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# Analysis of the Human Female Foot in Two Different Measurement Systems: From Geometric Morphometrics to Functional Morphology

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## ABSTRACT

*The relationship of geometric morphometrics (GMM) to functional analysis of the same morphological resources is currently a topic of active interest among functional morphologists. Although GMM is typically advertised as free of prior assumptions about shape features or morphological theories, it is common for GMM findings to be concordant with findings from studies based on a-priori lists of shape features whenever prior insights or theories have been properly accounted for in the study design. The present paper demonstrates this happy possibility by revisiting a previously published GMM analysis of footprint outlines for which there is also functionally relevant information in the form of a-priori foot measurements. We show how to convert the conventional measurements into the language of shape, thereby affording two parallel statistical analyses. One is the classic multivariate analysis of »shape features«, the other the equally classic GMM of semilandmark coordinates. In this example, the two data sets, analyzed by protocols that are remarkably different in both their geometry and their algebra, nevertheless result in one common biometrical summary: wearing high heels is bad for women inasmuch as it leads to the need for orthotic devices to treat the consequently flattened arch. This concordance bears implications for other branches of applied anthropology. To carry out a good biomedical analysis of applied anthropometric data it may not matter whether one uses GMM or instead an adequate assortment of conventional measurements. What matters is whether the conventional measurements have been selected in order to match the natural spectrum of functional variation.*

***Key words**: human female foot, conventional morphometrics, geometric morphometrics, high heels, orthotics*

> Follow the duck, not the theory of the duck.
> – – – Attributed to William R. Charlesworth, American ethnologist

## Introduction

Analysis of the variability of the human foot is central to many professions, some applied (e.g. footwear design, construction, and marketing) and others academic (physical anthropology) or medical (orthopedics, orthotics). Methods for measuring this organ have been with us for as long as there have been cobblers, and tables of averages and standard deviations of the measures within specified human population samples have existed nearly as long as there have been physical anthropologists (see, for instance[1] pp. 419–423, 1167–1182). In the applied context these are generally found under the rubric of »sizing systems«, such as the tables of 27 foot dimensions for some 7500 American soldiers of Freedman and colleagues[2] or the foot-relevant aspects of the Croatian Anthropometric System, a 1:140 sample of the population of Croatia[3]. The information may be gathered purely for purposes of fabrication or, when accompanied by measurements of locomotion, can be exploited further in studies of the associations between the form of the foot and its functions.

Complementary to this conventional approach via discretely measured distances, girths, and angles is the

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modern approach via three-dimensional surface scanning (see, e.g.[4,5]) or its two-dimensional reductions (e.g.[6,7]). These approaches are characterized by a far greater volume of raw data in a format unsuitable for tabulations in any conventional style. Typically they are converted to conventional measurements calculated *post-hoc* (see, e.g.[8]) or else submitted *in extenso* to methods such as shape regression or shape principal components analysis[7,9].

The purpose of the present paper is to show the overlapping information content of these two separate approaches, usually contrasted as »geometric morphometrics« *versus* »conventional morphometrics«, in the context of one particular functional theme, the relation of women's feet to women's customary footwear. In a more general functional context this nexus is currently a topic of active interest in functional morphology per se. Among the many discussions on the topic are a series of essays by the bioengineer and primatologist Charles E. Oxnard, for instance[10–12]. More recently the interplay between varieties of anthropometry and varieties of biometrics is becoming increasingly important in a variety of professional contexts, mainly as a result of the penetration of GMM ideas into anthropometrics both in the academy and in industry. The December, 2014, number of The Anatomical Record is expected to include the proceedings of a recent American symposium on this topic, expressing a general concern that the ways in which we teach GMM to the anthropologist, particularly the emphasis on beginning with principal components of shape, might not suit these other applications too well. This literature is concerned that geometric morphometric (GMM) analyses should not lose access to the insights that conventional morphometric analyses afford when applied to the same original digitized materials, insights that have typically been hard-won over years or even decades of applied decision analysis in medical or industrial contexts. The theme is related to the general concern for how hypotheses influence the definition and operationalization of landmark points, a concern as central to Rudolf Martin's approach to anthropometrics[1] from 1928 as to Bookstein's[13] definition of morphometrics from 1991 as »the study of the covariances of biological form« (meaning, in practice, the association of form with its causes or effects).

While there has been a good deal of biomathematical meditation on this topic, actual demonstrations of the comparative information content at issue are few. Oxnard[11] carried out analyses of the same question of functional morphology by both conventional multivariate analysis and his version of GMM (an adaptation of Thompson's method of transformation grids, the thin-plate spline having not yet been invented). He showed how the two methods led to quite similar interpretations of differences in the geometry of the anthropoid scapula between brachiating and non-brachiating species. GMM analyses of the ontogeny of the rodent skull have found that descriptive factors already familiar from conventional studies, such as »orthocephalization«, continue to apply to time trends both of mean shape and of shape variation: see the trend analyses of Henning Vilmann's celebrated longitudinal data in[13] and also the canalization analyses in[14,15]. And of course the descriptions of the hominization of the skull over the evolution of *Homo* are completely consistent between the older methods of assessing »globularization«, together with cranial base angle, and the contemporary assessments deriving from landmark and semilandmark point locations; likewise the occipital bunning of the Neanderthal[16].

These analyses were »academic«, overlapping hardly at all with concerns of the applied anthropologist such as human disease or human clothing; but recently there has been a pioneering application of the same GMM toolkit to a specifically applied domain, the design of human footwear. Domjanić et al.[7] summarize an extensive study of the joint effects of body mass index (BMI) and the wearing of high-heeled shoes on the footprint of typical young adult females in a mostly Croatian sample. The authors conclude that footprint shapes are affected by lifestyle factors and that GMM is a powerful tool for the extraction and description of those effects. At the same time, in a contribution to the Anatomical Record proceedings already mentioned, Bookstein[17] argues that in principle it should be possible to calibrate the information content of a GMM analysis to any list of shape features or factors deemed of interest a-priori whenever they are based in the same information resources, meaning, in practice, the same knowledge of where it would prove profitable to place your ruler down over the organism or its image.

It would be of interest to both communities, the geometric morphometricians and the applied anthropologists, if Bookstein's theorems could be subjected to a realistic test in some data set itself of mutual interest. As it happens, the Domjanić project offers just such a data resource. As reported in detail in her doctoral dissertation[18], besides the semilandmark representations of the footprints of the 83 female subjects there are also available a considerable variety of conventional anthropometric measurements of the same feet. These are not just any anthropometrics, but those that are most important for the construction of shoe lasts and thereby of actual footwear. In particular, the principal findings of the GMM analysis in[7] are aligned with four specific entries in that measurement vector (arch height, foot length, hallux length, and forefoot length). Can a conventional multivariate analysis of the conventional shape features and factors in the identical sample end up pointing to at least some of the same phenomena?

The answer to this question is »Yes«, and the principal purpose of this short essay is the description of how a conventional multivariate analysis can be turned to answer the same question that the GMM analysis ended up answering. The key to showing the agreement will be the manipulation of the space of *a-priori* shape features so as to focus on a subset of localizable features, the same kind of feature for which GMM's tools are specialized. In the text to follow we explain the design of the study, list the available measurement data, summarize the GMM findings, and then walk through an analysis of the conventional scores that arrives at least one of the same endpoints. A closing discussion elaborates on the implications of this convergence for the pedagogy of GMM and then for 21st-century applied anthropology more generally.

## Materials and Methods

### *General scheme of the female foot*

The best way to approach our empirical design is by consideration of a standard set of measurements of the shoe last, such as the one in Figure 1. The last is the working surface upon which the shoe is fabricated, and so determines the geometry of the inner shoe surface that is supposedly matched to the foot's outer skin surface. Lasts are a compromise between shoe models and the combination of actual foot measurements (by size-width class) with »allowances« to accommodate either comfort under flexing (toward the heel, over the instep) or design (toward the toe). Note, however, that the last, unlike the foot, has a feather-edge to which the sole is affixed in the course of production, and that the last is smoothly curved where the typical foot is irregular. See, in general[19].

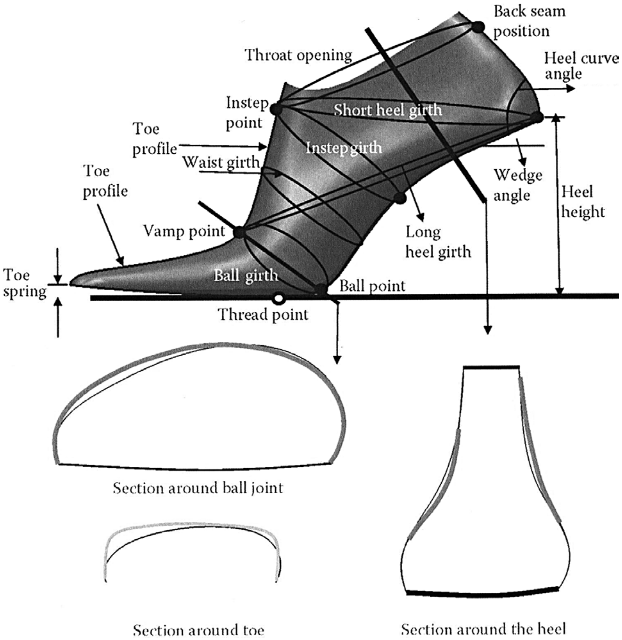

*Fig. 1. A variety of standard measurements associated with the manufacture of contemporary high-heeled shoes (from Luximon A, and Goonetilleke RD, 2008 with permission).*

### *Design*

The sample for our study is the same one reported in[7,18]: measurements on both feet of 83 young adult women of whom the great majority (73) were of Croatian extraction. Most analyses are carried out on a sample size of 166, corresponding to both left and right feet of the 83 subjects, and the left-right differences are of interest to the original investigators (as well as to the purveyors of shoes), but we shall not pursue the matter here. Nevertheless, because of this paired design, any significance tests applied here to the foot-by-foot data must be in the form of permutation tests that leave the pairing of left and right invariable. We do not demonstrate such tests in this paper.

### *GMM data*

The GMM data resource, as described in more detail in the cited references, consists of 85 landmarks and semilandmarks on the outlines of the footprints of all 166 feet. The footprints are not images of any impression, but are instead extracted from surface scans of the foot at a distance of 2 mm proximal to the plantar surface. Digitization involved one landmark per toe and two landmarks on the footpad outline, together with 7 semilandmarks per toe and 34 more for the outline of the footpad. Finally, the medial shadow of the foot was represented by a final 9 semilandmarks. The semilandmarks were slid to optimal positions by the thin-plate spline algorithm of[20], the resulting sets of 85 points Procrustes-registered, and their shape coordinates converted to principal components of shape. Finally, both the original shape coordinates and the principal component scores were analyzed for dependence on the covariates listed in the next paragraph, everything in the textbook-standard way[9,21].

### *Conventional data*

In addition to these 85 coordinate pairs for each foot, the available data included a variety of conventional measurements of organismal form or lifestyle. The subject-by-subject measures included, among other things, age, height, weight, shoe size, frequency of wearing high-heeled shoes, frequency of participation in active sports involving the lower limb, and a history of needing orthotic inserts, along with other measures. The foot-specific measurements included 14 separate measurements of the geometry of the foot known relevant to the construction of footwear: foot length, ball-to-heel length, ball length, ball width, ball angle, ball girth, instep size, angulation, dorsal arch height, dorsal arch girth, heel width, heel girth, arch width, and toe height. These measures are all defined in Table 1 and diagrammed in one or the other frame of Figure 2.

You will notice, in Figure 1, the high heel. This has nothing positive to do with human locomotion, but is instead a purely cultural phenomenon, a psychosexual factor connoting class, rank, wealth, or authority in some modern societies. Apparently the idea comes from Catherine de' Medici in the 16th century. Doctors have always recommended shoes with low, broad heels and broad round toes, and the choice of high heels stands for a cost-benefit balancing between agony and sexual selection. Frequent recourse to high heels contributes to forefoot pain and long-term damage and changes the foot alignment during walking and the ratio of loading be-

**TABLE 1**
OPERATIONAL DEFINITIONS OF 14 CONVENTIONAL FOOT MEASURES

| | |
|---|---|
| Foot length | Longest diameter of the foot, from FH to the FT |
| Ball-to-heel length | Distance from the FH to the center of the MPJ1 as projected onto the direction of the foot's longitudinal axis |
| Ball length | Projected distance from the FH to the center of the MPJ5 |
| Ball width | Diagonal distance between MPJ1 and MPJ5 |
| Ball angle | Angle between the ball width measurement and the foot length measurement |
| Ball girth | Circumference of the ball of the foot through MPJ1 and MPJ5 |
| Instep size | Circumference of the instep to a point at the top of the arch (see Figure 2). This quantity roughly matches the circumference labeled »waist girth« in Figure 1 |
| Foot slope | Angle to the horizontal of the line atop the instep in the direction from the foot-leg junction to the first toe |
| Dorsal arch height | Height from the ground to the foot-leg medial dorsal junction (DA1—DA2 in Figure 2) |
| Dorsal arch girth | Circumference of the foot through point DA1. This quantity roughly matches the quantity labeled »Instep girth« in Figure 1 |
| Heel girth | Circumference measured from under the tip of the heel to the instep at junction DA1 of foot and leg |
| Heel width | Widest diameter of the heel parallel to ball width in plantar view |
| Arch width | Distance from AW1—AW2 in Figure 2 |
| Toe height | Distance from TH1—TH2 in Figure 2 |

FH – foot heel, FT – tip of the most protruding toe, MPJ1 – first metatarsal-phalangeal joint, MPJ5 – fifth metatarsal-phalangeal joint, DA1 – dorsal junction of the foot to the foot-ground surface, DA2 – dorsal junction of the foot to the foot-ground surface, AW1 – narrowest part of the footprint of the plantar medial longitudinal arch region, AW2 – narrowest part of the footprint of the plantar medial longitudinal arch region, TH1 – the distal phalange of the first toe to the ground, TH2 – the distal phalange of the first toe to the ground

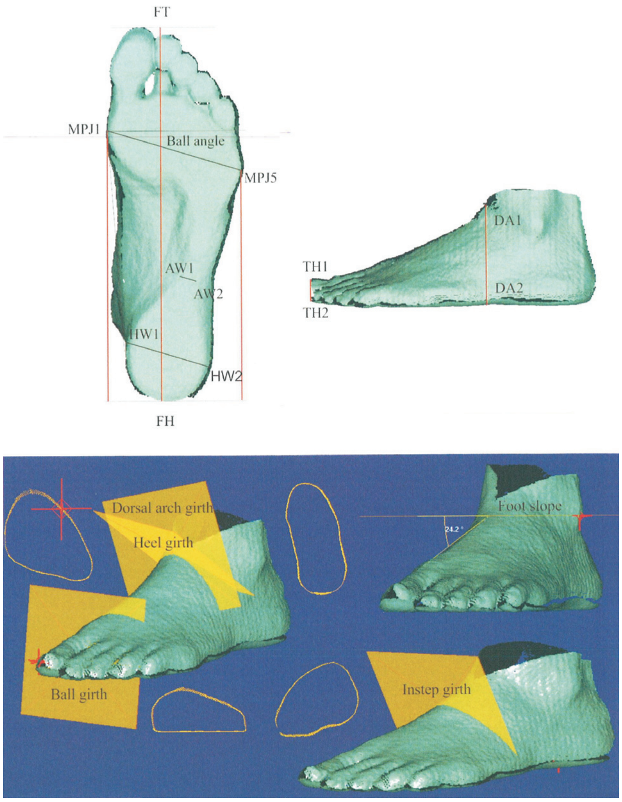

*Fig. 2. Diagrams of some of the standard measures of the foot, in connection with the conventional variables defined in Table 1*[18].

tween front and back[22,23]. In general, alas, such advisories have proved effective, if at all, only in specific delimited subcultures.

## Results and Discussion

A preliminary scan of the conventional data resources in search of interesting patterns uncovered an intriguing relationship between high heels and orthopedics. Of the sample as a whole, 33 never wore high heels, while the other 50 did so at least occasionally. Similarly, 52 of the sample reported no need for orthotic supports, versus 31 who mentioned them. But these two variables were strongly associated. Of the 31 reporting the use of orthotics, 24 (77%) used high-heels regularly, versus only 50% of those who reported no use of orthotics. This association is statistically significant at the 0.025 level by ordinary $\chi^2$-test. (It is hoped that this medical intervention was not prophylactic – that the high heels came first, not the orthotics.) Put most starkly: wearing high heels more than triples the odds of needing orthotics.

For the present paper, we attempted to determine what it might be about the footprint that conduced to the use of orthotic devices. It will turn out that this pattern is oblique to the principal components of shape with which the GMM analysis began, and perhaps for this reason went unreported in the publication by Domjanić et al.[7], but it nevertheless corresponds to the applied podiatric interest that is discussed at length in the original dissertation.

To construct an analysis of measured dimensions that accords in any way with analyses via shape coordinates, it is necessary to convert the measures of extent to shape variables, which is to say, ratios (see, for instance[24]). The size-free analysis of height and weight is well-known to go forward via the »body mass index« (BMI), typically taken as the ratio of weight to height squared. One can check the validity of the exponent of 2 in this formula by an explicit regression of log weight on log height. In the present sample, the resulting regression coefficient is 2.42±0.38 (standard error). The sample value is hence close enough to 2.0 for us to be able to exploit the standard formula: a good thing, as that is the formula used in both of the Domjanić references as well.

The measure of foot length correlates 0.723 with overall body height, suggesting that any measure of general foot size should have quite similar statistical properties to the overall height measure and thus that it should be normalized out by some manipulation involving foot length. We therefore proceeded to divide foot length out of each of the other 11 original foot size measurements. This is a division, not a regression; we explicitly computed the ratio of heel width to foot length prior to taking logarithms (see below). We did not turn to principal component analysis, the usual strategy for constructing such a divisor[13,25], because our search was to be specific to the detection of size measures that did not align with shape principal components – that instead connoted the sort of regional findings that were emphasized in the Domjanić et al.[7] text. As all the size measures available were linear (centimeters or millimeters, versus, say, units of area), the transformation of the logarithm was only for purposes of scale normalization, not accommodation of dimensionalities.

In effect, we were searching not for a principal component but for what Sewall Wright, beginning around 1920, would call a »general size« factor along with »special factors« focused on distinct regions of the organ or organism[21,26]. Absolute values of the correlations of foot length with the other 11 original size measures ranged from 0.233 to 0.911, clearly indicating the presence of more than one factor. A series of informal restrictions of the list of measures sent for principal component analysis (think of this as a version of rotation to simple structure) resulted in a subscale of eight of the 11 items which aligned with one single general factor for which the loadings ranged from 0.254 to 0.450 only. The items thus agglomerated included ball width and girth, instep size, dorsal arch height and girth, heel width and girth, and toe height. The computed BMI correlates 0.31 with this first principal component, indicating, in simple terms, that women who are fatter for their height have feet that are fatter for their length: a summary that is not surprising but is reassuring nevertheless.

While this general shape factor for the foot correlates quite satisfactorily with BMI, nevertheless it is not informative for either the effect of high heels (r=0.037) or the need for orthotics (r=0.035). If there is a signal of biomedical or podiatric interest in these data, it will have to arise not from this general factor but from the dimensions that are not included in it – the five measures omitted from the list of eight. These five, which thereby become the focus of our further examination, are the two ball length measures, the ball angle, the overall foot angle, and arch width.

It is appropriate at this point to note that arch width, as a variable, is in fact held in common between the two data sets. What is a measure relative to overall foot length in the conventional approach is a measure that is normalized to the corresponding Procrustes measure of scale, »Centroid Size«, in the GMM analysis. For a form that is highly directional, like these feet, Centroid Size is closely approximated by overall length, and hence the arch width shown in the figures of[7] and reported in its text is nearly the same measurement as the »normalized arch width« in the conventional analysis being reported here. It would be the same if it were taken between some fixed pair of semilandmarks – we return to this concern in our Discussion.

This is excellent news inasmuch as that common measurement, relative arch width, is in fact the crucial additional morphological fact intervening between the high-heel-use measure and the orthotic-use measure. For simplicity, and because this is not actually a podiatric study, we turn to ordinary linear regression[21] in place of the more nuanced technique of logistic regression. Using only this simple linear model for prediction of the need for orthotics (0 or 1) by the regular use of high heels together with normalized arch width, we find equivalent signal strengths for the two predictors here. If we had used the raw arch width measure, rather than its length-normalized version, the signal for morphology would have been even stronger: part of the need for orthotics appears to be a matter of absolute, not relative, arch width.

The nature of this prediction is as shown in Figure 3. Arch width is plotted across the horizontal here and orthotic use is on the vertical. Black points stand for data

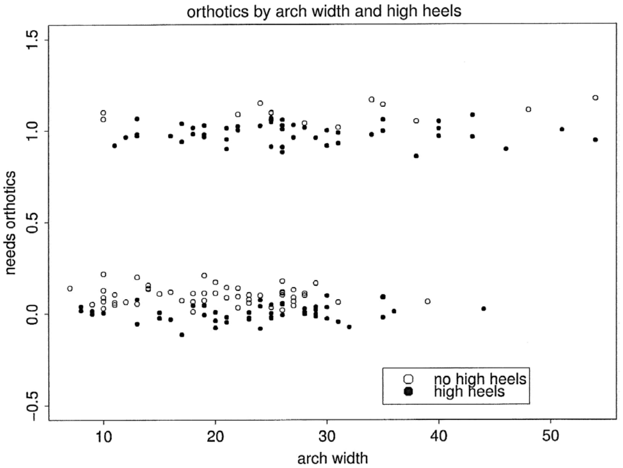

*Fig. 3. Scatter of arch width (horizontal axis) by use of orthotics (vertical axis) and recourse to high heels (see legend). Data are jittered in the vertical coordinate for legibility owing to the discretization of arch width to integers. The 166 points on this plot represent the two feet of each subject separately, each at its own measured arch width.*

from the 100 feet that have been abused in high heels, open circles for the data from the 66 other feet. Vertical positions of all points have been »jittered« (shifted by small random amounts) in order to circumvent what would otherwise be overlap due to the discretized measurement of that arch width (integer cm only). The association between high heels and orthotics already noted in the text is plain here as well – the great majority of points in the upper row are black, meaning that these feet wore high heels some of the time. But also there is a clear tendency for the points in the upper row to fall to the right of those in the lower row, meaning that arch width per se predicts orthotic use as well. Figure 4 is the same for normalized arch width; the narrative is even more convincing.

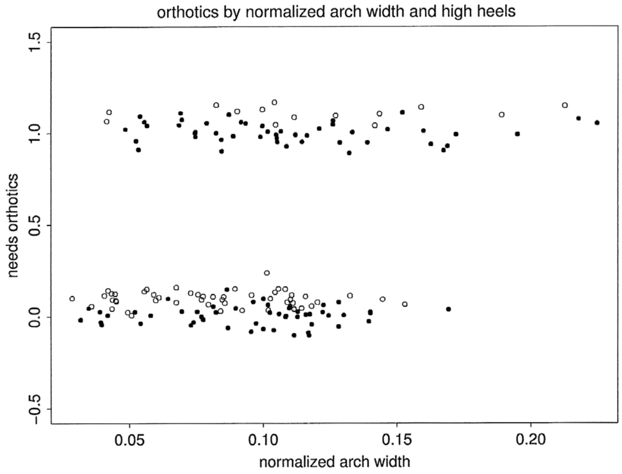

*Fig. 4. The same as Fig. 3 using relative arch width.*

In consideration of our original theme, the comparison of two distinct methodological approaches to the same applied anthropological question, it is of interest to compare Figure 4 to Figure 5, which depicts the analogous finding from the GMM analysis published by Domjanić and colleagues last year. The GMM representation clearly shows a similar effect – the use of high heels is associated with a wider (i.e. flatter) arch in the footprint, presumably leading in turn to the prescription for orthotics that we just found to be so strongly associated with the recourse to high heels. The GMM analysis does not, however, indicate the variability of this effect, whereas the conventional analysis clearly does (the comparison of the distributions of arch widths along the horizontal direction in Figure 4), nor can the GMM approach easily separate out the twofold crossclassification driving the narrative here (the correlations of arch width both with one of its causes, high heels, and one of its effects, the need for orthotics). Interestingly, the roles of high heels (or orthotics) versus BMI appear to reverse salience between the two analyses. In the GMM analysis, the effect of heels (or, the effect on orthotics) appears on PC1 and the difference between thin and fat feet on PC2 (see Figure 2 of[7]); whereas in the conventional analysis here, the effect of BMI is observed quite strongly on the first principal component of the size measures, while the entanglement with high heels or orthotics appears as a specific profile in the residuals from that dominant dimension. Put another way, the effects of BMI can be much more sharply distinguished from those of high heels in the conventional analysis than in the GMM approach. This would seem to argue for the relative merits of the conventional approach over the GMM.

*Fig. 5. The effect of frequent high heel use on the footprint. Contrasts of either average shape with the grand mean have been exaggerated by a factor of three for legibility (Figure 4 of[7]).*

The original Domjanić et al.[7] publication did not focus on orthotic use, the way we just did, but instead reported and diagrammed several diverse associations of foot shape coordinates with terms that turn out to align with conventional assessments. Specifically, the results reported there use terms like »low-arched versus high-arched«, »long and narrow versus short and wide«, »relative length of the forefoot«, and the like that can easily be produced from our conventional measurement list. Thus while the conclusion of that paper (to wit, that »geometric morphometrics proved to be a powerful tool for the detailed analysis of footprint shape«) is true, it is also true that the same feet, if subjected to a sufficiently sophisticated conventional analysis, would produce closely analogous findings – the conventional analysis based on a rich set of measurements of the commercial last appears to be just as promising as the GMM approach used in the earlier publication. In particular, the principal components of footprint shape, which are the concern of two half-pages of figures in the Domjanić et al.[7] paper, have nothing much to do with the findings reported there, findings that arose instead by regression of the full list of shape coordinates on the cause or effect of interest. The equivalent approach, in the analysis of the conventional measures, involved the production and then the discarding of that factor for »general shape«, which proved to correlate with BMI but with neither of the podiatric assessments, high heels or orthotics, that proved of further interest for our finding. (BMI also correlates with »sport«, meaning, we imagine, that feet that are pounded on become fitter and stronger, or perhaps that feet that are fitter and stronger are more conducive to sport, ballet, and the like.)

The lesson here is closely aligned with the take-home message of[17], which concluded that in any context of functional morphology there is no role for the principal components of shape that have hitherto proved so important in academic physical anthropology and paleoanthropology, and, furthermore, that when measurements of the shape coordinates can align with specific functional indices (such as how arch width via shape coordinates aligns with arch width via direct measurement on the footprint), it is of great importance that the biometrician carry out this explicit calibration as part of the formal analysis of any materials in front of her. This would recommend, at the least, specifying the semilandmark subscripts that correspond to the typical conventional arch width measurement, along with statements of the associated infelicities and difficulties. In the present context, for instance, note that arch width is measured at a diversity of positions along the foot axis, wherever the minimum is encountered, whereas in view of the mainly anteroposterior sliding of the semilandmarks in this vicinity only a »typical« or »average« location can be assigned in terms of a semilandmark scheme. In other words, to the extent that arch width is a particularly important measure of the foot, semilandmarks seem to be an inappropriate means of measurement. Analyses would better go forward in terms of the same notion (width at the juncture of minimum width) that characterizes the conventional approach, not the GMM toolbox.

This is not to claim that the GMM style of analysis is somehow to be subordinated as a matter of principle (or for any other reason). In the construction of the »general size factor« from the conventional measurements, the loadings on PC1 were not in fact uniform. This implies the presence of size allometry in the data set, and interpretations of this phenomenon go much better by diagrams of deformation than by tables of coefficients or loadings (see the icons on the horizontal axes of Figure 2 in[7]). The GMM approach has recorded positions of the toes, which are not part of the standard measurement set save for a classification in terms of the frontal profile of the foot (which toe is poking out the most). The analyses of BMI appear to be of roughly equal power in the two analytic contexts, and there is no denying the power of the GMM figures in drawing our attention to the conventional scalars (arch width, ball area) that actually convey the cause or effect at hand.

On the other hand, while both the conventional and the GMM approaches would benefit from an extension to three-dimensional data (so that the discussion and causal attribution of »fiat feet« could actually be accompanied by a measure of flatness), it would be quite difficult to quantify this height measure reliably in terms of any semilandmark. If arch height is important (and it probably is, given that there is a word for its inadequacy in particular cases), the study is likely to capture it better in terms of scalar measurements than semilandmarks. Furthermore, given the specific and unique role of the arch measurement in accounting for orthotic use, it would be a particularly efficient use of the investigator's time to pursue improvements of this measurement, in order to ascertain whether greater precision could be arrived at. Even if measurement of arch height actually requires a third dimension, inasmuch as arch height is also a strong conventional predictor of the need for orthotics (i.e. flat feet), then three dimensions we should have.

Even had its methodology been extended into three dimensions, the conclusion of the publication by Domjanić et al.[7] must be considered to be overstated. To declare that GMM »should be the method of choice for scientific research« is surely premature, inasmuch as GMM cannot handle other kinds of image-based input, such as evidence of gait or strain, and inasmuch as GMM has no machinery at present for the provenance of such simple and helpful measurements as minimum width or maximum height, the two crucial descriptors of arch form that intervene between the foot and the prescription for orthotics. In the literature of functional morphology there are general protocols for the complementary recourse to principal components versus localized features or residuals in a wide range of analytic contexts. Oxnard said it well in 1967:

> A series of features [of primate shoulders], chosen because of their association with the mechanically meaningful features of the musculature, have been found to vary (a) in association with the known contrasts in locomotion, and (b) in such a way as to render more efficient mechanically the associated muscular structure. Investigation of bony dimensions residual to such a study has shown that they are not highly correlated with primate locomotion but are, in contrast, associated with the commonly accepted taxonomic grouping of the order[10].

In other words, the information in the form relevant to function and the information relevant to taxonomy lie in complementary subspaces within the space of shape features. Principal components are for taxonomy, functional index construction for localization. A study can pursue both, but it needs to state clearly, at the outset, which hypotheses come under which set(s) of methods. As applied in the present context, Oxnard's point would be that the variation of these 166 adult female feet incorporate some functional aspects and some aspects that are not demonstrably functional, of which some are biologically determined (for instance, region of origin) while others represent simple measurement error. The specific variable that is high heels does not easily fit either pole of this dichotomy, but must be kept in mind anyway as an environmental perturbation (bearing more than the usual amount of Darwinian irony).

Such concerns for abusive footwear notwithstanding, to this distinction between the functional and the nonfunctional measurements correspond two general classes of statistical approach, one via regression residuals and other attempts at localization, the other via principal components and analogous attempts at generalization. A good study design, experimental or not, will carefully sort out these aspects at the beginning, ensuring, for instance, that when a clinical assessment is entailed, such as the need for orthotics in the present example, the observations the clinician is likely consulting should be part of the data base made available to him. If high heels are in fact part of the research, we must at least ask how high those heels are (and how tightly the shoes pinch, and so on). We need, in short, measures of the feet in the shoe, not only of the feet standing unshod: and those measures of shoes are very likely phrased in terms of the same conventional scalars, the measures inscribed on the lasts that are used to specify how much leather is required. When either channel, the GMM or the conventional, incorporates information that is not available from the other, then evidently a good study design involves the combination of information from both channels. It is that combination that, in an extension of the 2013 publication by Domjanić and colleagues, we have prototyped here.

Among the main tasks of footwear are protection, stability during standing, and pain-free locomotion that is efficient whenever it needs to be (e.g, during running). One could argue that the conventional measurements made after the model of the shoe last have almost nothing to do with any of these tasks. A plantar footprint might be adjudged far superior on these a-priori grounds, especially if it were modified for the different loading regimes of, e.g., standing versus walking versus jogging or playing tennis. Also, the last measurements do not quantify the insole and hence do not deal with the fit between insole and plantar foot shape. The morphometrics of the future might need to concentrate on imagery of the foot in action, not at rest (as in these studies), in order to more directly assess the mismatch between shoe and foot that most directly leads to pain. At the same time, it is clear that either data type, conventional or geometric, supports a statistical analysis that, all other differences aside, indicts the high-heeled shoe as the principal source of podiatric distress in this modern Croatian population. It is unclear if the goal of offering a greater variety of market-customized shoe lasts justifies the recourse to GMM when the basic conditions of the market are so paradoxical. The analogy of Virginia Slims cigarettes »for women« comes directly to mind here – an analogy that is not, of course, original with us.

## Conclusion

The concordance demonstrated in this paper bears implications for other branches of applied anthropology. The finding may not be newsworthy, but the concordance, we believe, is. To carry out a good biomedical analysis of applied anthropometric data it may not matter much whether one uses GMM or instead an adequate assortment of conventional measurements, as long as the conventional measurements were selected to match the natural spectrum of functional variation as clinicians and applied researchers have assessed the problem in the past. This is the way that shoe manufacturers, for instance, learned over the centuries to assess the variability of shoes in a manner matching salient dimensions of variability of their customers' feet. Choice of measurements, whether conventional (lengths, angles, circumferences) or geometric (landmark locations, boundary curves and surfaces), is an intrinsic part of good study design. Take adequate care of these information resources and the biometric analysis, if carried out according to competent statistical principles, may well lead to conclusions that are independent of particular content-neutral geometric or algebraic strategies.

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# ANALIZA ŽENSKIH STOPALA U DVA RAZLIČITA MJERNA SUSTAVA: OD GEOMETRIJSKE MORFOMETRIJE DO FUNKCIONALNE MORFOLOGIJE

## SAŽETAK

Odnos geometrijske morfometrije (GMM) i funkcionalne analize istih morfoloških izvora danas je tema za koju funkcionalni morfolozi pokazuju aktivni interes. Iako je GMM poznat kao nezavisan od prethodnih pretpostavki o značajkama oblika ili morfoloških teorija, njegova otkrića obično se podudaraju s nalazima studija koje se temelje na a priori popisima o karakteristika oblika kadgod su se prethodne spoznaje ili teorije pravilno uzete u obzir pri izradi studije. Ovaj rad pokazuje tu sretnu mogućnost tako da proučava prethodno objavljenu GMM analizu otisaka stopala za koje također postoje funckionalno relevantne informacije u obliku a priori mjerenja stopala. Pokazujemo kako konvencionalne mjere pretvoriti u jezik o obliku, čime su dobivene dvije paralelne statističke analize. Prva je klasična multivarijatna analiza »obilježja oblika«, a druga jednako klasična analiza geometrijske morfometrije (GMM) uz koordinate specifičnih točaka. U ovom primjeru, dva skupa podataka, iako su analizirana na dva značajno različita načina, geometrijski i algebarski, ipak imaju zajednički biometrijski sažetak: nošenje cipela s visokom petom loše je za žene jer za posljedicu ima potrebu za ortopedskim pomagalima kako bi se liječio spušteni stopalni luk. Ova podudarnost ima posljedice i za druge grane primijenjene antropologije. Da bi se provela dobra biomedicinska analiza primijenjenih antropometrijskih podataka može se reći da nije važno koristi li se GMM ili neki adekvatan izbor konvencionalnih mjerenja umjesto njega. Ono što je važno jest jesu li konvencionalne mjere odabrane tako da odgovaraju prirodnom spektru funkcionalne varijacije.