J Forensic Sci, Jan. 2003, Vol. 48, No. 1
Paper ID JFS2001337_481
Available online at: www.astm.org

Robert B. Kennedy[1]*; Irwin S. Pressman,*[2] *Ph.D.; Sanping Chen,*[3] *Ph.D.; Peter H. Petersen*[4]*; and Ari E. Pressman,*[5] *M.D., F.R.C.S.*

Statistical Analysis of Barefoot Impressions*

ABSTRACT: Comparison of the shapes of barefoot impressions from an individual with footprints or shoes linked to a crime may be useful as a means of including or excluding that individual as possibly being at the scene of a crime. The question of the distinguishability of a person's barefoot print arises frequently. This study indicates that measurements taken from the outlines of inked footprint impressions show a great degree of variability between donors and a great degree of similarity for multiple impressions taken from the same donor. The normality of the set of measurements on footprint outlines that we have selected for this study is confirmed. A statistical justification for the use of the product rule on individual statistical precisions is developed.

KEYWORDS: forensic science, footprint, barefoot impressions, convex hull, principal component analysis, product rule

To primitive man, barefoot impressions were important pointers to finding food (1). Early hunters became skilled at recognizing different animals from the shapes of their footprints. Human footprints could also be of interest at times. For instance, in his 15th year on the island, Robinson Crusoe (2) saw a human footprint in the sand. When he measured it against his own foot he found the print to be much larger.

> "It happened one day, about noon, going towards my boat, I was exceedingly surprised with the print of a man's naked print on the shore, which was very plain to be seen in the sand. I stood like one thunder-struck, ..."

In a forensic context, the comparison of the morphology, or shape, of barefoot impressions has been used previously in criminal investigations (3,4) and in the courtroom (5,6). Masson (5) describes a murder case where there were seven barefoot prints (five well-defined) of a right foot in the blood near the body. The feet of the suspects were soaked in a gummy fuchsine (bluish-red) ink, and they walked eight to ten steps along a paper. Not every print was used. Seven of the original eight suspects were cleared immediately by their footprint measurements. The eighth suspect was exonerated when the fine details of the print were compared and the court agreed that the suspect could not have made the bloody prints.

The purpose of the research here is to study the outlines of footprints of persons walking normally, to investigate whether one can prove that different people make verifiably distinct footprints. To support this hypothesis, a database of footprint outlines was gathered to provide a statistical basis for deciding whether the outlines of footprints of various people walking are distinguishable. This is more challenging than studying static prints of people standing or sitting, and there are several reasons for this choice.

There is interest in the forensic aspects of footprints because footprints of people walking, both with and without shoes, are frequently found at a crime scene. Furthermore, the impression that can be retrieved from the insole of a shoe can be easily compared to barefoot impressions of the walking foot. The inked walking impression and the insole impression exhibit a slight difference: the large toe may flare out to the side on the inked impression in some instances. However, the overall weight-bearing areas are similar. When walking both on paper and on the insole of a shoe, the toes grip the surface area of the paper and the insole. People push off with their toes during the toe-off phase of gait. This is evident when comparing the indented impressions on the insole and the wear marks on the outsole of the shoe. In hundreds of shoes tested by the principal author, the inked impression has conformed to the impressions on the insole of the shoe.

Sources of Variation in Walking

Walking is a cyclic process of human locomotion that requires at least one foot to be on the ground at all times. During the stance phase, the foot passes through processes of heel strike, foot flat, heel off, and toe off, during which time it leaves a footprint. This print represents the sum of the contact and acceleration phases through which the foot passes. The ground contact information can change significantly during the type of locomotion between running and walking, but the imprint that the foot makes during walking has reproducible characteristics. The bones of the foot alter in position during gait with different ligaments and muscles becoming taut at different times during the gait cycle. The osseous alignment, and thus the footprint made during locomotion, is dynamic and difficult to model because it is not a static model.

[1] Forensic Identification Research Services, Royal Canadian Mounted Police, Ottawa, Ontario K1A 0R2 Canada.
[2] School of Mathematics and Statistics, Carleton University, Ottawa, Ontario K1S 5B6 Canada.
[3] Business Survey Methods Division, Statistics Canada, Ottawa, Ontario K1S 1A1 Canada.
[4] Forensic Identification Research Services, Royal Canadian Mounted Police, Ottawa, Ontario K1A 0R2 Canada.
[5] Department of Orthopaedics, Mt. Sinai Hospital, Toronto, Ontario M5G 1X5 Canada.
* This research was supported by grants from the Canadian Police Research Centre.
Received 3 Oct. 2001; and in revised form 8 March 2002 and 21 July 2002; accepted 24 July 2002; published 11 Dec. 2002.

Abnormal gait patterns can be caused by multiple factors. A characteristic gait pattern develops in an individual on the basis of osseous anatomy and the coordination of a series of muscle groups involved in locomotion. Neurologic conditions can alter gait by producing muscle weakness, loss of balance, muscle contracture, or ataxic gait patterns. Carried loads, weight change, the use of canes, pregnancy (7), ill health, pain, or injuries such as fractures can have measurable effects on a footprint. Over or under inking, stretching of the skin, or deliberate attempts to walk abnormally may affect the print. There may be other sources of variation whose causes are not known. Ideally, one would prefer to identify characteristics that do not change.

Distinguishability of Human Footprints

Although this study is statistical in nature and based on precise measurements, the actual forensic examination is based on a comparison of the contours, shapes, and placements of parts of the foot, and the conclusion depends on the fact that the bare feet of individuals show a high degree of individuality. The distinguishability of human footprints was often assumed in early casework (8–10). We assume the absolute uniqueness of each print, that is, no two prints, even from the same individual, will ever be exactly identical.

We formulate this basic hypothesis: given a footprint outline trace made by Subject A (Alice), then Subject B (Bob), a distinct person, cannot produce a footprint outline trace indistinguishable from that of Alice.

Footprint Measurements

Early footprint research examined general characteristics such as the relationship between foot length and height. Topinard estimated that on average a person's footprint length was equal to 15% of a person's height (11). Robbins (12) measured the foot length of 550 subjects as the maximum distance from the heel to the tip of whichever toe gave the longest measurement. Gordon and Buikstra (13) analyzed the statures and foot lengths and widths of 867 soldiers in a combat boot-fitting study. Barker and Scheuer (14) investigated the Topinard estimate by collecting data from 105 seated and walking subjects.

Baba (15) studied 826 males and 1018 females to prove that there were significant differences in the ratios of breadth (i.e., ball width) to foot length and ball girth to foot length between French and Japanese populations. The length of the foot was determined to be the distance from the most posteriorly projecting point on the heel to the anterior tip of whichever toe gave the longest measurement. Hawes et al. (16) studied ethnic differences between 513 Asian and 708 North American males. Their method of measurement was to have all of the weight on the right foot, while the left was on a platform raised 25 cm higher. Calipers were used to measure the distance from the pternion to the tip of each toe, recording foot length as the maximum such measure. Breadth was measured between the first and fifth metatarsals in a plane perpendicular to the long axis of the foot. The reliability of foot measurements of 1197 Canadian subjects was studied as well (17). Kouchi and Mochimaru undertook a thorough study of 5000 Japanese footprints (18,19). They proved that there was a significant distinctive out-flaring of the Japanese foot, with a mean flexion angle of 8.4°.

Baba (15) discussed the challenge of making consistent foot measurements. The unreliability of standard footprint measurements was illustrated by Cobey and Sella (20). Measurements of talocalcaneal angles on radiographs have been shown to have no precision. The fact that the height of the arch and the foot length change as the tibia rotates was demonstrated by radiographic means. Kouchi and Mochimaru (18,19) scanned traces of feet into a computer database and used automated tools for the measurements. In order to avoid problems that arose in the toe region, the convex hull of this region was used to replace the actual trace.

The forensic view of the individuality of feet has been studied by Robbins (21), Qamra et al. (22), Laskowski and Kyle (23), Kennedy (24,25), and Barker and Scheuer (14). Robbins suggested that, from the viewpoint of anthropology, individuals would have unique footprints, using differing impressions of adult twins to reinforce this claim. Qamra et al. produced probability estimates for their studied population. Laskowski and Kyle used ratios of measurements to develop probabilities that a subject had made a particular impression.

This paper is a continuation of Kennedy's earlier work, where manual linear measurements of inked impressions were collected. These measurements were compared using a database program.

The human foot contains ridge detail similar to that found on a fingerprint. In this study, however, only the shape and placement are studied, since recovered barefoot impressions rarely show ridge detail. Medical researchers (15) define the breadth of a foot as the distance from the medial margin of the head of the first metatarsal bone to the lateral margin of the head of the fifth metatarsal bone, measured with calipers. Radiographic examination can provide further landmarks (20,26).

Our data consist solely of the inked impressions of the plantar surface. Successful systematic comparison here must be based on quantitative measurements derived from footprint outlines against a background of their inherent variation.

Barker and Scheuer (14) consider the issue of inter-rater reliability, i.e., do different observers obtain the same set of measurements from the same footprint? Mochimaru and Kouchi (18) found that the error in measuring flexion angles was halved by moving to automated measurements. Based on the experience of others and the anticipated volume of future work, machine-based measurements were used in this study.

A fundamental question is whether or not any two people can make indistinguishable footprint impressions. The stability of footprint measurements for the same individual and the variation for different individuals are addressed here.

Methods

Data Collection

There were two phases in this study. First, a collection of barefoot impressions from ($n = 960$) Caucasian males was analyzed to establish the normality of the probability distributions of the foot impression measurements in the general population. This gave a probabilistic structure for this study. This database did not contain many of the measurements added at the next phase. Barefoot impressions were collected from adult volunteers from the general population in shopping malls, office buildings, colleges, etc.

An inkless pad (Identicator) and special chemically-treated paper were used. Each person was instructed to walk normally and to step onto the pad with one foot and then onto the paper with the next step of the same foot. The procedure was then repeated with the other foot to produce one pair of impressions on each sheet of paper (Fig. 1). Each impression was scanned using an Epson GT10000 scanner set at 72 dpi. The two statistical packages used for the analyses were SAS version 8 and SPSS 7.5.

The second phase was a repeated-measure experiment for studying the critical issue of intra-personal (individual) variations of the footprint measurements. The magnitudes of the variations between different footprints of the same individual are contrasted to the interpersonal (population) variations.

This experiment has a full factorial design with two factors. First, 20 subjects (11 male and 9 female) were randomly selected. Three sets of barefoot impressions were collected daily from each subject over a three-day period. Finally, the same experienced graphic artist traced each set of barefoot impressions. Each trace was scanned and the data passed to an automated graphics program running under AutoCAD R13.

Alignment and Measurement Definitions

There are different approaches in the literature for the choice of the correct alignment of the footprint. In static experiments or radiographs, there are anatomical landmarks that can be readily identified, e.g., the metatarsal heads, the calcaneus, and the maleoli. Such measurements could not be performed on a walking foot. The data in this study are restricted to the impression of the plantar surface of the walking foot on paper.

The scans of many prints were analyzed and numerous instances were found where the precise pixel to choose for the heel point of the print was ambiguous. There was even more choice regarding the appropriate pixel on the scanned picture of the footprint that gave the most appropriate point for measurement of length. Each alternative led to different measurements. The robustness of measurements was determined by whether successive prints by the same subject gave the same or similar results. A 1° change in choice of orientation was sufficient to produce observable differences in length and width.

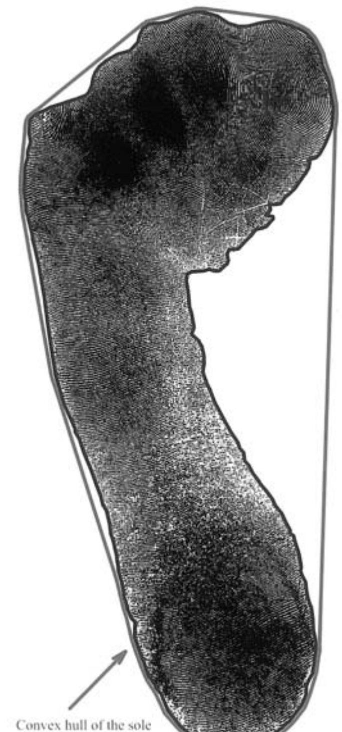

FIG. 2—*The convex hull of the sole.*

FIG. 1—*Typical footprint impressions collected from a volunteer.*

The Enveloping Cone and the Central Axis of the Foot

A new measure introduced here is proposed as being appropriate for the walking footprint environment. The *convex hull* of a set of points on the plane is the polygon of smallest area that contains these points; it is unique. The convex hull is frequently used in computational geometry (27) and biology.

The footprint tracing was considered as a two-dimensional shape. The convex hull of the sole (Fig. 2) of the foot was found, and successive segments joining adjacent pairs of pixels of the convex hull were found. The line segment of maximal length on each side of the sole was selected. It is a special feature of the footprint that there is always a significantly longest segment of the boundary of the cone on each side of the sole.[6] These lines were projected to meet at the apex of an *enveloping cone* (Fig. 3) located below the heel. In future work, we intend to compare the cone angle with the angle between the first and fifth metatarsal heads. Caussé (5) and Masson (6) used the tangent line to the interior side (e.g., left side of the right foot) as the basis of their geometric measurements.

The *central axis* of the footprint outline is defined as the bisector of the tangent cone, i.e., the line bisecting the cone angle through the apex. The outline of the footprint is rotated so that the central axis is vertical with the apex at the bottom. Note that the central axis is not the medial axis (18,28). However, it has proven to be a reliable alternative and many other measurements depend on it.

[6] The software excluded the middle third of every foot. This gave the correct answer in all the normal instances and provided meaningful results for rare instances of exceptionally flat feet.

The Metatarsal Ridge

The *metatarsal ridge* is defined here as the ridge that separates the ball of the foot from the toe pads. It is the best-defined portion of the footprint. The five metatarsal heads form five semicircular bumps at different heights to make up this curve. In anatomical terms, the metatarsophalangeal articulations are the junctures formed by the reception of the rounded heads of the metatarsal bones in articular cavities on the ends of the first phalanges (29). There is an associated crease as the foot bends (30).

The sole of the foot is defined to be the plantar impression minus the toes. Toe stems found in prints were removed by a trained graphic artist to give a continuous metatarsal curve beneath the toes. The remainder of the ridge and the shading of the print were incorporated to make the best possible approximation.

The tangent cone was found using a recursive method, and the print rotated so that the central axis, e.g., the bisector of the cone, was vertical. The *center of the left heel,* LC1, is the intersection of the central axis with the line joining the two points of tangency of the tangent cone to the heel at LBI and LB2[7] (Figs. 3 and 4). The right heel was treated similarly. We investigated the use of the triple point of Kouchi and Mochimaru (19), but the center of the heel was found to be a more stable indicator over repeated measurements.

Each tracing was scanned and converted to vector format. There are twelve polyline tracings on each pair of feet, ten for the toes and two for the ball of the feet. All measurements are made on the polylines using AutoCad 13 and the AutoLisp programming language. For example, when the polyline describing a toe is identified, an AutoLisp function finds its center of gravity to locate the center of the toe. LD1X and LD1Y give the X and Y coordinates of the center of the big toe on the left foot. The center of the heel is determined by the location where a straight polyline between the two locations where the enveloping cone touches the heel, crosses the central axis of the foot. LD1 (Table 1) measures the distances from the center of the heel to the center of the big toe and is one of our 38 (Left) variables.

In total, $180 = 20 \times 3 \times 3$ sets of numerical measurements for each foot were collected in the repeated measurements phase. Approximately 200 different measurements were taken from each tracing of every barefoot impression (see Table 1 for a partial list). The degree of similarity in the instance of two tracings of the same subject on two different days given in Fig. 5 is not exceptional. Our database has 323 fields. Some measurements depend on the foot length (e.g., foot width at 1-cm intervals), so some fields can be empty. Some fields are not measurements (e.g., sex). The measurements were divided into five groups:

- foot measurements (lengths, widths, LD/RD, LE/RE, LF/RF, LG/RG, etc. (see Table 1 for definitions)
- F-points (coordinates of points of metatarsal ridge, toes, etc.)
- L-points (widths of slices orthogonal to the axis, etc.)

[7] Our notation consistently uses L to denote locations or measurements on the left foot, and R for the right.

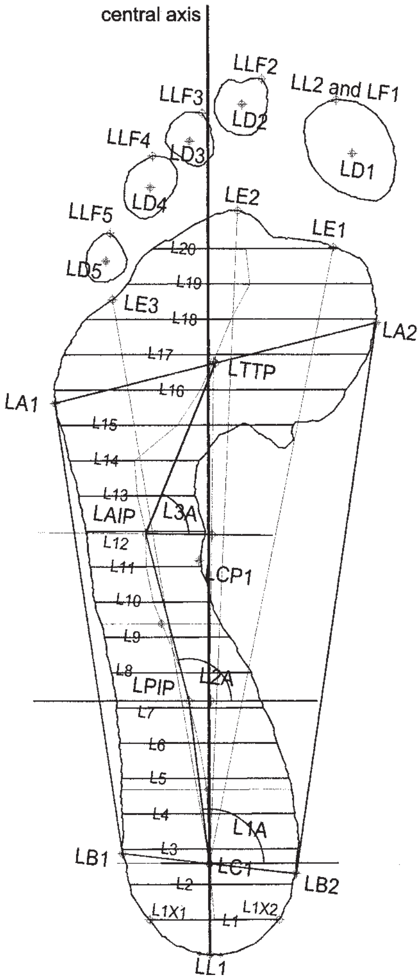

FIG. 4—*Some of the points measured on the outline of the foot.*

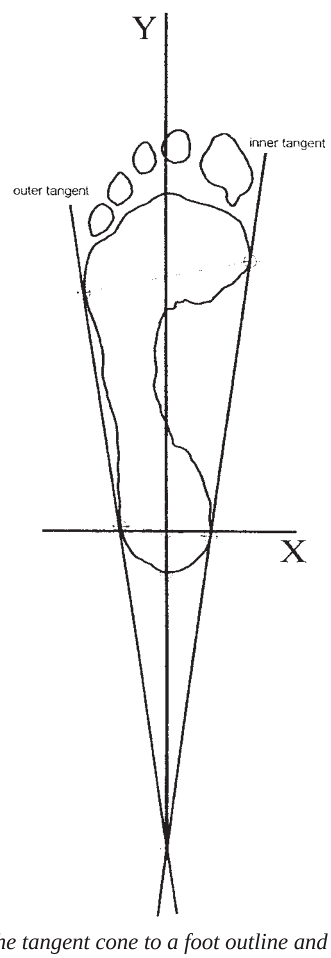

FIG. 3—*The tangent cone to a foot outline and the central axis.*

TABLE 1—*Field names, their location, and definitions.*

LLength	length of foot, from bottom of heel to tip of toe giving the greatest measurement
LBWidth	width of ball of foot
LHWidth	width of heel
LD1	center of heel to center of 1st toe
LD2	center of heel to center of 2nd toe
LD3	center of heel to center of 3rd toe
LD4	center of heel to center of 4th toe
LD5	center of heel to center of 5th toe
LE1	bottom of heel to 1st metatarsal head
LE2	bottom of heel to 2nd metatarsal head
LE3	bottom of heel to 5th metatarsal head
LF1	bottom of heel to center of 1st toe
LF2	bottom of heel to center of 2nd toe
LF3	bottom of heel to center of 3rd toe
LF4	bottom of heel to center of 4th toe
LF5	bottom of heel to center of 5th toe
LG1	center of heel to 1st metatarsal head
LG2	center of heel to 2nd metatarsal head
LG3	center of heel to 5th metatarsal head
LDBA1	length of the outer side tangent to the foot
LDBA2	length of the inner side tangent to the foot
L1A	angle between horizontal and a line draw between C1 and PIP
L2A	angle between horizontal and a line draw between AIP and PIP
L3A	angle between horizontal and a line draw between AIP and TTP
LABA1	angle between horizontal and the outer tangent
LABA2	angle between horizontal and the inner tangent
LD1A	area of first toe
LD1P	perimeter of first toe
LD2A	area of second toe
LD2P	perimeter of second toe
LD3A	area of third toe
LD3P	perimeter of third toe
LD4A	areaof fourth toe
LD4P	perimeter of fourth toe
LD5A	area of fifth toe
LD5P	perimeter of fifth toe
LCENA	area of foot minus the toes
LCENP	perimeter of foot minus the toes

- areas (toes, soles)
- angles

An analysis of variance (ANOVA) was conducted for all variables in order to estimate different variance components, in particular the individual and the population variance.

The 20 subjects selected for our repeated measure study were treated as a randomly selected sample of the general population.[8] This permitted the analysis of the data as a two-way random-effects model (variance-components model) with two main variance components: the "personal effect" and the "daily effect." For each quantitative measure, the variance of the former σ_P^2 represents the *interpersonal* (i.e., population) variance (Fig. 6), and the variance of the latter σ_I^2 is the *intrapersonal* (i.e., individual) variance (31).[9]

The square roots of these two variance components give the corresponding standard deviations σ_P and σ_I. These can be estimated from classic analysis of variance (ANOVA). The standard deviations help determine the size of the *tolerance window*. This window is called a *bin* in variable number of tandem repeat (*VNTR*) DNA

[8] Data gathering for a trial with over 500 subjects is currently underway.

[9] It is noteworthy that in their nineteenth century research, Caussé investigated the within-person variability of geometrical measurements, and Masson (6) considered the between-person aspect.

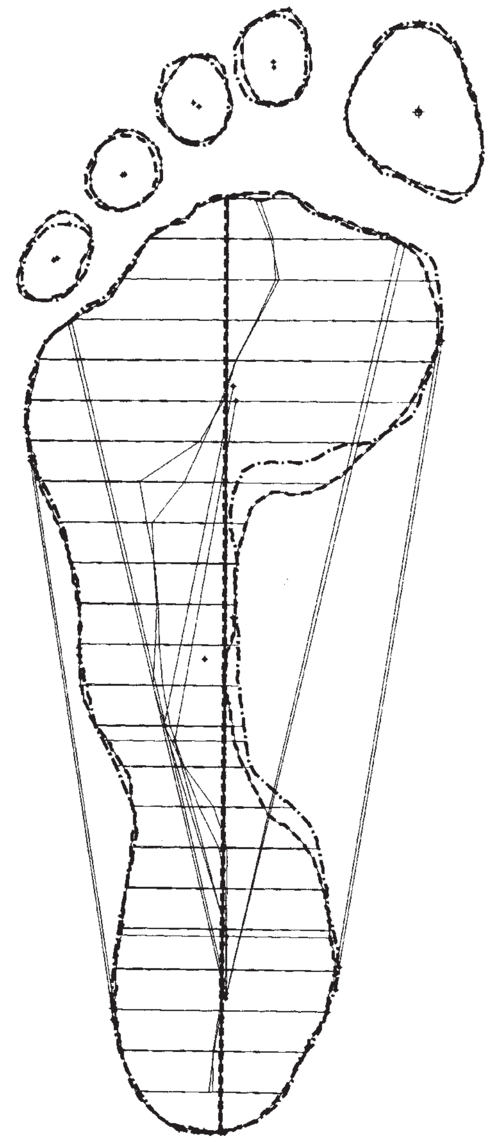

FIG. 5—*An overlay of two oriented foot outlines from the same person taken on successive days.*

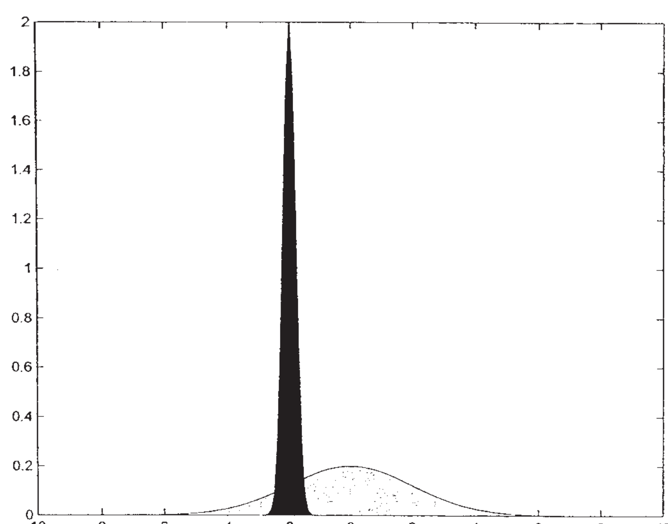

FIG. 6—*Two normal distributions with the standard deviation ratio equal to 10. The narrow peak represents the individual distribution; the wide one represents the population distribution.*

profiling. The size of this window determines the chance match probability.

To include an individual based on a quantitative measure, the size of the tolerance window should be sufficiently wide relative to the individual variation or standard deviation σ_I to insure a substantive probability that repeated sample measurements from the same individual would fall into the window. On the other hand, in order to minimize the probability of random matching of a wrong individual, the size of the tolerance window should be sufficiently narrow with respect to the population variation or standard deviation σ_P, so that it covers only a small percentage of the general population.

The Standard Deviation Ratio

The ratio of the two standard deviations, σ_P/σ_I, is called the *standard deviation ratio*. The standard deviation ratio indicates the fraction of the total population distribution of a single measure, such as foot length, that is covered by the individual variation. The larger the standard deviation ratio, the more useful the measure and the more accurate the match using this measure. Figure 6 illustrates the distinction between the population and individual variations using the normal distribution, when $\sigma_P/\sigma_I = 10$, for one single measurement, e.g., LBWIDTH. The broad distribution represents the population; the narrow one represents the much smaller variation that one individual might have for this measure. A large standard deviation ratio clearly indicates a small overlap of the individual variation with that of the population.

Results

The General Population: Normality of Measurements

Many elementary statistics texts state that quantitative measurements in physical anthropology, e.g., height of a human male population, tend to have a normal distribution. Using a data set of 960 Caucasian males, the normality of the 38 quantitative measurements derived from barefoot impressions of each foot was verified. Many of the variables and control measurements compiled in the second phase are not studied here because they were not gathered in the pilot study. Hence, we restrict ourselves to the 38 measurements from the pilot study. Most of the collected quantitative measurements closely follow the normal distribution. The normal probability plots of variables LLENGTH and LBWIDTH are given in Fig. 7 as examples demonstrating this close fit.

For variable LLENGTH, the Shapiro-Wilk statistic is 0.9990 with a *p*-value of 0.8779 (Cramer-von Mises statistic = 0.0186, $p > 0.2500$); for variable LBWIDTH, the Shapiro-Wilk statistic is 0.9982 with a *p*-value of 0.4289 (Cramer-von Mises statistic = 0.0494, $p > 0.2500$). These results confirm the hypothesis of normality for our measurements. On the basis of these results, a normal probability distribution for the quantitative measurements derived from barefoot impressions was assumed.

Repeated-Measure Experiment

This experiment is a crucial part of this study. Table 2 gives a summary of the estimated individual and population variances, as well as their ratio, for a number of selected measurements. For easier discussion, the square root of the estimated variance ratio, or the ratio of the estimated individual and population standard deviation, are also tabulated.

It is apparent that the majority of the variables have an estimated standard deviation ratio of 10 or greater. In other words, the estimated population standard deviation is at least 10 times as great as that of the individual standard deviation. This is an important finding of this study and illustrates the utility of using barefoot impressions for forensic examination.

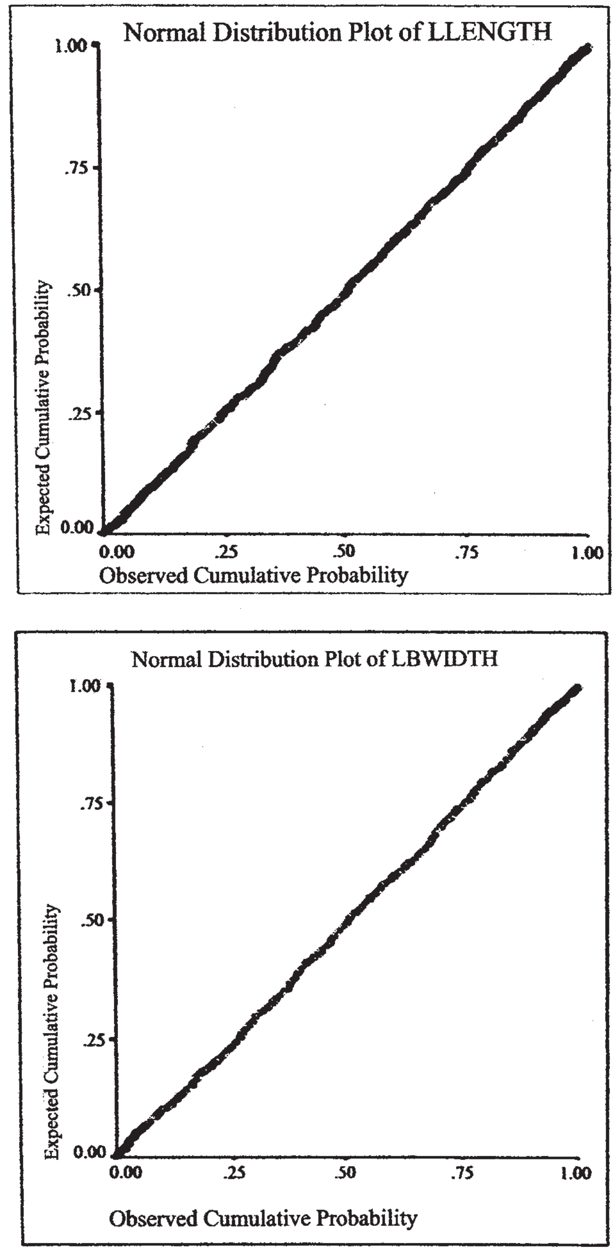

FIG. 7—*The normal probability plots of LLENGTH and LBWIDTH to illustrate the fit of the data to the assumption of normality.*

Implications of the Repeated-Measure Experiment

When comparing impressions, the tolerance window may exclude a number of impressions from an individual, as long as there is a reasonable likelihood of establishing a match from some of the many samples. Thus, a narrow tolerance window was chosen that, on a single measurement on average, covered 25% of all the impressions from the same person. It is apparent from Fig. 6 that a narrow tolerance window around an individual mean excludes a great proportion of the other persons in the population. We experimented with various tolerance window sizes and found that 25% sufficed in that we made the match and excluded false positives.

TABLE 2—*Individual and population variance of selected footprint measurements.*

Variable Name	Estimated Population Mean	Estimated Population Variance σ_P^2	Estimated Individual Variance σ_I^2	Estimated Variance Ratio σ_P^2/σ_I^2	Estimated Standard Deviation Ratio σ_P/σ_I
LLength	249.95	370.76	1.507	246.0698	15.6866
LBWidth	89.73	68.71	0.549	125.1583	11.1874
LHWidth	51.41	26.14	0.0549	476.3703	21.8259
LD1	204.67	244.78	2.110	116.0179	10.7712
LD2	208.91	264.90	0.980	270.2762	16.4401
LD3	200.31	229.91	0.896	256.5396	16.0169
LD4	187.42	173.50	0.926	187.3437	13.6874
LD5	170.28	136.79	0.842	162.5051	12.7478
LE1	207.39	229.49	1.075	213.5161	14.6122
LF1	249.62	371.41	1.155	321.5254	17.9311
RLength	250.65	382.91	2.415	158.5673	12.5924
RBwidth	88.70	64.98	0.486	133.6458	11.5605
RHwidth	51.80	25.18	0.330	76.2563	8.7325
RD1	204.73	287.05	1.250	229.5690	15.1515
RE1	207.28	262.56	2.605	100.7868	10.0393
RF1	250.58	382.34	2.550	149.9594	12.2458
LL2Y	248.23	356.37	1.456	244.7124	15.6433
LA1X	−42.99	14.92	0.135	110.4514	10.5096
RL2Y	177.60	367.21	2.479	148.1116	12.1701
RA1X	−42.68	13.29	0.1728	76.9040	8.7695
L2X1	−23.27	3.44	0.01928	178.5300	13.3615
L2X2	23.47	3.40	0.01827	186.3075	13.6495
R2X1	23.38	3.07	0.01538	199.5072	14.1247
R2X2	−23.45	4.61	0.00402	1147.9110	33.8808
LCENA	10266.85	4116122	10508.93	391.6784	19.7909
RCENA	10228.62	4132702	13903.22	297.2478	17.2409
LD3A	190.95	2567.87	10.837	236.9542	15.3933
RD3A	191.90	2931.00	11.979	244.6721	15.6420
LABA1	1.71	0.000342	4.81E-07	711.4339	26.6727
RABA1	1.71	0.000266	1.14E-06	232.6409	15.2526
LABA2	1.43	0.000342	4.8E-07	712.7149	26.6967
RABA2	1.44	0.000266	1.14E-06	232.1963	15.2380
LANGLEAB	0.28	0.001369	1.95E-06	701.3948	26.4839
RANGLEAB	0.27	0.001063	4.57E-06	232.5055	15.2481

The narrowness of the tolerance window requires additional discussion. This choice was motivated primarily by two facts reflecting the rather special situation concerning the use of barefoot impression in forensics.

First, the variability in the process is difficult to control during the acquisition of the samples due to the reasons listed in the Sources of Variation in Walking section above. Barefoot impressions demonstrate a higher level of intra-personal variability than, for instance, RFLP DNA typing. Not all barefoot impressions collected are of good quality and usable in the forensic context. Second, the acquisition of barefoot impression samples is a straightforward, simple, low-cost process compared to other sophisticated, high-tech forensic procedures. Hence we can have many repeated impressions available for study.

The conjunction makes it both desirable and practical to adopt a narrow tolerance window to exclude a substantial proportion of the data acquired from the subject (or suspect) to control the variability of the process. We appreciate the variability of the process, yet still we will always be left with an adequate number of samples for purposes of comparison for a possible identification.

In the historical papers, we noted earlier that not all data were used. Similarly, when the principal author collects footprint data for a criminal investigation, many prints are taken from the same individual. The subject's bare feet are inked before he/she walks on one side of a 12 by 3-ft length of paper and returns on the other side. Only prints not distorted by the person turning at the end of the paper and only those that are fully formed are considered. Frequently up to 50% of the prints are discarded as being of insufficient quality to afford a good comparison. The remaining prints are compared to each other to ensure that they have the same weight-bearing characteristics. This is usually the case.

We unreservedly want to rule out a false positive identification even if it means excluding the prints of the guilty party. Nonetheless, given the inherent intra-personal variation, a mismatch by one impression does not invalidate a match by another impression from the same individual. All that is required is a single print that makes the identification, because there is an almost zero probability that any other person could make that impression.

The likelihood of finding the same individual from among many depends on the number of measurements used. Since the measurements chosen are unique to the same individual, while subject to random variation in the general population, the scheme described here gives a very good chance of finding a particular person. The narrow tolerance windows greatly reduce the probability of chance matches with other individuals in analyzing the repeated sample. We have noticed in studying repeated measurements of the same foot that when one of the main measures such as LLENGTH falls within the tolerance window there is a high likelihood that most of the other measurements will fit also.

A chance match depends on the number of variables used and the standard deviation ratio of each variable. From Table 2, many of the measurements with an estimated standard deviation ratio of 10 or more can each provide a worst-case chance match probability of 2 to 3%. However, since these variables may be statistically correlated with each other, one cannot simply multiply the individual chance match probabilities when multiple measurements are used for identification. Nonetheless, classic statistical methods, such as principal component analysis (PCA), permit statistically independent measurements to be extracted from a set of possibly correlated variables (32). This method of generating new orthogonal variables for personal identification is the basis for the eigenface method of human facial identification (33).

A principal component analysis was performed on the first 38 of the 200 measurements on the barefoot impressions. The first five principal components (corresponding to orthogonal eigenvectors) were extracted. The orthogonality guarantees that the correlation between any two principal components is always zero. As Table 3 demonstrates, the first five principal components account for approximately 97% of the total variance of the 38 variables.

A variance component analysis was performed to estimate the standard deviation ratios of these new rotated and statistically independent variables. The estimated standard deviation ratios for the five principal components are, respectively, 14.11, 25.00, 12.76, 14.63, and 25.00.[10] All five principal components have an estimated standard deviation ratio greater than 10 or equivalently an individual statistical precision of less than 0.0254 (see Table 3). Thus, based on our data, barefoot impressions show a high degree of individuality, as the probability of a chance match is less than one in one hundred million ($0.254^5 \times 10^{-8}$).

Using the measurements selected in this phase, at least five principal components (new statistically independent variables transformed from the original variables) were identified with an estimated standard deviation ratio of 10 or greater. In future continuing work, there are plans to analyze the remaining variables plus further nonlinear *shape variables*, e.g., Fourier descriptors and spline coefficients. These are more numerous and may also have even greater population-to-individual standard deviation ratios. The final worst-case chance match probabilities may match those noted in DNA profiling.

[10] Based on maximum-like estimation (MLE), the variance component estimate for individual variation is zero, meaning that the estimated standard deviation ratio is in fact infinity. Here 25 is a conservative alternate estimate.

TABLE 3—*Principal component analysis results.*

Component	Sums of Squared Loadings	% of Variance Explained	Cumulative % of Variance	Estimated s.d. Ratio
1	15.48	41.85	41.85	14.11
2	10.44	28.21	70.06	25.00
3	5.58	15.08	85.14	12.76
4	3.31	8.96	94.10	14.63
5	1.02	2.77	96.87	25.00

TABLE 4—*Maximum chance match probabilities using a single measure and a 25% tolerance window.*

Standard Deviation Ratio	Maximum Chance Match Probability
6:1	0.0423
8:1	0.0317
10:1	0.0254
12:1	0.0211
15:1	0.0169
20:1	0.0127

Table 4 illustrates the chance match probability for various standard deviation ratios based on the normal distribution. These probabilities provide the calculation basis for previously discussed statistical precision. Note that the maximum chance match probability shown occurs only when the individual happens to have the same mean measure as the general population. If a measurement is significantly different from the population mean, the chance match probability can be much smaller. In addition, the above table is for comparison using a single measure. When multiple measurements are used, as is normally the case, the chance match probability can be made extremely small, as indicated above.

Discussion

This preliminary study provides the first step towards confirming that, with high statistical precision, barefoot impressions are extremely individual. Using principal component analysis, five orthogonal components have been identified that permit the legitimate five-fold application of the product rule on their individual statistical precision in matching footprints. All five principal components have an individual statistical precision of less than 0.0254; so, based on the population from which our sample comes, barefoot impressions show a high degree of individuality. The probability of a chance match is less than 0.0254^5, or 1:100,000,000. Larger samples will be collected to corroborate these results as the low probability is related to the tolerance windows used.

In summary, a systematic method has been developed for orienting inked footprint impressions and making measurements on them. The normality of these measurements was verified. The repeated measurement study has established the theoretical basis for using barefoot impressions for forensic examination by demonstrating the small intra-personal versus interpersonal standard deviation ratio of many footprint measurements.

Acknowledgments

The authors wish to thank all those individuals who volunteered their barefoot impressions for this study. J. D. Schneider wrote most of the software supporting this research. The authors are grateful to Brian Yamashita for his careful reading and critical improvements to the manuscript. The authors are also grateful to the anonymous referees for their suggested improvements.

References

1. Ostrum JH. Were some dinosaurs gregarious? Paleog Paleoclimat Paleocol 1972;11:287–301.
2. Defoe D. Robinson Crusoe, the life and strange surprising adventures of Robinson Crusoe, of York, mariner. London: W. Taylor, 1719.
3. Kennedy RB. Bare footprint marks. In: Siegel JA, Saukko PJ, Knupfer GC, editors. Encyclopedia of forensic sciences, Vol. 3. London: Academic Press, 2000;1189–95.
4. Bodziak WJ. Footwear impression evidence. Boca Raton: CRC Press, 2000;381–411.
5. Caussé S. Des empreintes sanglantes des pieds, et de leur mode de mensuration. Annales d'hygiène publique et de médicine légale, 1854;1(Janvier):174–89.
6. Masson Dr. Contributions à l'étude des empreintes en médicine légale. Annales d'hygiène publique et de médicine légale, 1886;16(Juillet):336–45.
7. Foti T, Davids JR, Bagley A. A biomechanical analysis of gait during pregnancy. J Bone Joint Surg 2000;82:625–32.
8. Anon. Donald Delbert KETT and William Chester KETT. RCMP Gazette 1949;11(11):17–20.
9. Hofstede JC. Convicted by his shoes. RCMP Gazette 1965;27(2):6–11.
10. Cassidy MJ. Footwear identification. Ottawa: Canadian Government Printing Centre,1980.
11. Topinard P. L'Anthropologie, Vol 1. 2nd ed. Paris: Reinwald, 1877.

12. Robbins LM. Estimating height and weight from size of footprints. J Forensic Sci 1986;31:143–52.
13. Gordon CC, Buikstra JE. Linear models for the prediction of stature from foot and boot dimensions. J Forensic Sci 1992;37:771–82.
14. Barker SL, Scheuer JL. Predictive value of human footprints in a forensic context. Med Sci Law 1998;38:341–6.
15. Baba K. Foot measurement for shoe construction with reference to the relationship between foot length, foot breadth, and ball girth. J Human Ergol 1975;3:149–56.
16. Hawes MR, Sovak D, Miyashita M, Kang SJ, Yoshihuku Y, Tanaka S. Ethnic differences in forefoot shape and the determination of shoe comfort. Ergonomics 1994;37(1):187–96.
17. Hawes MR, Sovak D. Quantitative morphology of the human foot in a North American population. Ergonomics 1994;37(7):1213–26.
18. Kouchi M. Analysis of foot shape variation based on the medial axis of foot outline. Ergonomics 1995;38(9):1911–20.
19. Mochimaru M, Kouchi M. Automatic classification of the medial axis of foot outline and its flexion angles. Ergonomics 1997;40(4):450–64.
20. Cobey JC, Sella E. Standardizing methods of measurement of foot shape by including the effects of subtalar rotation. Foot and Ankle 1981;2(1): 30–6.
21. Robbins LM. The individuality of human footprints. J Forensic Sci 1978;23:778–85.
22. Qamra SR, Sharma BR, Kaila P. Naked foot marks—a preliminary study of identification factors. Forensic Sci Int 1980;16:145–52.
23. Laskowski GE, Kyle VL. Barefoot impressions—a preliminary study of identification characteristics and population frequency and their morphological features. J Forensic Sci 1988;33(2):378–88.
24. Kennedy RB. Preliminary study on the uniqueness of barefoot impressions. Can Soc Forens Sci J 1996;29(4):233–8.
25. Kennedy RB. Uniqueness of bare feet and its use as a possible means of identification. Forensic Sci Int 1996;82:81–7.
26. Mann, RA, editor. DuVries surgery of the foot. 4th ed. St. Louis: C. V. Mosby Co., 1978;57.
27. Preparata FP, Shamos MI. Computational geometry. New York, Berlin: Springer-Verlag, 1985.
28. Sokal RR, Rohlf FJ. The principles and practices of statistics in biological research. San Francisco: W. H. Freeman, 1995.
29. Johnston TB, Davies DV, Davies F. Gray’s anatomy. 38th ed. London: Longman and Green, 1958.
30. Mann RA, editor. DuVries surgery of the foot. 4th ed. St. Louis: C. V. Mosby Co., 1978;19.
31. Scheffé H. The analysis of variance. New York: John Wiley and Sons, 1959; 221–44.
32. Jolliffe IT. Principal component analysis. New York: Springer, 1986.
33. Turk M, Pentland A. Eigenfaces for recognition. J Cognitive Neuroscience 1991;3(1):71–86.

Additional information and reprint requests:
Sgt. Robert Kennedy
Royal Canadian Mounted Police
Forensic Identification Research Services
1200 Vanier Parkway
NPS Building, Room 503
Ottawa ON K1A 0R2 Canada
E-mail: robert.kennedy@rcmp-grc.gc.ca