Section: Original Research

Article Title: An Investigation of Structure, Flexibility and Function Variables that Discriminate Asymptomatic Foot Types

Authors: Sarah P. Shultz[1], Jinsup Song[2], Andrew P. Kraszewski[3], Jocelyn F. Hafer[3,4], Smita Rao[3,5], Sherry Backus[3], Rajshree Mootanah[3,6], and Howard J. Hillstrom[3]

Affiliations: [1]School of Sport and Exercise, Massey University, Wellington, New Zealand. [2]Gait Study Center, Temple University School of Podiatric Medicine, Philadelphia, PA. [3]Leon Root M.D. Motion Analysis Laboratory, Hospital for Special Surgery, New York, NY. [4]Department of Kinesiology, University of Massachusetts Amherst, Amherst, MA. [5]Department of Physical Therapy, New York University, New York, NY. [6]Medical Engineering Research Group, Faculty of Science and Technology, Anglia Ruskin University, Chelmsford, Essex, UK.

Journal: *Journal of Applied Biomechanics*

Acceptance Date: November 15, 2016

DOI: http://dx.doi.org/10.1123/jab.2016-0001

“An Investigation of Structure, Flexibility and Function Variables that Discriminate Asymptomatic Foot Types”
by Shultz SP et al.
Journal of Applied Biomechanics

An investigation of structure, flexibility and function variables that discriminate asymptomatic foot types

Sarah P. Shultz[1], Jinsup Song[2], Andrew P. Kraszewski[3], Jocelyn F. Hafer[3,4], Smita Rao[3,5], Sherry Backus[3], Rajshree Mootanah[3,6], Howard J. Hillstrom[3]

[1]School of Sport and Exercise, Massey University, Wellington, New Zealand

[2]Gait Study Center, Temple University School of Podiatric Medicine, Philadelphia, PA USA

[3]Leon Root M.D. Motion Analysis Laboratory, Hospital for Special Surgery, New York, NY USA

[4]Department of Kinesiology, University of Massachusetts Amherst, Amherst, MA USA

[5]Department of Physical Therapy, New York University, New York, NY USA

[6]Medical Engineering Research Group, Faculty of Science and Technology, Anglia Ruskin University, Chelmsford, Essex, UK

Funding: This study was supported by the NICHD-NCMRR (1R03HD053135-01)

Conflict of Interest Disclosure: The authors declare no conflict of interest.

Address for Correspondence

Sarah Shultz
School of Sport and Exercise
Massey University
63 Wallace Street, Mt Cook, Wellington 6041
New Zealand
Telephone: +64 4 979 3496
Fax: +64 4 801 4994
E-mail: s.p.shultz@massey.ac.nz

Running Title: Determinants of Foot Type

Abstract

It has been suggested that foot type consider not only foot structure (high, normal, low arch), but also function (over-pronation, normal, over-supination) and flexibility (reduced, normal, excessive). Therefore, this study used canonical regression analyses to assess which variables of foot structure, function, and flexibility can accurately discriminate between clinical foot type classifications. The feet of 61 asymptomatic, healthy adults (18-77 years) were classified as cavus (N=24), rectus (N=54), or planus (N=44) using standard clinical measures. Custom jigs assessed foot structure and flexibility. Foot function was assessed using an emed-x plantar pressure measuring device. Canonical regression analyses were applied separately to extract essential structure, flexibility, and function variables. A third canonical regression analysis was performed on the extracted variables to identify a combined model. The initial combined model included 30 extracted variables; however five terminal variables (malleolar valgus index, arch height index while sitting, first metatarsophalangeal joint laxity while standing, pressure-time integral and maximum contact area of medial arch) were able to correctly predict 80.7% of foot types. These remaining variables focused on specific foot characteristics (hindfoot alignment, arch height, midfoot mechanics, Windlass mechanism) that could be essential to discriminating foot type.

Key Words: clinical biomechanics, kinematics, musculoskeletal

Word Count: 3232

Introduction

Healthy feet are important for performing occupational tasks, physical activity and recreation. Although the literature can be conflicting,[1-3] studies[4-6] have shown that deviation from the rectus foot type can increase the risk of lower extremity injuries, specifically those associated with overuse. Planus foot types are often associated with a lower arch structure and have been linked to increased frontal plane motion and subsequently different plantar pressures across the forefoot[7] and midfoot.[8,9] Additionally, a lower arched foot has been associated with increased risk for hallux rigidus, or osteoarthritis of the first metatarsophalangeal joint. Conversely, cavus foot types often present with changes in both structure (i.e. higher arch) and function (e.g. diminished contact area and simultaneous increases in force-time[10] and pressure-time[11] integrals), demonstrating reduced shock attenuation. In order to fully understand the role of foot type in lower extremity injury and pathology, a more robust model is needed that not only includes variables of structure, flexibility and function, but also accounts for relationships between the three factors.

Previous research has begun to explore relationships between foot structure and function, with specific emphasis on the impact of arch height on indicators of pronation and supination.[12-14] Radiographic foot structure has been associated with plantar pressures under the midfoot and first metatarsal head.[14] Specifically, feet with decreased arch height have greater prevalence of increased 2nd submetatarsal peak pressures, higher malleolar valgus index values, and lower center of pressure excursion index.[7] Because malleolar valgus index measures static hindfoot alignment, a higher value would indicate a more pronated foot. Similarly, a lower center of pressure excursion index would indicate diminished concavity and thus, overpronation.[15] Combined with an increased peak pressure under the 2nd metatarsal head, it would seem that the planus foot type presents with low arched structure and over-pronated function. Furthermore, variables of foot function (e.g. lateral forefoot pressure, center of pressure excursion) have been used to predict foot structure.[10] This is manifested in the clinical population, as diabetic patients have reported greater prevalence of ulcers underneath the first and second metatarsal heads with a planus foot type and ulcers beneath the fourth and fifth metatarsal heads with a cavus foot type.[16] It is believed that these clinical associations exist because of the changes in pressure distribution under flatter or higher arched feet.

In addition to structure and function, recent studies have suggested that flexibility also plays an important role in the biomechanical behaviour of the foot.[7,17,18] In a study of military trainees at West Point, women had significantly higher arch height flexibility than men, which may be linked to their higher incidence of injuries.[17] Similarly, reduced flexibility at the 1st metatarsophalangeal joint, as well as increased malleolar valgus index, were associated with higher hallucial loading.[19] Clinically, patients with hallux limitus and rigidus have reduced flexibility at the first metatarsophalangeal joint; the established associations between flexibility and function support this reduction as a cause, rather than a symptom, of either foot pathology. Although these relationships between structure, flexibility, and function have been supported in basic science, clinical and epidemiological research, their implications on discriminating foot type have received less focus.

Several variables of foot structure, flexibility, and function have independently shown significant differences between planus, rectus, and cavus foot types; however, foot type is often clinically classified using only structural variables.[20] For example, manual goniometers are often used to make clinical assessments, but these instruments have poor inter-rater reliability and joint angle errors can be as much as 5 degrees during examination.[21] Radiological parameters are more reliable at assessing foot structure, but are only able to explain 50% of the variance in a model of foot function.[13] While foot structure is important, the evidence to date suggests that structure, function, and flexibility are all contributing factors to discriminating foot type, as well as increasing risk of injury and pathology. Previous research has focused on establishing relationships between foot structure and function,[7,12] without identifying which variables of structure, flexibility, and function are necessary for describing foot type. Therefore, the purpose of this study is to use canonical regression analyses to assess which variables of foot structure, flexibility, and function can accurately discriminate between the three simplest foot type classifications: cavus, rectus, and planus. It is hypothesized that the most efficient model for classifying foot types will include variables representing foot structure, flexibility, and function. By identifying the contributing factors to foot type, it may be possible to develop interventions that prevent the onset and progression of foot type related pathologies.[22]

Materials and Methods

This study is a retrospective analysis of a previously collected dataset.[7,12,19] To increase reliability, all measurements were conducted by the same investigator. Data analysis was then performed by a different investigator who was blinded to foot type. A brief summary of the subjects and variables are presented below.

Subjects

Sixty-one asymptomatic adults (18-77 years) participated in this study. Subjects were reportedly free of ankle or foot pathology and current symptoms of pain, and were able to walk normally and independently. Exclusion criteria included a history of neuromusculoskeletal disease, uncontrolled cardiac disease, or lower extremity surgery within the past 12 months, as these conditions could affect normal gait. All subjects were initially classified as having a planus, rectus, or cavus foot type; classification was based on clinical measures of resting calcaneal stance position (RCSP; Figure 1a) and forefoot to rearfoot relationship (Figure 1b), as previously described.[7] Specifically, the rectus foot type has a relatively neutral rearfoot alignment (RCSP +/- 2°) and forefoot to rearfoot relationship (0 to 4° of varus). The planus foot type has a valgus rearfoot alignment (RCSP≥4°) or varus forefoot to rearfoot relationship (≥4°), while the cavus foot type has a varus rearfoot alignment (RCSP≥0°) and valgus forefoot to rearfoot relationship (≥1°).[23] The study was approved by the Institutional Review Board. Prior to completing the study, all subjects provided informed consent. Subject characteristics can be found in Table 1.

Assessment of predictor variables

Measurement protocols for foot structure and function have been detailed elsewhere.[7,12,19] Each variable of interest has been briefly described below.

Foot Structure

Malleolar valgus index quantified the degree of pronatory malalignment in the hindfoot while standing in a posture that equally distributed weight across both feet.[7,24] Malleolar valgus index was assessed bilaterally using a scanned image of the foot in resting calcaneal stance position and was reported as a percentage of the deviation from the transmalleolar midpoint relative to the longitudinal foot bisection, normalized to ankle width (Figure 1c).

Arch height (cm) was assessed at one half of the foot length (Figure 1d), in both sitting (non weight-bearing) and standing (weight-bearing) positions (Arch Height Index Measurement System, Jak Tool and Model, LLC, Cranbury, NJ); arch height was not used in the statistical models, but necessary for further calculations. Arch height index (AHI) was calculated as the ratio of arch height to ipsilateral truncated foot length.[7,25] The arch rigidity index ratio ($AHI_{standing}/AHI_{sitting}$) described arch stiffness,[26] while arch height flexibility (mm/kN) [[($AH_{standing} - AH_{sitting}$)/(0.4 x body weight)]] normalized the change in arch height to the change in load between sitting and standing.[27]

Foot Flexibility

Dorsiflexion angle and flexibility of the first metatarsophalangeal joint was measured using a custom jig, with the subject in bilateral sitting and standing postures (Figure 1e).[19] A moment was applied to the sagittal axis of the first metatarsophalangeal joint (measured by a torque transducer), while the resulting angular excursion was assessed using a potentiometer. The slope of the angle versus moment curves (°/N.cm) was determined for early (initial 25% of joint range of motion) and late flexibility (final 25%). Measures of early and late flexibility were assessed during both sitting and standing trials.[19] The angular excursion of the first metatarsophalangeal joint for an applied moment of 50 N-cm was referred to as first metatarsophalangeal joint laxity.

Foot Function

A mid-gait protocol[28] was used to collect plantar loading data, ensuring that subjects walked at a self-selected pace across an emed-x plantar pressure measuring device (novel GmbH, Munich, Germany); 5 trials were collected per foot. The pressure-time and force-time curves were used to calculate parameters in individual plantar regions of a twelve segment mask for each trial;[29] an average value across all five trials was used in the statistical analysis. Foot function variables included peak pressure (N/cm^2), maximum force (N), pressure time integral (N·s/cm^2), force time integral (N·s), and maximum contact area (cm^2). To calculate center of pressure index (%), the foot was initially trisected into anterior, middle, and posterior regions; an additional line was also constructed between the initial and final points of the center of pressure throughout the stance phase. Center of pressure excursion was computed as the deviation of the center of pressure from the constructed line, at the instance where the trisecting line delineated the anterior one third of the foot (Figure 1f). Center of pressure excursion index was calculated as the center of pressure excursion normalized to foot width, and is a measure of the concavity of the center of pressure curve in the metatarsal head region.[24]

Statistical Analysis

Data analysis utilized a total of 76 variables that assess foot structure, function, and flexibility (See Appendix 1). The goal of the statistical analyses was to find a reduced dimensional model in which the remaining structure, function, and flexibility variables were predictive of foot type with at least 70% accuracy. Forefoot to rearfoot relationship and RCSP measurements were not included in the canonical regression analyses, as these variables were used to identify foot type as per clinical practice. Arch height (standing and sitting) was also not included in the regression analyses, as it was used to calculate AHI and hence expected to be highly correlated. Therefore, 72 variables were initially assessed as potential predictors of foot type. All analyses were completed using IBM SPSS v 20 (Armonk, NY).

A canonical regression analysis intends to select a subset of the predictor variable pool whose linear combination best predicts or classifies the outcome variable according to an *a priori* strategic scheme. It does this by iteratively selecting variables from a subset of the original predictor variables. In the event that removal of any variable resulted in a large (>3.0%) decrease in the percentage of foot type correctly predicted, the variable was re-introduced to the analysis. It was then substituted for another variable of similar correlation strength to the standardized canonical discriminant functions. This iterative process of selection was terminated when the removal of any variable resulted in less than 70% of all feet being correctly predicted. Because canonical regression analyses are a type of correlational analysis, 70% accuracy should be the minimum value necessary to identify strong relationships between variables and foot type. Two canonical regression analyses, one applied to structure and flexibility variables and the other applied to function variables, were performed to extract the parameters associated most strongly with foot type. A third canonical regression analysis was performed on the pooled extracted structure, function, and flexibility variables to find a combined model.

Cross-validation is a standard statistical method that is used to validate a model with data from which the model was not built. In this study, the cross-validation of the canonical regression analyses was completed using a jack knife, or "leave one out", procedure. Using this procedure, a more conservative estimate of classifier performance is obtained by leaving one value out of the model, re-computing the canonical regression functions, and testing them with the point left out. Thus, it is expected that this estimate of % correct classification from the jack knife test will be lower than the original estimate.

The initial analysis began with all 11 predictor variables related to foot structure and flexibility. With the exception of first metatarsophalangeal joint laxity and early flexibility while seated, all variables met inclusion criteria for the combined model. The function model initially applied all 61 predictor variables. Variables were removed when the differences between the means of each foot type were less than 10%. Twenty-one function variables met inclusion criteria for the combined model (Figure 2). The 30 extracted variables were pooled and applied to the initial combined structure, flexibility, and function model (Table 2). Analysis was terminated when the removal of each remaining variable resulted in a large (>3.0%) decrease in the percentage of foot type correctly predicted.

Results

The first canonical regression analysis correctly predicted 82.5% of all foot types using 11 foot structure and flexibility variables (Figure 2). Four variables (malleolar valgus index, $AHI_{sitting}$, late first metatarsophalangeal joint flexibility while sitting, first metatarsophalangeal joint laxity while standing) remained in the terminal analysis to correctly predict 70.2% of all foot types (Figure 3a). Cross-validation of the terminal analysis of structure and flexibility variables resulted in 64.9% correct classification.

The second canonical regression analysis correctly predicted 99.2% of foot type using 61 variables related to foot function (Figure 2). By the terminal analysis, only 9 variables of foot function (center of pressure excursion index; peak pressure and force time integral of hallux; maximum force of second toe; peak pressure of sub metatarsal head 2; Maximum force and force time integral of sub metatarsal head 5; pressure time integral and maximum contact area of medial arch) were required to correctly predict 69.7% of foot types (Figure 3b). Cross-validation of the terminal analysis of function variables resulted in 60.7% correct classification.

Initial analysis of the thirty combined structure, flexibility, and function variables yielded 98.2% correctly predicted foot type. Terminal analysis identified five variables (malleolar valgus index, $AHI_{sitting}$, first metatarsophalangeal joint laxity while standing, pressure time integral and maximum contact area of medial arch), which were able to correctly predict 80.7% of foot types (Figure 3c). Cross-validation of the terminal analysis for the combined model resulted in 64.9% correct classification.

Discussion

While three distinct classifications of foot type can be identified based upon foot structure (high, normal, low arch), variations in foot function (over-pronating, normal, over-supinating) and flexibility (reduced, normal, excessive) must also be considered. The aim of this study was to better describe foot type from a comprehensive set of objective and reliable measures. The canonical regression analysis was able to remove measures of foot structure, function, or flexibility that ultimately contributed very little to foot type discrimination.

Additionally, some parameters had more variability, or were co-linear to existing variables, which reduced their importance in the regression model. The final, computationally efficient model included malleolar valgus index, $AHI_{sitting}$, first metatarsophalangeal joint laxity, pressure time integral and maximum contact area of the medial arch. Taken together, structure, flexibility, and function were able to increase prediction accuracy by employing fewer variables than either independent model. These findings support the inclusion of measures of foot structure, flexibility, and function when classifying foot type.

The malleolar valgus index and $AHI_{sitting}$ remained in the final combined model and previous research has indicated some success of both variables at classifying foot type.[7,24] Malleolar valgus index is a measure of hindfoot alignment, which is critical to clinical assessment and treatment of symptomatic foot function. Malleolar valgus index has previously discriminated planus and rectus foot types,[24] but has been unsuccessful in differentiating cavus from rectus feet.[7] AHI, a measure of the medial longitudinal arch height normalized to foot length, also has discriminatory sensitivity to cavus, planus, and rectus foot types.[7] Although AHI in both sitting and standing postures were included in the initial analysis, it is possible that due to collinearity with $AHI_{sitting}$, $AHI_{standing}$ was not required in the terminal model.

Given the role of first metatarsophalangeal joint laxity in informing Windlass mechanism status, it is unsurprising that it remained in the terminal model. Specifically, the available angular motion (dorsiflexion) of the first metatarsophalangeal joint is interrelated to the arch height and length of the plantar fascia. Rao et al[19] found increased first metatarsophalangeal joint laxity (both sitting and standing) in individuals with a low arch, compared to those with a high arch. Similarly, it has been suggested that a planus foot type could limit motion at the first metatarsophalangeal joint.[30] Although the importance of the hallux is evident, the contribution of clinical measures of the hallux and first metatarsophalangeal joint to foot type has previously received less attention, in part due to lack of access to an assessment device that measures both stiffness and range of motion.

The two function variables (pressure time integral and maximum contact area beneath the medial arch) are important to the combined model as they both specify the contact mechanics of the midfoot. Pressure time integral and maximum contact area under the medial arch were the only functional variables that remained in both terminal models. Changes in contact area have been associated with both cavus and planus foot types,[8,9,31] consequently, contact area of the medial arch remained in the terminal model. Additionally, the inclusion of medial arch pressure time integral reinforces the differences in magnitude and duration of midfoot loading between cavus and planus feet. Thus, it would seem that these foot characteristics may represent the essential features required to describe foot type.

There were several potential limitations to this study. Given the comprehensive analysis of structure, flexibility, and function variables, there was no additional dataset that assessed all 72 variables. The lack of an independent sample prevented validation of the model; future research is currently being designed which will address this limitation. Foot type was classified on the Root criteria, which is only one of many approaches to classifying foot type; therefore, the model could be biased to that approach. Additionally, the Root criteria use goniometric assessment; although both measures are reliable and were completed by an experienced rater, there could have been potential classification error. Similar to the general population, there was an unequal distribution of foot types across the sample size. While this imbalance may be more epidemiologically valid, there is a potential for unequal group variance. The study did not account for soft tissue structures or function, which are compromised in a flatter foot.[32] Finally, the study focused on asymptomatic feet. Given that more musculoskeletal pathologies have been associated with non-rectus foot types,[11,33] future work should be done to predict foot type in symptomatic individuals as well.

In summary, foot type was predicted with 80% correct classification when only five structure, flexibility, and function variables were included in the model. Models comprised of only structure and flexibility, or function variables were also capable of good performance, but not with the same computational efficiency (i.e. number of parameters). Malleolar valgus index and $AHI_{sitting}$ proved to be important measures of foot structure, describing hindfoot alignment and arch height. First metatarsophalangeal joint laxity was identified as an important measure of flexibility, impacting the Windlass mechanism. Pressure time integral and maximum contact area of the medial arch demonstrated importance in distinguishing foot function, specifically the mechanics of the midfoot. The five terminal model variables represented all three dimensions: structure, flexibility, and function. Given the high percentage of correct classification, they could be considered determinants of foot type. While the canonical regression analyses were able to identify the essential features needed to discriminate foot type, future research is required to determine the influence of pathology. Meanwhile, this model highlights variables that might be important when designing in vivo investigations of pathological foot conditions and the associated treatment strategies, which could directly benefit the patient and practitioner.

Conflict of Interest Statement

This study was supported by the NICHD-NCMRR (1R03HD053135-01). The authors did not have any financial or personal relationships with the funding agencies that could inappropriately bias the presented research.

References

1. Michelson JD, Durant DM, McFarland E. The injury risk associated with pes planus in athletes. *Foot Ankle Int.* 2002;23(7):629-633.

2. Nakhaee Z, Rahimi A, Abaee M, Rezasoltani A, Kalantari KK. The relationship between the height of the medial longitudinal arch (MLA) and the ankle and knee injuries in professional runners. *Foot.* 2008;18(2):84-90.

3. Esterman A, Pilotto L. Foot shape and its effect on functioning in Royal Australian Air Force recruits. Part 1: Prospective cohort study. *Mil Med.* 2005;170(7):623-628.

4. Carvalho ACA, Hespanhol LC, Costa LOP, Lopes AD. The association between runners' lower limb alignment with running-related injuries: A systematic review. *Br J Sports Med.* 2011;45:339.

5. Tong JW, Kong PW. Association between foot type and lower extremity injuries: systematic literature review with meta-analysis. *J Orthop Sports Phys Ther.* 2013;43(10):700-714.

6. Kaufman KR, Brodine SK, Shaffer RA, Johnson CW, Cullison TR. The effect of foot structure and range of motion on musculoskeletal overuse injuries. *Am J Sports Med.* 1999;27(5):585-593.

7. Hillstrom HJ, Song J, Kraszewski AP, et al. Foot type biomechanics part 1: structure and function of the asymptomatic foot. *Gait Posture.* 2013;37(3):445-451.

8. Queen RM, Mall NA, Nunley JA, Chuckpaiwong B. Differences in plantar loading between flat and normal feet during different athletic tasks. *Gait Posture.* 2009;29(4):582-586.

9. Jonely H, Brismee JM, Sizer PS, Jr., James CR. Relationships between clinical measures of static foot posture and plantar pressure during static standing and walking. *Clin Biomech (Bristol, Avon).* 2011;26(8):873-879.

10. Teyhen DS, Stoltenberg BE, Collinsworth KM, et al. Dynamic plantar pressure parameters associated with static arch height index during gait. *Clin Biomech (Bristol, Avon).* 2009;24(4):391-396.

11. Burns J, Crosbie J, Hunt A, Ouvrier R. The effect of pes cavus on foot pain and plantar pressure. *Clin Biomech (Bristol, Avon).* 2005;20(9):877-882.

12. Mootanah R, Song J, Lenhoff MW, et al. Foot Type Biomechanics Part 2: are structure and anthropometrics related to function? *Gait Posture.* 2013;37(3):452-456.

13. Morag E, Cavanagh PR. Structural and functional predictors of regional peak pressures under the foot during walking. *J Biomech.* 1999;32(4):359-370.

14. Cavanagh PR, Morag E, Boulton AJ, Young MJ, Deffner KT, Pammer SE. The relationship of static foot structure to dynamic foot function. *J Biomech.* 1997;30(3):243-250.

15. Joshi R, Song J, Mootanah R, Rao S, Backus SI, Hillstrom HJ. Structure and function of the foot. In: Altchek DW, DiGiovanni CW, Dines JS, Positano RG, eds. *Foot and Ankle Sports Medicine*. Philadelphia, PA: Lippincott Williams & Wilkins; 2013:11-29.

16. Bevans JS. Biomechanics and plantar ulcers in diabetes. *Foot.* 1992;2:166-172.

17. Theriot CP, Zifchock RA, Neary M, Hillstrom H, Song J, Brechue W. Arch Flexibility: A Proposed Categorization Scheme and the Effects of Short-Term Intense Military Training. Paper presented at: World Congress of Biomechanics2014; Boston.

18. Nilsson MK, Friis R, Michaelsen MS, Jakobsen PA, Nielsen RO. Classification of the height and flexibility of the medial longitudinal arch of the foot. *J Foot Ankle Res.* 2012;5:3.

19. Rao S, Song J, Kraszewski A, et al. The effect of foot structure on 1st metatarsophalangeal joint flexibility and hallucal loading. *Gait Posture.* 2011;34(1):131-137.

20. Razeghi M, Batt ME. Foot type classification: a critical review of current methods. *Gait Posture.* 2002;15(3):282-291.

21. Jarvis HL, Nester CJ, Jones RK, Williams A, Bowden PD. Inter-assessor reliability of practice based biomechanical assessment of the foot and ankle. *J Foot Ankle Res.* 2012;5:14.

22. Budiman-Mak E, Conrad KJ, Roach KE, et al. Can foot orthoses prevent hallux valgus deformity in rheumatoid arthritis? A randomized clinical trial. *J Clin Rheumatol.* 1995;1(6):313-322.

23. Root ML. *Normal and abnormal function of the foot.* 1st ed. Los Angeles: Clinical Biomechanics Corp.; 1977.

24. Song J, Secord D, Hillstrom HJ, Leavitt. Foot type biomechanics: Comparison of planus and rectus foot types. *J Am Podiatr Med Assoc.* 1996;86:16-23.

25. Butler RJ, Hillstrom H, Song J, Richards CJ, Davis IS. Arch Height Index Measurement System: Establishment of reliability and normative values. *J Am Podiatr Med Assoc.* 2008;98:102-106.

26. Shultz SP, Sitler MR, Tierney RT, Hillstrom HJ, Song J. Consequences of pediatric obesity on the foot and ankle complex. *J Am Podiatr Med Assoc.* 2012;102(1):5-12.

27. Zifchock RA, Davis I, Hillstrom H, Song J. The effect of gender, age, and lateral dominance on arch height and arch stiffness. *Foot Ankle Int.* 2006;27(5):367-372.

28. McPoil TG, Cornwall MW, Dupuis L, Cornwell M. Variability of plantar pressure data. A comparison of the two-step and midgait methods. *J Am Podiatr Med Assoc.* 1999;89(10):495-501.

29. Ellis SJ, Stoecklein H, Yu JC, Syrkin G, Hillstrom H, Deland JT. The accuracy of an automasking algorithm in plantar pressure measurements. *HSS J.* 2011;7(1):57-63.

30. Glasoe WM, Nuckley DJ, Ludewig PM. Hallux valgus and the first metatarsal arch segment: a theoretical biomechanical perspective. *Phys Ther.* 2010;90(1):110-120.

31. Fernandez-Seguin LM, Diaz Mancha JA, Sanchez Rodriguez R, Escamilla Martinez E, Gomez Martin B, Ramos Ortega J. Comparison of plantar pressures and contact area between normal and cavus foot. *Gait Posture.* 2014;39(2):789-792.

32. Angin S, Crofts G, Mickle KJ, Nester CJ. Ultrasound evaluation of foot muscles and plantar fascia in pes planus. *Gait Posture.* 2014;40(1):48-52.

33. Menz HB, Dufour AB, Riskowski JL, Hillstrom HJ, Hannan MT. Planus foot posture and pronated foot function are associated with foot pain: The Framingham Foot Study. *Arthritis Care Res (Hoboken).* 2013;65(12):1991-1999.

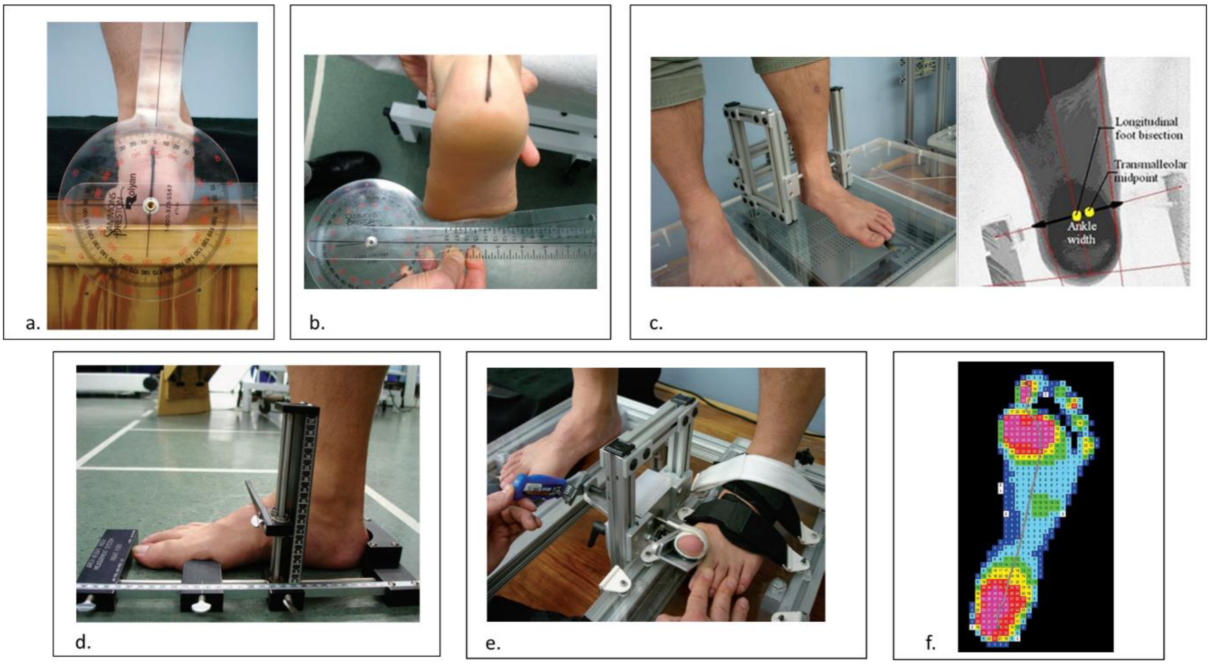

Figure 1. ***Techniques used to assess foot structure, flexibility, and function***. Foot type classification was assessed using a) resting calcaneal stance position, and b) forefoot to rearfoot relationship. Foot structure was assessed by c) malleolar valgus index, and d) arch height parameters. Dorsiflexion angle and flexibility of the first metatarsophalangeal joint was measured using e) a custom jig. Foot function was assessed using f) plantar pressure measuring device. Plantar pressure distribution includes center of pressure excursion (black line). White solid lines trisect the foot into anterior, middle and posterior regions; white dashed line indicates constructed line between first and last pressure points of stance phase. All images courtesy of Joshi et al.[15]

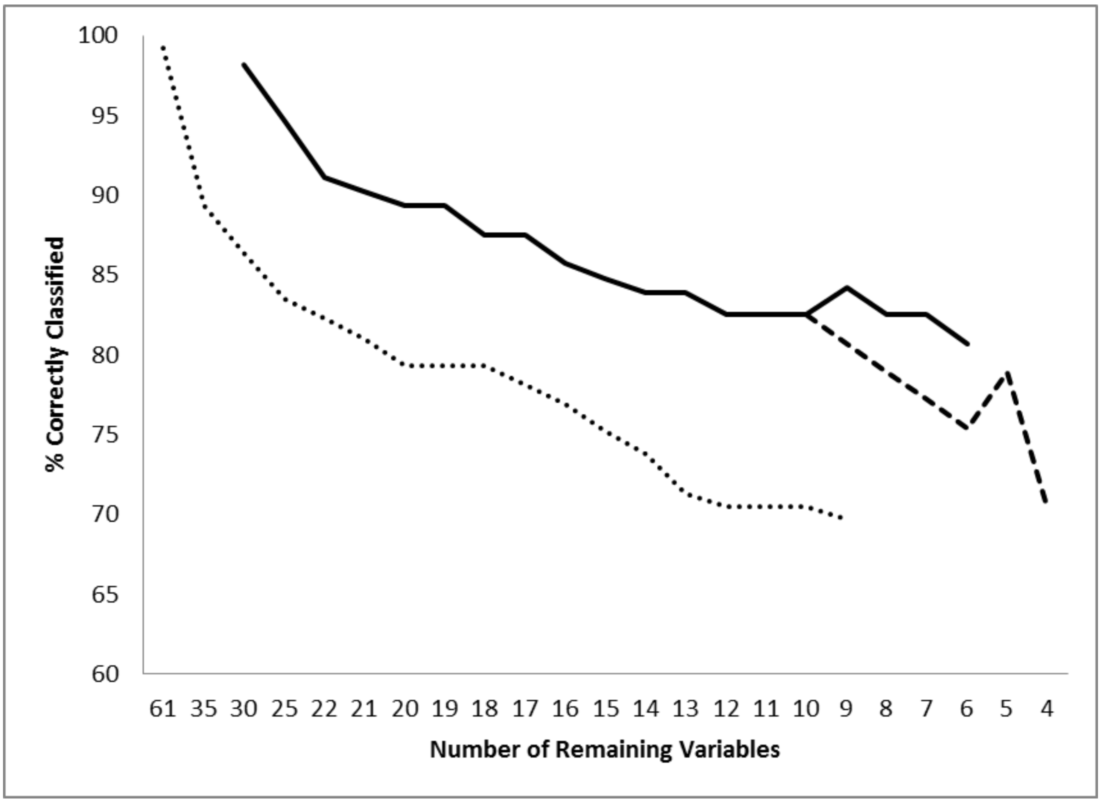

Figure 2. ***The percentage of correctly classified foot type, in relation to the number of remaining variables, for each canonical regression analysis completed.*** The models for structure and flexibility (dashed line), function (dotted line), and combined structure, flexibility and function (solid line) are presented.

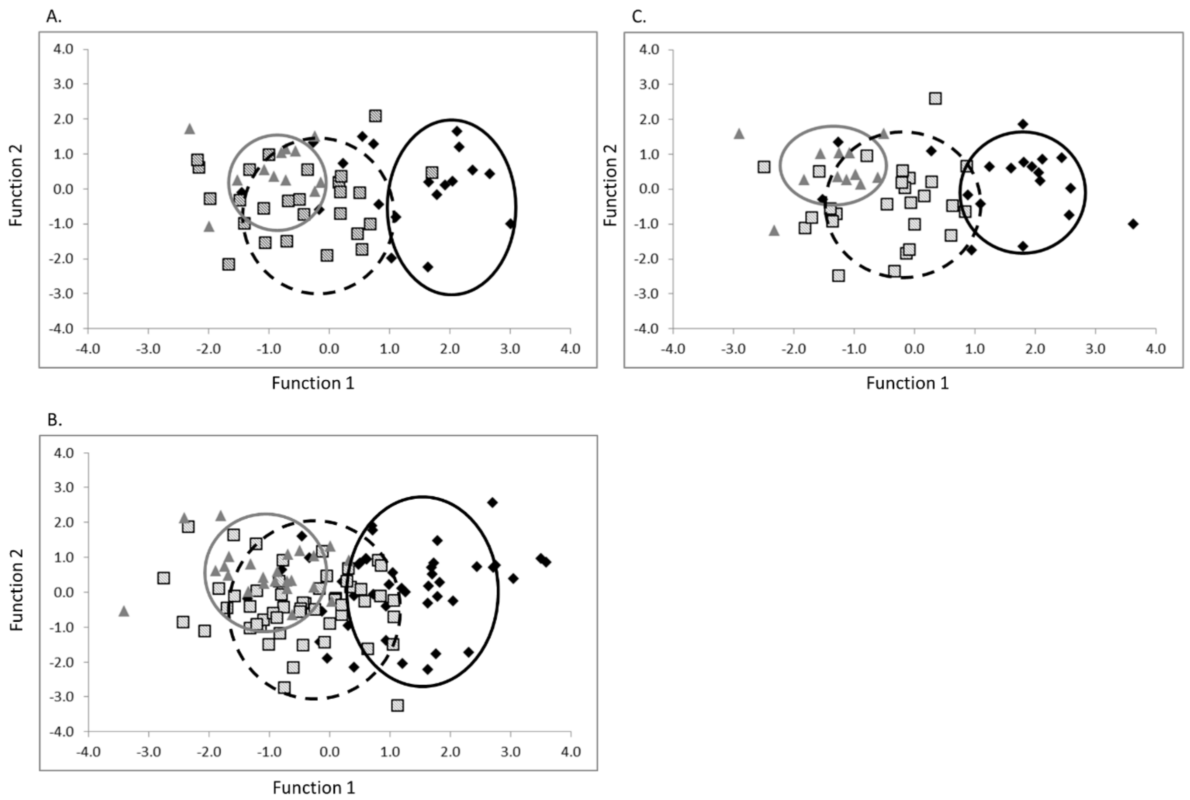

Figure 3. ***Comparison of terminal canonical regression analyses for classifying foot type by (A) structure and flexibility, (B) function, or (C) combined models.*** Grey lined circles indicate common clustering of cavus classifications (grey triangles). Black dashed circles indicate common clustering of rectus classifications (patterned squares). Black lined circles indicate common clustering of planus classification (black diamonds). The x and y axes in the canonical regression analyses are Function 1 and Function 2, which are linear combinations of the outcome variables and are orthogonal to each other.

"An Investigation of Structure, Flexibility and Function Variables that Discriminate Asymptomatic Foot Types"
by Shultz SP et al.
Journal of Applied Biomechanics

Table 1. Subject characteristics for each foot type

	Foot Type		
	Planus (N=22)	Rectus (N=27)	Cavus (N=12)
Gender	10 males, 12 females	8 males, 19 females	6 males, 6 females
Age (years)	35.6 ± 11.0	33.1 ± 9.8	42.8 ± 16.2
Height (m)	1.71 ± 0.11	1.66 ± 0.11	1.74 ± 0.11
Weight (kg)	68.85 ± 14.97	67.54 ± 14.14	73.47 ± 15.80
Body Mass Index (kg/m^2)	23.3 ± 4.3	24.4 ± 4.1	24.0 ± 3.5

Table 2. Thirty extracted variables used in the initial analysis of the combined model

Malleolar Valgus Index	PP-Hallux	PTI-Hallux
$AHI_{SITTING}$	PP-Toe 2	PTI-Sub Metatarsal Head 2
$AHI_{STANDING}$	PP-Sub Metatarsal Head 2	PTI-Sub Metatarsal Head 5
Early Phase Hallucial Flexibility (Standing)	PP-Lateral Heel	PTI-Medial Arch
Late Phase Hallucial Flexibility (Sitting)	PP-Medial Arch	FTI-Hallux
Late Phase Hallucial Flexibility (Standing)	MF-Hallux	FTI-Toe 2
1st Metatarsophalangeal Joint Laxity (Standing)	MF-Toe 2	FTI-Sub Metatarsal Head 5
Arch Height Flexibility	MF-Sub Metatarsal Head 2	FTI-Medial Arch
Arch Rigidity Index Ratio	MF-Sub Metatarsal Head 5	Area-Medial Arch
Center of Pressure Excursion Index	MF-Medial Arch	Area-Lateral Arch

Note. AHI: arch height index; PP: plantar pressure (N/cm^2); MF: Maximal force (N); PTI: pressure-time integral ($N\cdot s/cm^2$); FTI: force-time integral (N·s)

“An Investigation of Structure, Flexibility and Function Variables that Discriminate Asymptomatic Foot Types”
by Shultz SP et al.
Journal of Applied Biomechanics

Appendix 1. A list of the 76 variables used to assess foot structure, function, and flexibility

Foot Structure Variables

1. Resting Calcaneal Stance Position (degrees)**
2. Forefoot-Rearfoot Relationship (degrees)**
3. Malleolar Valgus Index (%)
4. Arch Height (sitting) (cm)**
5. Arch Height (standing) (cm)**
6. Arch Height Index (sitting) (%)
7. Arch Height Index (standing) (%)
8. Arch Rigidity Index
9. Arch Height Flexibility (mm/kN)

Foot Flexibility Variables

10. First metatarsophalangeal joint laxity (Sitting) (degrees)
11. First metatarsophalangeal joint laxity (Standing) (degrees)
12. Early Phase Hallucial Flexibility (Sitting) (degrees/N.cm)
13. Early Phase Hallucial Flexibility (Standing) (degrees/N.cm)
14. Late Phase Hallucial Flexibility (Sitting) (degrees/N.cm)
15. Late Phase Hallucial Flexibility (Standing) (degrees/N.cm)

Foot Function Variables

16. Center of Pressure Excursion Index (%)

17-28. Peak plantar pressure (N/cm^2) under the following regions:

a. Hallux
b. Toe 2
c. Toes 3-5
d. Sub Metatarsal Head 1
e. Sub Metatarsal Head 2
f. Sub Metatarsal Head 3
g. Sub Metatarsal Head 4
h. Sub Metatarsal Head 5
i. Lateral Heel
j. Medial Heel
k. Lateral Arch
l. Medial Arch

29-40. Maximum force (N) under the following regions:

a. Hallux
b. Toe 2
c. Toes 3-5

d. Sub Metatarsal Head 1
e. Sub Metatarsal Head 2
f. Sub Metatarsal Head 3
g. Sub Metatarsal Head 4
h. Sub Metatarsal Head 5
i. Lateral Heel
j. Medial Heel
k. Lateral Arch
l. Medial Arch

41-52. Pressure Time Integral (N·s/cm^2) under the following regions:

a. Hallux
b. Toe 2
c. Toes 3-5
d. Sub Metatarsal Head 1
e. Sub Metatarsal Head 2
f. Sub Metatarsal Head 3
g. Sub Metatarsal Head 4
h. Sub Metatarsal Head 5
i. Lateral Heel
j. Medial Heel
k. Lateral Arch
l. Medial Arch

53-64. Force-Time Integral (N·s) under the following regions:

a. Hallux
b. Toe 2
c. Toes 3-5
d. Sub Metatarsal Head 1
e. Sub Metatarsal Head 2
f. Sub Metatarsal Head 3
g. Sub Metatarsal Head 4
h. Sub Metatarsal Head 5
i. Lateral Heel
j. Medial Heel
k. Lateral Arch
l. Medial Arch

65-76. Contact Area (cm^2) under the following regions:

a. Hallux
b. Toe 2
c. Toes 3-5
d. Sub Metatarsal Head 1

e. Sub Metatarsal Head 2
f. Sub Metatarsal Head 3
g. Sub Metatarsal Head 4
h. Sub Metatarsal Head 5
i. Lateral Heel
j. Medial Heel
k. Lateral Arch
l. Medial Arch

**denotes variables that were not used in the canonical regression analyses