Changes in Male Foot Shape and Size with Weightbearing

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Accurate, consistent measurement of foot-ankle geometry is essential for the design and manufacture of well-fitting, functional, comfortable footwear; for the diagnosis of certain biomechanical disorders; and for consistent longitudinal monitoring and assessment of pedorthic treatment outcomes. We sought to formulate a basic set of measures characterizing the principal geometric dimensions of the foot, to investigate how these measures vary with increasing weightbearing, and to explore the implications of weightbearing changes in pedal geometry for orthopedic footwear design and manufacture. The right feet of 40 healthy men aged 22 to 71 years were scanned using the Department of Veterans Affairs Pedorthics Optical Digitizer in neutral alignment, sequentially bearing 0%, 10%, 25%, 50%, and 100% of the subjects' body weight. With support of the full body weight, the following mean changes in the pedal parameters were observed: heel-to-toe length, 1.5%; ball width, 4.3%; maximum heel width, 4.8%; and instep height, –9.3%. On average, 71% of the changes sustained in the pedal parameters at full weightbearing occurred when, or before, 25% of the body weight was applied. (J Am Podiatr Med Assoc 96(4): 330-343, 2006)

Mechanically, the foot is a complex linkage mechanism comprising 26 osseous links (28 osseous elements if the sesamoids that serve as bearings for the hallux are included) interarticulated at 40 surfaces. Movements at the joints are actuated by one or more of the 30 intrinsic and 6 extrinsic muscles originating or terminating in the foot. The direction and range of motion at the respective joints of the foot are determined by the resultant force in the muscles acting across the joint, the resultant restraining force of the respective subset involved of the 125 ligaments that bind the foot's osseous linkages together, and the osseous boundary constraints of the respective joints.[1-5] Functionally, the foot serves as our "interface" with the world. It adapts to variations in local terrain to provide a stable base of support for the body during stance, and it serves as the actuating mechanism that propels the body forward during gait. In addition, the foot rotates and derotates the lower limb during gait through elevation and depression of the longitudinal arch. This effectively extends the leg, increasing step length and lowering the vertical excursion of the body center of mass, thus reducing the energy expended during gait. In the performance of these tasks,

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the foot effectively and efficiently transmits forces to and from the musculoskeletal system and the ground, minimizing the strength, energy, and power required to stand, walk, and run.

Properly fitting, functional, and comfortable footwear is necessary for maximum mobility and function in healthy people. It is also essential for the successful therapeutic and rehabilitative care of persons with neuromusculoskeletal disorders and systemic pathologies that adversely affect the feet, such as diabetes mellitus, osteoarthritis, multiple sclerosis, Charcot-Marie-Tooth disease, and Hansen's disease.[6-20] For people with such disabilities, well-fitting, functional footwear can be the difference between functional independence and forced reliance on crutches or confinement to a wheelchair. In the case of diabetes mellitus with chronic peripheral neuropathy and vascular disease, appropriate footwear helps prevent pedal ulceration, necrosis, gangrene, and amputation.

Clinical experience has shown that footwear that fits "too tightly" can create stresses and strains in pedal tissues that cause irritation, inflammation, fasciitis, and pain. If this situation is allowed to persist, the resultant nonelastic strain energies transferred to pedal tissues can lead to tissue mechanical failure.[21-23] Conversely, footwear that fits "too loosely" can give rise to intermittent, localized loads that can exceed tissue critical strength and also lead to mechanical failure. These situations are particularly pertinent for women, who have disproportionately high rates of injury. In an American Orthopaedic Foot and Ankle Society survey,[24, 25] 73% of the 356 women surveyed reported having experienced injuries to their feet and ankles from ill-fitting footwear, and in studies[26, 27] of US military personnel, 40% of the female personnel sampled had incurred foot and ankle injuries due to improperly fitting and functioning footwear, compared with approximately 4% of their male counterparts.

Well-fitting, functional, and comfortable footwear is a major determinant of whether people can lead active, comfortable, productive lives. What "proper" fit and function are, however, is specific to the user and the application. In clinical practice, podiatric physicians and pedorthists usually guess what types of footwear and pedorthic devices are needed to achieve prescribed supportive/corrective/assistive/protective functions and what tissue stresses and strains can be safely tolerated without impeding foot-ankle function or increasing risk of injury. Whether a particular orthosis or footwear design effectively and efficiently achieves its prescribed objectives has historically been, and remains, a subjective, trial-and-error assessment made by the podiatric physician or pedorthist. This assessment process is physically and fiscally costly for patients and clinicians.

Determining how and where foot shape and dimensions change under load is a necessary first step in quantifying footwear design and in assessing fit. However, studies of changes in foot shape and size with loading have been limited to date. In a retrospective investigation of how pedal dimensions change with age, Kouchi[28] concluded that changes in foot length and longitudinal arch length with aging are negligible. In a study of 300 subjects, Nanna et al[29] observed no statistically significant differences in the dimensions of healthy subjects' left and right feet. However, they found statistically significant differences in the foot-ankle dimensions of the male and female subjects they tested. Wunderlich and Cavanagh[30] investigated differences in adult foot shape and size as a function of sex and reported significant differences in a variety of dimensional parameters between female and male feet. These studies did not consider variations in foot shape and size with weightbearing, however. Such studies have been considerably more limited.

Cheng et al[31] measured the foot length and width of 2,829 children in weightbearing states using electronic calipers. They reported that foot length and width increased linearly with age, on average from 3 to 12 years of age in girls and from 3 to 15 years of age in boys, after which time lengths plateaued. They measured an average increase for all ages of children of 3.1% in foot length and 4.8% in foot width with full weightbearing. Tsung et al[32] made plaster impression casts of the feet of eight male subjects in the full weightbearing, semiweightbearing (~50% body weight), and nonweightbearing states. Positive plaster models of the subjects' feet were made from the casts. The casts were then scanned with an optical digitizer and imported into a prosthetics-orthotics computer-aided design system, in which a series of prescribed measurements were performed. They reported dimensional changes with full weightbearing of 3.4% in foot length, 6.0% in foot width, 8.7% in heel width, and 20% in arch height and with semiweightbearing of 2.7% in foot length, 2.9% in foot width, 5.9% in heel width, and 15.4% in arch height.[32]

In research to develop accurate, repeatable, and consistent quantitative measures for the assessment of footwear fit, we extensively investigated the changes in foot shape and dimension that occur with the application of loads. The objectives of the present study were 1) to formulate a basic set of measures characterizing the principal geometric dimensions of the foot, 2) to investigate how these measures vary with increasing weightbearing, and 3) to explore the impli-

cations of weightbearing changes in pedal geometry on (orthopedic) footwear design and manufacture.

Methods

Forty healthy men 22 to 71 years of age without any pedal musculoskeletal or biomechanical abnormalities were recruited, and their informed consent was obtained before study participation. Approval of the study protocol was granted by the Subcommittee for Human Studies, Veterans Affairs New York Harbor HealthCare System. The subjects' feet were optically scanned under increasing amounts of weightbearing using the Department of Veterans Affairs Pedorthics Optical Digitizer. The three-dimensional (3-D) Pedorthics Optical Digitizer is a prototype device composed of three laser scan heads (model 3030; Cyberware Laboratory, Monterey, California) mounted on two servo motor–controlled (Galil Motion Control, Rocklin, California), synchronously driven, horizontal translation rails (Automation Systems Technologies, Hauppauge, New York), with an integrated, pedal support platen and strain gauge–instrumented force platform, and a suprastructure handrail for patient upper body support and balance (Fig. 1).[33, 34]

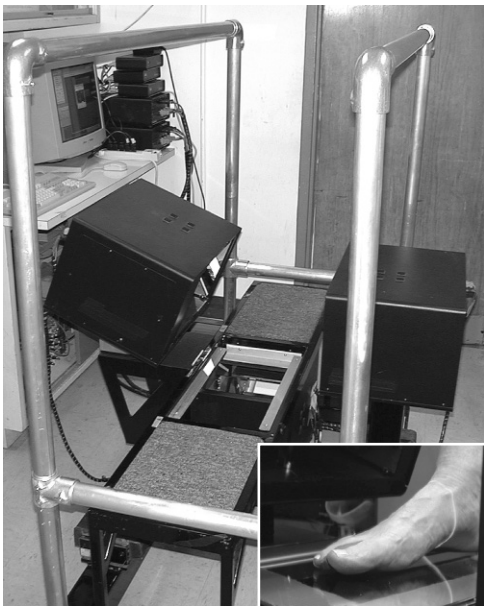


Figure 1. The Department of Veterans Affairs Pedorthics Optical Digitizer measures the foot's spatial geometry and surface topography. As seen in the inset, a planar beam of near-infrared light from lasers in the two dorsal scan heads and the single plantar scan head was projected onto a subject's foot as he stood on a transparent, contoured platen with 0.5-inch heel height while sequentially supporting 0%, 10%, 25%, 50%, and 100% of his body weight on his foot.

The Department of Veterans Affairs Pedorthics Optical Digitizer can capture the 3-D spatial locations of more than 60,000 points over the surface of a foot in 9 sec or less (256 points around each vertical cross-section, which are incrementally spaced 1.0 mm apart along the longitudinal axis of the foot). Differences in the intensity of the laser light specularly reflected from the subjects' skin and *a priori* positioned photoreflective markers enable the relative spatial locations of anatomical landmarks to be detected and preserved. Comprehensive calibration of the digitizer (ie, mapping of the spatial locations of points every 1.0 mm throughout the digitizer's 30 × 30 × 40-cm scannable spatial envelope) provided an accuracy of 0.5 mm or greater along each reference direction. Empirical tests of the optical digitizer combined with the Department of Veterans Affairs pedorthics computer-aided design system in digitizing and measuring fiducial pedal dimensions produced an accuracy of 0.67 mm or better along the longitudinal x-axis of the foot and of 0.23 mm or better along the y- and z-axes, perpendicular to the longitudinal axis.

The optical scans of the subjects' feet were acquired in accordance with the following protocol:

1) The subjects' shoes were doffed, and their feet were elevated and acclimated to room temperature.

2) The projected surface locations of eight fiducial, anatomical landmarks (the medial apex of the first metatarsal head, the lateral apex of the fifth metatarsal head, the apex of the medial malleolus, the apex of the lateral malleolus, the apex of the medial tuberosity of the navicular, the lateral apex of the tuberosity of the base of the fifth metatarsal head, the medial posterior border of the longitudinal arch, and the plantar apex of the second metatarsal head [Fig. 2]) were identified and *a priori* marked with 0.25-inch-diameter photoreflective markers.

3) The subjects were positioned in the digitizer in a standing posture, with the right foot positioned on the transparent, contoured platen with 0.5-inch heel height, mounted on top of the instrumented support platform, with their upper bodies balanced, supporting and off-loading weight from their feet to the digitizer's suprasupport structure as required to attain the specified pedal loading state for the respective scan. The magnitude and center of pressure of the portion of the subject's body weight supported by his right foot were measured by means of the instrumented force platform integrated in the digitizer frame.

4) Before initiation of each scan, the subject's pedal-tibial orientation was set in neutral alignment. The subjects were instructed to apply a specified percentage of their body weight (0%, 10%, 25%, 50%, or 100%) on their right leg and foot, balancing and off-loading

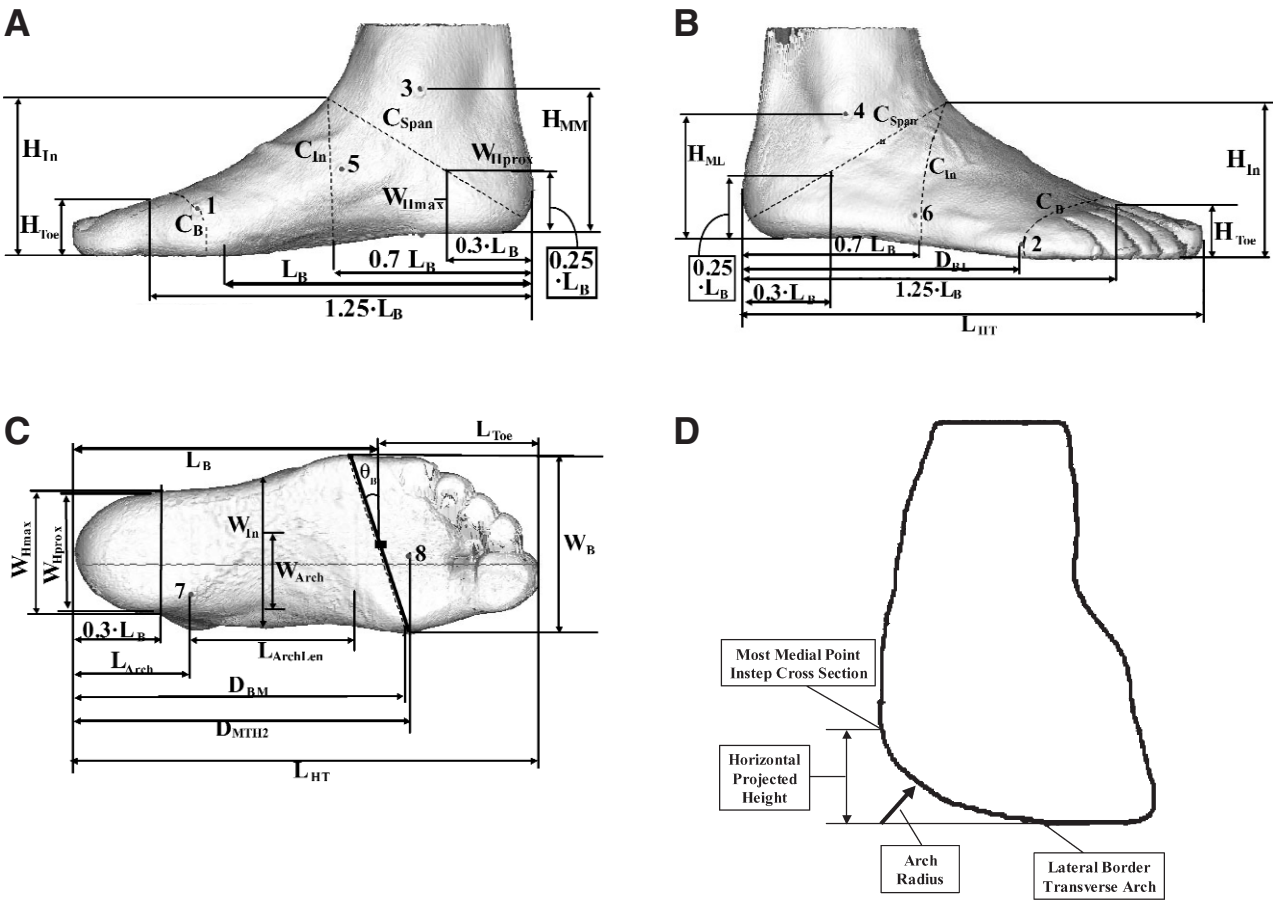


Figure 2. Medial (A), lateral (B), and plantar (C) views in the Department of Veterans Affairs pedorthics computer-aided design system of the shaded solid model and the cross-section (D) from an optical scan of a subject's foot. The locations, orientations, and dimensions of the parameters formulated in the study, and defined in Appendix 1, to characterize the shape and size of the subjects' feet are shown relative to the eight fiducial anatomical landmarks.

weight in excess of the specified amount through their contralateral leg and arms to the digitizer suprastructure. To assist the subjects in achieving and maintaining the specified load and resultant center of pressure during a scan, the force-platform measurements were acquired, processed, and output in real time on a computer located adjacent to the digitizer. Approximately 14 sec were required to complete each scan, 9 sec of which involved actual data acquisition. On completion of each scan, the subjects were told to keep the right foot in position on the platen and to relax, transferring most of their weight from the right leg and foot to the contralateral leg and to their arms resting on the digitizer suprasupport structure. After 3 to 4 min of rest, the next target load level was selected, the subject's right leg and foot were realigned in neutral, and the foot was scanned again, until scans at all of the specified loads were completed. For the unloaded (0% weightbearing) state, it was found that to maintain neutral ankle, subtalar, forefoot, and phalangeal alignment and to avoid "noise" from inadvertent movements, the subject's foot had to be kept in contact with the platen. Thus the load in the 0% state was not truly zero but was between 0% and 1% of the subject's body weight.

At the completion of scanning, the resulting data characterizing the 3-D surface geometry of the subject's feet and ankles at the given loading levels were imported into the Department of Veterans Affairs pedorthics computer-aided design system, where noise was filtered out, the eight fiducial anatomical landmarks were identified and labeled, and the set of specified parameters characterizing foot-ankle geometry were measured.[35]

In derivation of the set of fiducial measures characterizing the 3-D spatial geometry of the foot and ankle, the parameters most commonly used in pedorthic practice to grade shoemakers' lasts and assess

footwear fit were selected, in conjunction with the set of principal anthropometric measurements of the foot and ankle recorded in the surveys of the lower limbs of US military personnel.[36, 37] From this collection, the set of measures clinically found to best characterize foot-ankle geometry and those deemed to be most important for footwear design and assessment of fit were selected. The selected parameters and their definitions are given in Appendix 1. The locations of the parameters and their relationship to foot geometry are shown in the computer-aided design–shaded solid pedal images in Figure 2. The selected parameters are defined in relation to the eight fiducial, anatomical landmarks identified and marked before the scan. In addition to the eight anatomical landmarks, a horizontal reference line was drawn on the plantar surface of the shaded solid model of each subject's foot and was used in the Department of Veterans Affairs pedorthics computer-aided design system to measure the values of the respective fiducial dimensions. The reference baseline was drawn on the plantar surface of the digitized model of the foot from the middle of the heel through the middle of the second metatarsal head (landmark 8 on Fig. 2C). Pedal length parameters were almost always measured along or parallel to the reference baseline. Similarly, pedal width and height parameters were measured perpendicular to the reference baseline (except for ball width).

To control for morphological differences among the subjects and to facilitate comparative analysis of the study results, the measurements of each subject's foot were normalized with respect to heel-to-ball length (L_B). Specifically (except for heel-to-ball length), the measurements of each subject's foot were divided by the subject's heel-to-ball length and then multiplied by the mean value of the heel-to-ball length for the study sample population. A subset of the principal pedal dimensions was also statistically analyzed to determine the degree to which these values corresponded to those of the general, healthy male population in the United States.[36, 37] In addition, sample correlation coefficients were computed between the subjects' principal parameters (ie, ball widths and heel widths) to investigate the interrelationship of these parameters—in other words, to determine whether they were statistically correlated or independent, and thus whether all of the parameters need to be measured.

Results

A set of parameters characterizing the 3-D shape and size of the foot and ankle was derived from the set of measures most commonly used in pedorthics to grade lasts and to assess footwear fit and from the set of measures of the foot and ankle used in anthropometric studies of the lower limbs of US military personnel.[36, 37] The values of these parameters were measured sequentially for the right feet of 40 healthy male subjects 22 to 71 years of age (mean ± SD age, 46 ± 13 years; median age, 47 years), ranging from 1.4 to 1.9 m in height (mean ± SD, 1.75 ± 0.09 m; median, 1.75 m) and 49 to 120 kg in weight (mean ± SD, 82 ± 17 kg; median, 81 kg) as 0%, 10%, 25%, 50%, and 100% of the subjects' body weight was supported by their right foot. The mean values of the pedal parameters measured in the study are given in Table 1 as a function of the percentage of body weight supported by the right foot. The mean values of the pedal parameters with the right foot supporting 25% of the body weight, normalized with respect to the right foot heel-to-ball length, are given in Table 2. The statistical normality of the pedal parameters measured in the study was assessed using the Shapiro-Wilk test.[38] The Shapiro-Wilk W and *P* statistics for the study sample population are given in Table 3 for a subset of the pedal dimensions measured in the study. The pedal dimensions are also plotted as a function of the percentage of body weight supported by the right foot in Figure 3. The distributions of the principal parameters, normalized by ball length, were calculated for each respective load level. The resulting distributions for the case of 25% weightbearing are shown in Figure 4. In the plots, each abscissal column covers a data range equal to 50% of the sample standard deviation for the respective parameter. The sample correlation coefficients among the principal parameters were also calculated to test the validity of the clinical and commercial pedorthic practice of measuring only two or three pedal dimensions and ignoring the rest. The resulting values of the normalized ball width *versus* normalized heel width for the subjects are shown in Figure 5.

Discussion

Foot shape and size vary significantly from person to person. This is reflected in the relative size of the standard deviations of the pedal dimensions measured in the study (Table 2). This is also evident in the histograms of the parameters plotted in Figure 4. As shown, most of the histograms have nine or ten abscissal columns, with the four middle columns constituting approximately 70% of the total number of subjects in the sample population. This reflects an approximate Gaussian distribution. Statistical normality of the pedal parameters is further established by means

Table 1. Normalized Principal Pedal Dimensions Characterizing the Three-dimensional Shape and Size of the Subjects' Feet as a Function of the Percentage of Body Weight Supported by the Foot

	Body Weight Supported by the Foot				
Pedal Parameter	0%	10%	25%	50%	100%
Foot length (mm)	260.16	262.84	263.65	264.56	265.84
Ball length (mm)	178.88	179.93	180.33	180.82	181.67
Medial ball reach (mm)	189.16	190.94	191.41	192.30	193.05
Lateral ball reach (mm)	168.60	168.91	169.26	169.33	170.28
Second metatarsal head reach (mm)	199.60	199.81	199.63	199.83	201.20
Ball width (mm)	100.33	102.66	103.34	104.12	104.66
Ball circumference (mm)	252.27	254.30	254.97	256.26	256.10
Ball angle (°)	–11.88	–12.47	–12.44	–12.81	–12.61
Instep height (mm)	83.48	79.29	77.69	76.71	75.66
Instep width (mm)	86.25	89.16	89.83	90.77	91.08
Instep circumference (mm)	268.20	268.01	267.39	267.95	267.12
Span (mm)	347.01	349.24	350.13	351.55	352.91
Medial malleolus height (mm)	86.75	80.49	79.23	78.39	79.42
Lateral malleolus height (mm)	73.57	68.09	67.13	65.95	64.61
Maximum heel width (mm)	70.05	72.47	73.06	73.43	73.38
Proximal heel width (mm)	62.06	61.25	60.98	60.71	60.60
Arch reach (mm)	69.98	70.51	70.34	70.54	71.50
Arch radius (mm)	19.71	16.86	17.46	15.54	14.84
Longitudinal arch length (mm)	96.87	97.06	96.75	97.53	97.32
Transverse arch width (mm)	55.48	47.99	45.01	43.89	43.16
Arch width ratio (mm)	115.23	97.00	90.63	87.57	84.54
Toe region length (mm)	81.13	82.91	83.32	83.74	84.17
Toe region height (mm)	29.23	27.72	26.95	26.47	25.82

Note: Data are given as means. All measurements are normalized with respect to ball length (L_B) (except ball length and ball angle) to facilitate intersubject comparisons, ie, the measurements were multiplied by the factor (mean L_B)/L_B to compensate for differences in the subjects' skeletal morphological size, where mean L_B is the mean ball length for the subject sample population and L_B is the ball length of the respective subject's foot.

of the Shapiro-Wilk test. As seen in Table 3, for a level of significance of $\alpha = .05$, the corresponding Shapiro-Wilk test P values for most (seven of eight) of the pedal parameters are greater than α, indicating that the respective parameters are Gaussian-distributed.[38]

The results in Tables 1 and 4 further show that, on average, 57% of the changes in the pedal dimensions that occurred with support of the full body weight on the right foot arose in the initial phase of loading, ie, when applying 0% to 10% of body weight. With support of 25% of body weight, on average, 71% of the changes observed with support of the full body weight had already occurred. Consequently, the changes that occur in the later phases of loading, ie, when applying 25% to 100% of body weight, are less than or equal to the changes that arise during initial loading. This finding is consistent with empirically established clinical pedorthic practices, in which casts and impressions of the feet are taken with the patient sitting erect, a plaster wrap bandage is applied, and then both feet are placed on the floor in neutral alignment. The resultant load applied on each foot in this position is approximately 10% of the patient's body weight, as verified by us in clinical measurements using a bathroom scale. As further verified in clinical measurements, if the patient also places the forearm on top of the ipsilateral knee and leans forward, applying the weight of the upper body onto the leg and foot, approximately 25% of the patient's body weight is supported by the foot. When a person stands erect on a level surface with his or her legs in neutral alignment, orthogonal to the floor, with equal weight on both feet, the load on each foot is approximately 50% of body weight. In the absence of deformity and functional neuromuscular disorder, pedal segmental alignment in these positions approximates that during quiet standing and during midstance in gait. Loading of the foot with 10% to 50% of body weight, in neutral alignment, has been empirically found to generally afford good results for pedal measurement and casting. The study results corroborate this. Conversely, if measurements of a patient's foot and ankle are acquired without any load applied, then the dimensions and shape of the foot vary significantly from instance to instance and dras-

Table 2. Principal Pedal Dimensions Measured with the Subjects' Right Feet Supporting 25% of Their Body Weight

Pedal Parameter	Mean (SD)	SD/Mean
Foot length (mm)	263.65 (4.65)	0.0176
Ball length (mm)	180.33 (14.00)	0.0776
Medial ball reach (mm)	191.41 (3.21)	0.0168
Lateral ball reach (mm)	169.26 (3.21)	0.0190
Second metatarsal head reach (mm)	199.63 (6.41)	0.0321
Ball width (mm)	103.34 (6.08)	0.0588
Ball circumference (mm)	254.97 (16.56)	0.0650
Ball angle (°)	–12.44 (3.69)	–0.2967
Instep height (mm)	77.69 (9.15)	0.1178
Instep width (mm)	89.83 (5.78)	0.0643
Instep circumference (mm)	267.39 (19.51)	0.0729
Span (mm)	350.13 (12.46)	0.0356
Medial malleolus height (mm)	79.23 (8.06)	0.1018
Lateral malleolus height (mm)	67.13 (6.38)	0.0950
Maximum heel width (mm)	73.06 (3.97)	0.0543
Proximal heel width (mm)	60.98 (4.43)	0.0727
Arch reach (mm)	70.34 (5.71)	0.0811
Arch radius (mm)	17.46 (10.04)	0.5751
Longitudinal arch length (mm)	96.75 (7.87)	0.0813
Transverse arch width (mm)	45.01 (8.08)	0.1794
Arch width ratio (mm)	90.63 (16.63)	0.1834
Toe region length (mm)	83.32 (4.65)	0.0558
Toe region height (mm)	26.95 (3.37)	0.1248

Note: All measurements are normalized with respect to ball length.

Table 3. Shapiro-Wilk Normality Test Statistics for a Subset of the Principal Pedal Dimensions Listed in Table 1

	Shapiro-Wilk Test Statistics	
Pedal Parameter	W	*P* Value
Foot length	0.9494	.0722
Ball length	0.9747	.5012
Ball width	0.9504	.0782
Ball circumference	0.9133	.0048
Ball angle	0.9483	.0664
Maximum heel width	0.9618	.1923
Proximal heel width	0.9746	.4972
Instep height	0.9675	.2998
Instep width	0.9810	.7248

Note: All measurements were normalized with respect to ball length. For a given significance level α, if the associated *P* value is greater than α, then the parameter is deemed to have a Gaussian distribution with a high degree of certainty.

tically differ from the measures acquired in a neutral alignment with a minimal load applied (eg, neutrally aligned on a platen with ≤1% of body weight applied).

As seen in Table 4, the changes in the subjects' foot and ankle dimensions measured by sequentially applying increasing percentages of body weight were smaller than those previously reported by other investigators, in particular, Tsung et al,[32] who measured changes in the length and width of the left and right feet of eight men in the zero weightbearing, semiweightbearing (~50% of body weight), and full weightbearing states by making plaster impression casts of the subjects' feet that were subsequently optically scanned and imported into a computer-aided design system for parameter measurement, and Cheng et al,[31] who measured foot size changes in 2,829 Chinese children with full weightbearing using electronic calipers. The differences in the changes in the principal dimensions of the foot with weightbearing measured in this study *versus* those previously reported by Tsung et al and Cheng et al, respectively, were 1) heel-to-toe length, 1.5% *versus* 3.4% *versus* 3.1%; 2) ball width, 4.3% *versus* 6.0% *versus* 4.8%; and 3) maximum heel width, 4.8% *versus* 8.7% *versus* not reported. These differences are appreciable. As noted in the "Methods" section, calibration and subsequent laboratory tests of the individual and composite Department of Veterans Affairs Pedorthics Optical Digitizer and pedorthics computer-aided design/computer-aided manufacturing systems established the error of the measurement procedure used in this study to be 0.67 mm or smaller along the longitudinal axis of the foot (eg, in heel-to-toe length) and 0.23 mm or smaller with respect to dimensions orthogonal to the longitudinal axis of the foot. In this study, the mean heel-to-toe length (L_{HT}) of the test subjects was 263.7 mm when supporting 25% of body weight. As such, the maximum relative error in measurement would be 0.67/263.7 or 0.25%. Similarly, for a mean ball width (W_B) of 103.3 mm, the maximum relative error in measurement of the subjects' ball width would be 0.23/103.3 or 0.22%. Thus it is unlikely that the accuracy of the instrumentation and software used in this study to measure pedal dimensions contributed significantly to the differences in the reported values. Other factors, such as inherent differences in the subjects, in the measurement-acquisition methods used, or in the definitions of the parameters measured, are thus the most likely source of the discrepancies.[39]

Investigation of the interrelationships among the principal pedal dimensions measured and the changes that occurred with weightbearing revealed little intercorrelation. In particular, in the case of pedal ball width and heel width, the sample correlation coefficient (*R*) was 0.50, which shows a mild-to-weak correlation. Thus for the subjects in this study there was no appreciable correlation between the ball and heel

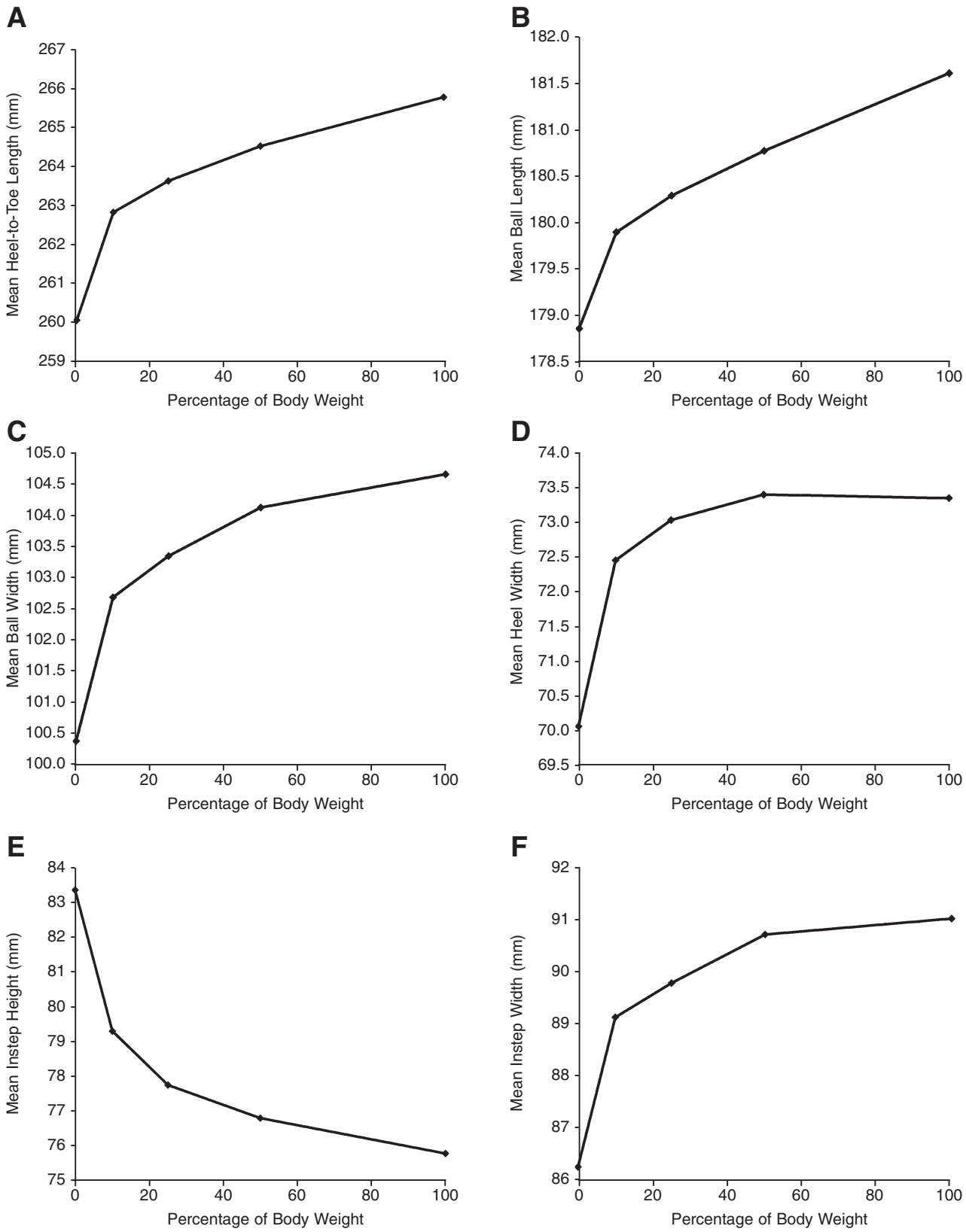


Figure 3. Mean normalized values of a subset of the principal pedal parameters given in Appendix 1. Heel-to-toe length (A), ball length (B), ball width (C), maximum heel width (D), instep height (E), and instep width (F) are shown as a function of the percentage of body weight supported by the foot.

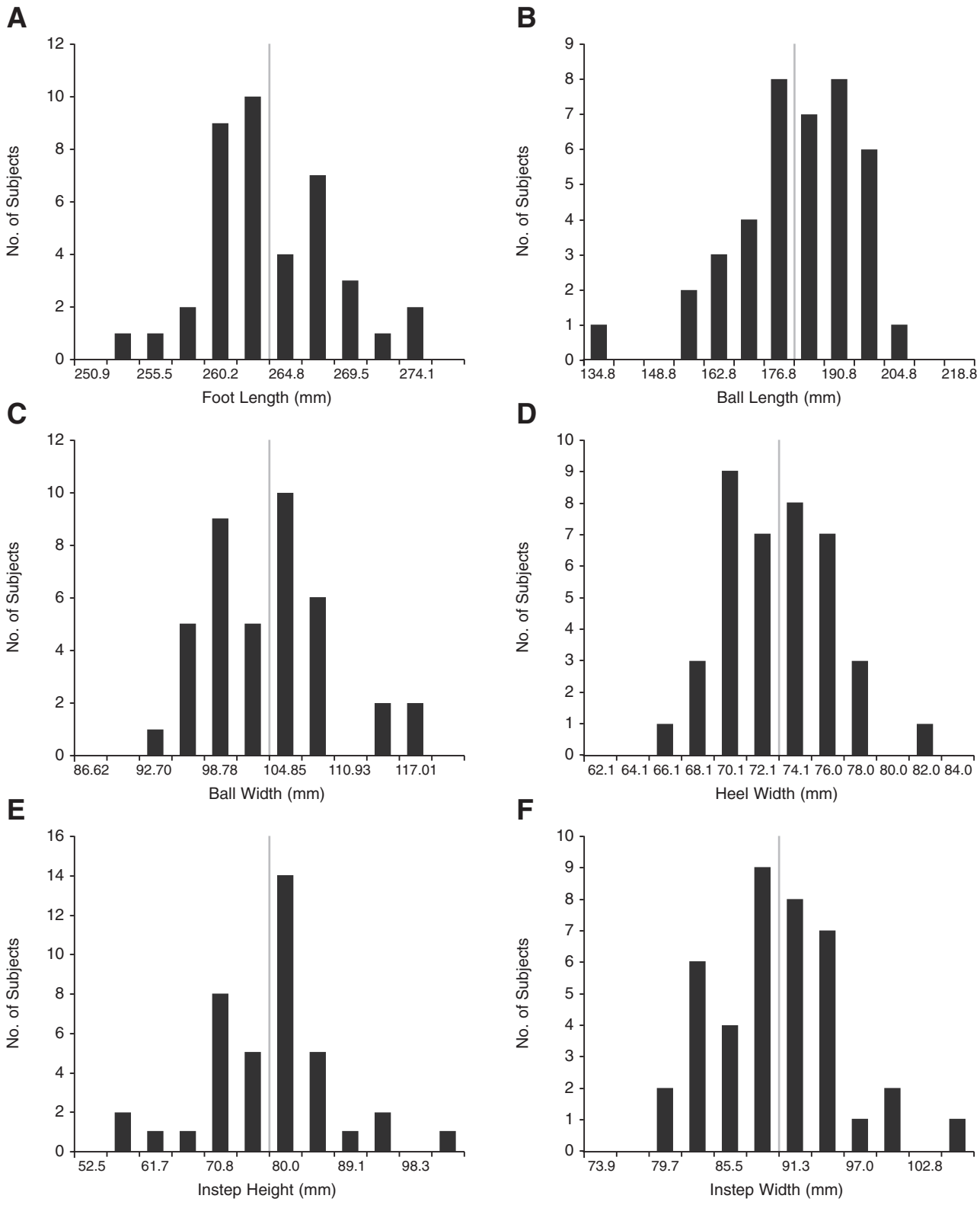


Figure 4. Histograms of the subset of the principal pedal parameters shown in Figure 3 with the subjects' feet supporting 25% of their body weight: foot length (A), ball length (B), ball width (C), maximum heel width (D), instep height (E), and instep width (F). Each of the abscissal columns covers a range of 50% of the sample standard deviation for the mean normalized values of the respective parameters. The distributions of the parameters are seen to be approximately Gaussian-shaped, as verified by the Shapiro-Wilk test in Table 3 for a significance level of $\alpha = .05$. The vertical gray lines denote the location of the respective mean value on the x-axis.

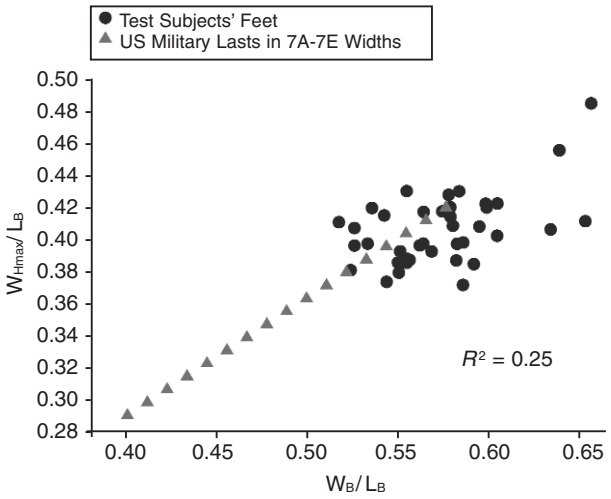


Figure 5. Ball width and maximum heel width measurements normalized by the respective subjects' ball lengths and the corresponding ball and heel width measurements for the set of US military oxford shoe lasts in ball width sizes 7A to 7E. The substantial differences between the subjects' pedal ball and heel widths and the corresponding values of the closest US military last would result in a poor fit for most of the subjects.

widths of their feet. This reflects that the shapes and sizes of people's feet vary considerably and are not algebraically scaled, as are many commercial shoe lasts. The lack of correlation among the pedal parameters is further evidenced by the degree of scatter of the data in Figure 5. As previously noted, and as seen in Table 3 and Figure 4, the heel width and ball width measurements for the subjects in this study were (approximately) Gaussian-distributed. Because they are also uncorrelated, they can be assumed to be statistically independent. This has a variety of implications, primary among which is limitation in the accuracy with which foot shape and size are characterizable by heel-to-toe length and forefoot aspect ratio, as is commonly done in the sizing and fitting of most commercial footwear.

To show the extent of the problem, the ball width and heel width of the set of US military men's oxford shoe lasts normalized with respect to ball length are plotted together with the normalized ball width and heel width measurements of our subjects' feet (Fig. 5). The set of US military lasts covers an expansive range of sizes (sizes 1 to 16 in heel-to-toe length and sizes 7A to 7E in ball width). The values for the US military lasts seen in Figure 5 constitute a linear least squares regression fit of the population pedal measurements. Even with the extensive range of sizes covered by the US military lasts, the data in Figure 5 show that most of our subjects' feet are poorly fit by US military lasts and the footwear fabricated from them. Wider lasts at the heel or at the ball are needed if the quality of fit provided by the footwear is to be improved for more people. These results corroborate the findings of Chantelau and Gede,[40] who measured the feet of 568 subjects with diabetic polyneuropathy and of 100 (nondiabetic) control subjects and reported that more than two-thirds of the subjects' feet, with and without diabetic neuropathy, were considerably wider than commercially available footwear.

Figure 5 further reveals that increasing last dimensions solely at the ball would accommodate only a few people. Increases in last aspect ratios at the heel,

Table 4. Changes in the Mean Normalized Dimensions of the Foot When Supporting a Specified Percentage of Body Weight Relative to the Respective Values in a Zero Weightbearing State and as a Percentage of the Total Change Incurred When the Foot Supports the Full Body Weight

	Change in Mean Normalized Pedal Dimensions When Supporting a Specified % of Body Weight Relative to Values in a Zero WB State				% of Total Change When Supporting Full Body Weight		
Pedal Parameter	10% WB	25% WB	50% WB	100% WB	10%	25%	50%
Foot length (mm)	2.69	3.50	4.41	5.68	47.3	61.6	77.6
Ball length (mm)	1.05	1.45	1.94	2.79	37.7	52.0	69.5
Ball width (mm)	2.33	3.00	3.79	4.33	53.8	69.4	87.5
Ball circumference (mm)	2.03	2.70	4.00	3.83	52.9	70.5	104.3
Ball angle (°)	–0.59	–0.56	–0.93	–0.73	80.9	76.1	127.3
Maximum heel width (mm)	2.43	3.01	3.38	3.33	72.8	90.5	101.6
Proximal heel width (mm)	2.23	3.11	4.54	5.89	37.8	52.8	77.0
Instep height (mm)	–4.19	–5.80	–6.77	–7.83	53.6	74.0	86.5
Instep width (mm)	2.90	3.57	4.51	4.82	60.2	74.0	93.6

Abbreviation: WB, weightbearing.

at the ball, and at both are needed if significantly more people are to be fit well. This is further evident in the digitized scans of the study subjects' feet shown in Figures 6 and 7. As seen in Figure 5, the subjects' ball and heel width measurements inherently may be partitioned into four sectors, each corresponding to a distinct foot shape category: 1) feet with narrow ball and heel widths (Fig. 6A); 2) feet with relatively wide ball and heel widths (Fig. 6B); 3) feet with average or narrow ball widths but relatively wide heel widths ("U-shapes") (Fig. 7A); and 4) feet with relatively wide ball widths but narrow heel widths ("V-shapes") (Fig. 7C). Judicious modifications of last dimensions to more nearly match the dimensions of the subjects' feet in each of these respective

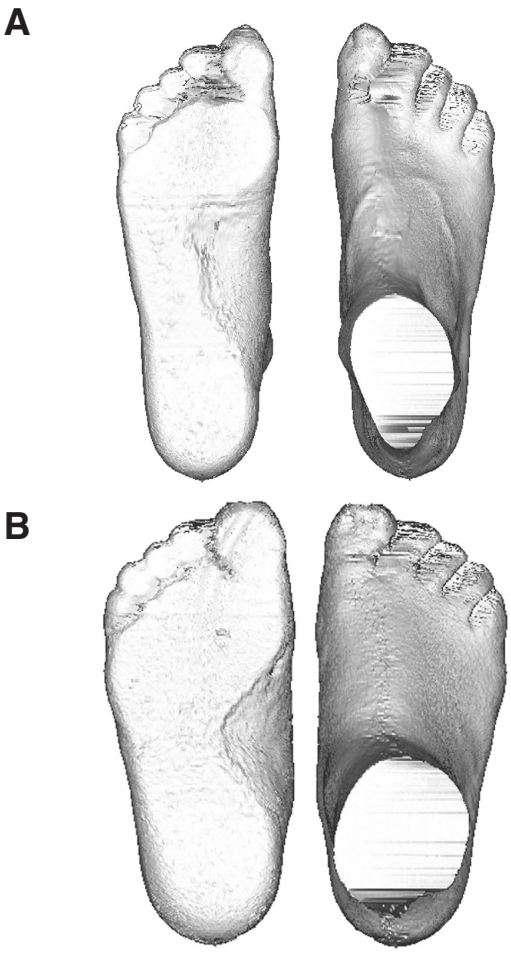


Figure 6. Examples of subjects' feet from two of the principal categories of pedal shape with respect to forefoot and heel aspect ratio: feet with relatively narrow to average ball and heel widths (A) and feet with relatively wide ball and heel widths (B).

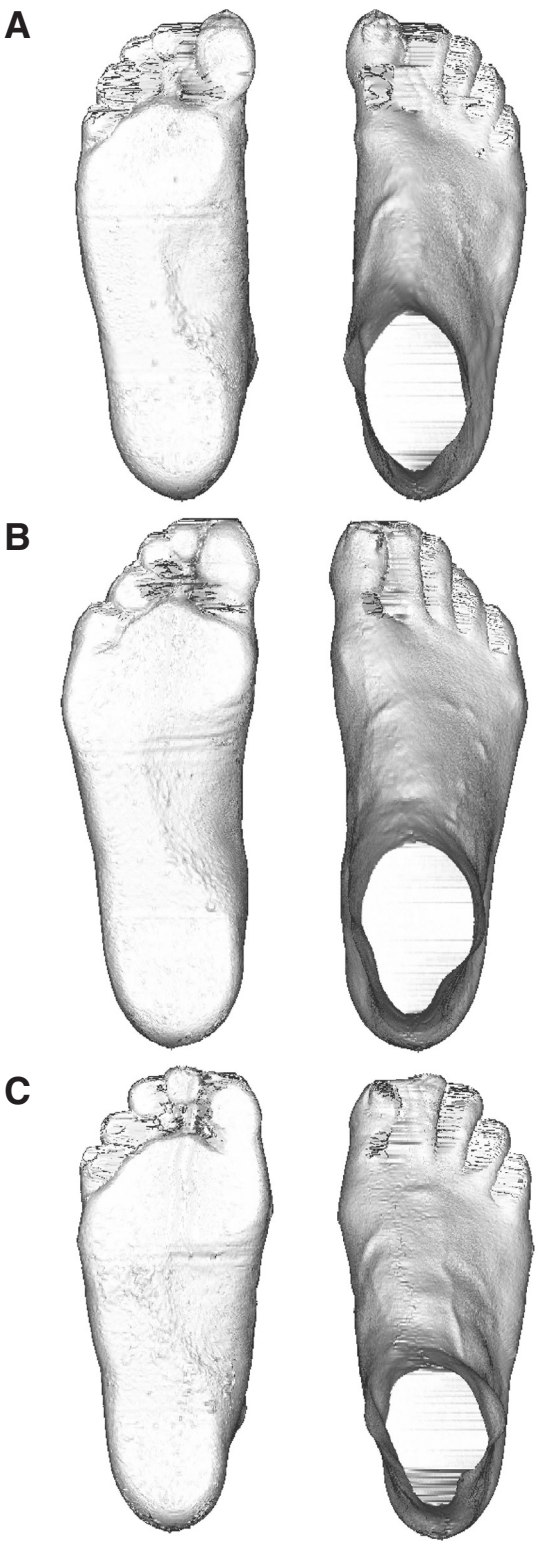


Figure 7. Examples of subjects' feet from three different forefoot and heel aspect ratio categories: "U-shaped" feet with average or narrow ball widths but relatively wide heel widths (A), feet with average ball and heel widths (B), and "V-shaped" feet with relatively wide ball widths but narrow heel widths (C).

foot shape categories would significantly improve the quality of footwear fit provided to a much greater number of people, as opposed to the straight linear regression approximation used in US military and current commercial footwear.

The implications of this finding are further evident in the relatively large values of the sample standard deviations of the pedal parameters given in Table 2. In particular, the sample standard deviation of pedal ball width for the subjects' feet was 6.1 mm. Similarly, the sample standard deviation of the subjects' pedal ball circumference was 16.6 mm and of their heel width was 4.0 mm. If footwear were manufactured in only one width per heel-to-toe length size, as is common practice in the current commercial footwear market, then even if people could tolerate an error of ±6.1 mm between the ball width of their feet and that of a given brand and style of shoes, in concert with an error of ±16.6 mm in the ball circumference of the shoes, and a difference of ±4.0 mm in the width of the shoe heel compared with the heel width of their feet, less than 70% of the population (1 SD) would be able to even don a pair of the given "one-width-per-size" shoes. The remaining 30% or more of the population would be forced to go to an oversized or undersized pair of shoes to even try them on. Because it is unlikely that people would tolerate shoes with ball widths, ball circumferences, and heel widths that were this much smaller than their feet, "one-width-per-size" shoes are usually made larger than the nominal length size. Thus, if 70% of the population is to be fit by a given brand and style of shoe, people would have to accept ball width errors of up to +12 mm, ball circumference errors of up to +33 mm, and heel width errors of up to +8 mm. Such dimensional differences are extremely large and, as previously noted, can cause excessive loads at resulting pseudoarthroses, leading to tissue insult, injury, and pain.[24-27] Judicious choice of footwear last dimensions can prevent this and can provide a much better fit for more people than currently achieved even by US military footwear, which provides the broadest range of sizes available.

Conclusion

People's feet vary considerably in size and shape. A set of 23 measures characterizing the 3-D shape and size of people's feet and ankles was derived. Values of the respective parameters for the right feet and ankles of 40 healthy men aged 22 to 71 years were acquired as a function of the percentage of body weight supported by their feet. The resulting measurements show that the principal dimensions of the foot undergo significant change when applying body weight; most of the change occurs during the initial phases of loading, ie, when applying 0% to 10% of body weight. The dimensional changes that occur during the latter stages of loading, ie, when applying 25% to 100% of body weight, are generally less than or equal to the initial changes incurred. This substantiates the common clinical pedorthics practice of casting and measuring patients' feet in neutral alignment while supporting 10% to 25% of their body weight.

Analysis of the measurements of the study subjects' feet showed that the respective pedal parameters were approximately Gaussian-distributed, and most had little to no intercorrelation. In particular, pedal heel width and ball width were shown to be relatively statistically independent, with relatively wide dispersions. As such, foot shape and size are not characterizable by heel-to-toe length and forefoot aspect ratio only, as is currently commercially done. The subjects' heel width and ball width measurements show that variations in the pedal aspect ratio are not linearly scalable but rather are more accurately classified by four distinct categories: 1) feet with narrow or average ball and heel widths, 2) feet with relatively wide ball and heel widths, 3) U-shaped feet with average or narrow ball widths but relatively wide heel widths, and 4) V-shaped feet with relatively wide ball widths but narrow or average heel widths. The manufacture of custom orthopedic footwear using the measurements of our subjects' feet and those of 51 female subjects from a concurrent parallel study[33] and judicious modification of footwear lasts so that their dimensions more closely match people's pedal dimensions in each of these respective shape categories, instead of using a scaled linear regression fit of the forefoot aspect ratio for the population as a whole, would significantly improve the quality of fit, comfort, and function of footwear for a much larger percentage of the population.

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Appendix 1: Definitions of Selected Parameters

Foot Length (heel-to-toe length) (L_{HT})—The projected horizontal distance from the first digitized cross-section at the heel to the most anterior digitized point on the toes.

Ball Length (L_B)—The projected horizontal distance from the first digitized cross-section at the heel to the midpoint of the (oblique) line from the apex of the first metatarsal head to the apex of the fifth metatarsal head, namely, the ball line.

Medial Ball Reach (D_{BM})—The projected horizontal distance from the first digitized cross-section at the heel to the apex of the first metatarsal head.

Lateral Ball Reach (D_{BL})—The projected horizontal distance from the first digitized cross-section at the heel to the apex of the fifth metatarsal head.

Second Metatarsal Head Reach (D_{MTH2})—The projected horizontal distance from the first digitized cross-section at the heel along the reference baseline to the apex of the second metatarsal head.

Ball Width (W_B)—The projected horizontal distance from the apex of the first metatarsal head on the medial aspect of the foot to the apex of the fifth metatarsal head on the lateral aspect of the foot.

Ball Circumference (C_B)—Measured in the pedal optical scan as the circumferential distance around the perimeter of the foot in the vertical, oblique cross-section through the ball line.

Ball Angle (Θ_B)—The acute angle between the reference baseline and the ball line.

Instep Height (H_{In})—The vertical distance from the pedal support surface to the apex of the foot dorsum in the frontal cross-section located a distance of $0.7 \cdot L_B$ anterior to the first digitized cross-section through the heel.

Instep Width (W_{In})—The projected horizontal distance between the medial border of the foot and the lateral border of the foot in the frontal cross-section located a distance of $0.7 \cdot L_B$ anterior to the first digitized cross-section through the heel.

Instep Circumference (C_{In})—The circumferential distance around the perimeter of the foot in the frontal cross-section located a distance of $0.7 \cdot L_B$ anterior to the first digitized cross-section through the heel.

Span Circumference (C_{Span})—The circumferential distance around the perimeter of the foot in the inclined, transverse cross-section passing through the posterior distal crest of the heel to the proximal dorsal intercept with the instep frontal cross-section at a distance of $0.7 \cdot L_B$ anterior to the first digitized cross-section through the heel.

Medial Malleolus Height (H_{MM})—The height of the apex of the medial malleolus above the pedal support surface.

Lateral Malleolus Height (H_{ML})—The height of the apex of the lateral malleolus above the pedal support surface.

Maximal Heel Width (W_{Hmax})—The maximal horizontal projected distance across the heel below a level of $0.25 \cdot L_B$ above the horizontal pedal support surface, in the frontal cross-section located at a distance of $0.3 \cdot L_B$ anterior to the first digitized cross-section through the heel.

Proximal Heel Width (W_{Hprox})—The width of the heel in the frontal cross-section located a distance of $0.3 \cdot L_B$ anterior to the first digitized cross-section through the heel, at a height of $0.25 \cdot L_B$ above the horizontal pedal support surface.

Arch Reach (L_{Arch})—The projected horizontal distance along the reference baseline from the first digitized cross-section at the heel to the posterior border of the longitudinal arch defined by the center of the landmark at the anteromedial border of the calcaneal fat pad.

Arch Radius (H_{Arch})—The minimal radial distance to the surface of the foot in the instep frontal cross-section (located a distance of $0.7 \cdot L_B$ anterior to the first digitized cross-section through the heel), measured as the smallest radial distance to the surface of the foot from the intercept of the vertical projection of the most medial point on the foot with the horizontal pedal support surface.

Longitudinal Arch Length ($L_{ArchLen}$)—The projected horizontal distance along the reference baseline from the posteromedial border of the arch defined by the center of the landmark at the anteromedial calcaneal border to the anteromedial border of the arch posterior to the first and second metatarsal heads.

Transverse Arch Width (W_{Arch})—The projected horizontal distance from the contact point of the fat pad at the lateral border of the arch to the intercept of the pedal horizontal support surface with the vertical projection of the most medial point of the foot in the frontal cross-section through the instep at a distance of $0.7 \cdot L_B$ anterior to the crest of the heel.

Toe Region Length (L_{Toe})—The distance from the midpoint of the ball line along the reference baseline to the most anterior point digitized on the front of the toes.

Toe Region Height (H_{Toe})—The height of the most proximal aspect of the toes above the horizontal support surface in the frontal cross-section located at a distance of $1.25 \cdot L_B$ anterior to the first digitized cross-section through the heel.

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