8.8% of the stance phase, with a 95% confidence interval (CI) of [68.7, 73.4].
  - MLAS was 8.93 ±4.47 deg/kN, with a 95% CI of [7.72, 10.13].
- For test-retest reliability, the Pearson *r* was:
  - 0.792 (*p*=.019) for tMLAAmax **(Figure 3)**.
  - 0.768 (*p*=.026) for MLAS **(Figure 3)**.
- One-way ANOVA with faster walking speed showed:
  - Decreased tMLAAmax (*F*=1.915, *p*=.182).
  - Decreased MLAS (*F*=10.686, *p*=.004) **(Figure 4)**.

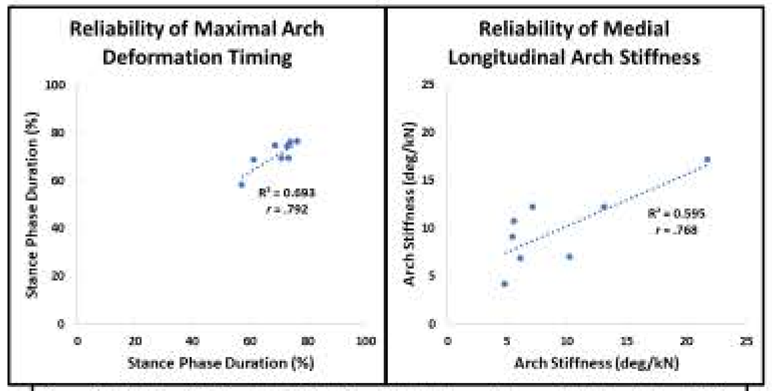

Figure 3. tMLAAmax (*left*) and MLAS (*right*) were both shown to have high test-retest reliability.

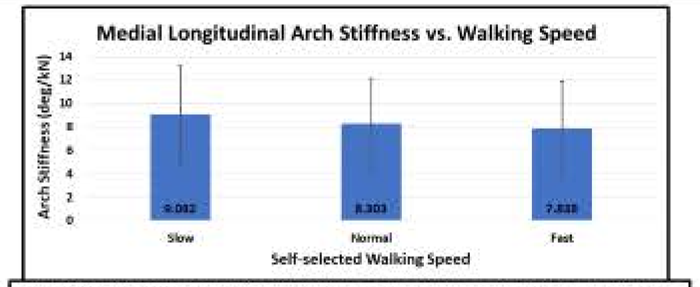

Figure 4. MLAS decreased significantly as walking speed increased, indicating a stiffer arch.

Discussion

- Measurements of both tMLAAmax and MLAS were found to be highly reliable.
- tMLAAmax occurred well after 50% of stance, indicating that previous arch stiffness metrics measured at mid-stance are unlikely to represent the maximal deformation of the arch.
- With faster walking speed, tMLAAmax occurred earlier, although this finding was not significant.
- Arch stiffness (inversely related to MLAS value) increased with faster walking speed, corroborating evidence in the literature showing that with increasing speed, there is less MLAA deformation and greater ground reaction force[2].
- While the foot arch is comprised of both active and passive elements[11], we showed here that the body can dynamically adapt to a greater propulsive need by increasing medial longitudinal arch stiffness.

Conclusion

- We introduced a dynamic metric of foot arch stiffness and showed that it:
  - Represented a different and more relevant timepoint during stance than previous methods.
  - Produced reliable results across separate days.
  - Confirmed existing evidence regarding how arch stiffness responds to changes in walking speed.

Methods

- Subjects (*n*=56) completed 3-5 walking trials each at a self-selected typical speed on a walkway equipped with force plates and a 10-camera motion-capture system.
- A subset of the subject pool (*n*=21) also completed walking trials at self-selected slow and fast speeds, and eight (*8*) of these subjects returned at a later date for an identical retest.
- Reflective markers were placed on the foot, with the calcaneal, navicular, and first metatarsal head markers subsequently used for the MLAA calculation **(Figure 2)**.
- Using the method described by Eichelberger et al.[5], a dynamic sagittal plane was defined through the midline of the foot, and the calcaneal, navicular, and first metatarsal head markers were then projected onto this plane to determine the MLAA **(Figure 2)**.
- The percent of stance at which the MLAA was maximally deformed was defined as tMLAAmax.
- The change in MLAA and resultant ground reaction force (rGRF) at tMLAAmax were used to calculate medial longitudinal arch stiffness:
  - **MLAS = ΔMLAA / rGRF.**
- Averages, standard deviations, and 95% confidence intervals were calculated for tMLAAmax and MLAS.
- Test-retest reliability was determined for tMLAAmax and MLAS using a Pearson correlation.
- A one-way ANOVA was run to evaluate the effects of walking speed on tMLAAmax and MLAS.

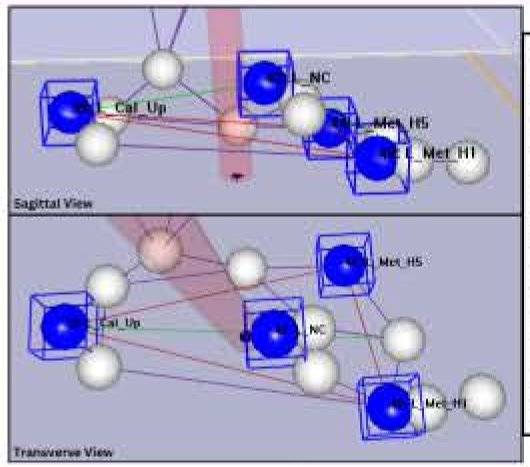

Figure 2. Positions of the reflective markers on the foot, with both pertinent (*blue*) and additional (*white*) markers shown. Dynamic sagittal midline plane (*green*) used in the calculation of MLAA. Calcaneus (*L_Cal_Up*), navicular (*L_NC*), fifth metatarsal head (*L_Met_H5*), and first metatarsal head (*L_Met_H1*).

Acknowledgments

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References

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