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EVALUATING AND IMPROVING FOOTPRINT MEASUREMENT: ORIENTATION AND LENGTHS

ABSTRACT: This project was undertaken in order to develop a reliable technique for measuring foot angle, foot length and toe length. Two volunteers, one adult and one juvenile, made ink footprints on paper, and these were then photocopied many times to provide materials for testing observer errors. Various methods of making and measuring footprints are reviewed, and the most promising set of methods was evaluated in terms of inter-observer and intra-observer errors. After error analysis, the techniques were improved and retested, resulting in the production of a very reliable method of delineating a longitudinal axis of the foot. This axis became the basis from which to measure foot angle and foot length. A new technique for measuring toe length was also devised, one that reflects the functional length of the forefoot and can be consistently measured by any observer. While many methods described in the literature are used without thorough testing, studies like this one will eventually provide us with a set of valid and consistently used standards for footprint analysis.

KEY WORDS: Footprint measurement – Error analysis – Toe length – Foot angle

INTRODUCTION

Feet are very useful subjects. Studies of the feet can help us understand absolute and relative growth, evaluate the effects of therapeutic methods, monitor coordination and motor development, improve sports techniques, and answer basic research questions in biomechanics and human evolution. In studying the feet, footprints are perhaps the best tools. Footprints are generally cheap, quick and harmless to produce, and can provide permanent records that take up little storage space. However, few standards for measuring footprints have been adopted by the majority of those engaged in clinical and basic science research. Therefore, we began this project in an effort to produce consistent and compatible standards for future work.

One of our main goals was to develop a reliable technique for measuring the angle of gait, or foot angle. In the past, studies of foot angle have not all used the same technique, making their results incompatible with one another. Therefore, we attempted to provide a meaningful and reliable standard of the foot's direction. This first goal is related to the second in that, if a proven and consistent technique of determining foot angle can be developed, a standard orientation of the foot for other measurements (e.g. foot length) will also be produced.

The other major aim of this project was to develop a better method of measuring foot and toe lengths from human footprints. In the future, we plan to use the method to describe accurately the growth of the toes during human development. Manley-Buser *et al.* (2001) used relative toe length in a comparative and paleontological context, showing an ontogenetic decline in the relative length of the toes which was particularly evident in the skeleton. Footprint analysis, however, did not show the same significance of this trend. This may be in part because the technique was somewhat imprecise. Furthermore, while skeletal measurements may be more precise, collections of foot skeletons are not very common, and extensive use of X-rays in a longitudinal study is risky. An improved technique of measuring toes from the footprint might have helped in their study. In addition, a valid description of relative growth of the toes will allow us to estimate the age of an individual from the footprint alone and, in a clinical setting where age is known, significant deviations from normal foot growth could be described and analyzed. Adjunct to this second goal was the production of a method that would accurately locate the region of the joints between the metatarsals and the proximal phalanges. This would help to pinpoint the position of toe extension during walking, as the heel leaves the ground and weight passes from the ball of the foot towards the toes, just before toe-off. Finally, we hope eventually to expand on the work of Manley-Buser *et al.* (2001) by applying our methods to ancient footprints such as those from the fossil locality of Laetoli, in Tanzania.

LITERATURE REVIEW: PREVIOUS METHODS

Making footprints

As Walsh (1994) pointed out, "the accuracy of the measurements is dependent on accurately imaging the foot ..." (p. 127). Indeed, various methods of making footprints or measuring foot/gait parameters have been used, and are described in the literature. Since it would not be feasible to test all the different published methods, we have assessed a number of methods in theoretical terms, in an effort to find the one(s) most likely to provide accurate and precise results.

There are many electronic/electrical methods of foot and gait analysis that leave no footprints at all. Rather they collect distance, angle and time data "on the fly". For most electronic techniques, measuring is automated and very fast. Unfortunately, many of these methods have such low image resolution that foot angle and the anatomical parts of the foot are completely obscured (Walsh 1994). Electronic, pressure-sensitive plates embedded in a walkway, can be of sufficient quality to provide more detailed images (Selby-Silverstein 1994), but these are expensive and immobile, and still do not generally produce footprints with a high degree of anatomical detail. Indeed, Urry and Wearing (2001) found significant distortions of measured parameters in electronic footprints, as opposed to ink footprints.

In an effort to obviate the need for anatomical detail, some researchers have marked the feet or shoes of subjects with small pieces of fabric, reflective tape, nails, ink-soaked moleskin, or some other surrogate for particular anatomical landmarks. For example, Murray *et al.* (1964) described a photographic method which relied on the placement of reflective fabric strips on the shoes of subjects. Dougan (1924), using white paper on a carbon paper runner, altered several pairs of gaiters, making "special shoes equipped with specially placed hobnails in order to get a more perfect imprint on the paper." In a study by Boenig (1977), "one triangle and one square of [ink-soaked] moleskin was placed on the approximated midline of the sole of each shoe on the toe and heel respectively." All of these techniques suffer from the limitations caused by the observers' somewhat arbitrary placement of markers, and many are also hampered by the use of footwear which obscures the anatomy of the subjects' feet. Indeed, any methods that rely on shoes are to be avoided whenever possible, since the shoes obscure foot anatomy in any individual and do not fit all subjects in the same way. For these reasons, prints made of bare feet are probably best.

A number of methods of footprinting can be adapted for barefoot subjects. Some techniques produce ephemeral prints which are wiped away or erased after each trail is measured. For example, Hilton (1994, Hilton, Greaves 1995) used a naturally occurring, open area of sandy soil to study gait parameters of American Indians in Venezuela. Grieve and Gear (1966) used a "slightly moistened composition floor", and Clarkson (1983) employed a layer of moist paper under a dry layer of paper, leaving wet footprints which were then outlined in ink before they dried. Finally, Walsh (1994) describes a technique in which chalked shoes were used to make prints on a black rubber mat. All of these methods have the advantage that some or all of the materials can be reused with each new subject, and the area usable by each subject can be made quite large. However, except for Clarkson's (1983) method which involved shod subjects and produced edges of doubtful precision, these produce no permanent records for future study. Furthermore, even during the measurement phase, footprints made by these methods are somewhat delicate so that they can be damaged even by the act of measuring them. Hence, permanent footprints are preferable when precise measurements are required.

Permanent prints of unshod individuals can be obtained in a variety of ways. In 1932, Morton (1932) described a technique which he used while travelling in Africa. He employed a "kinetographic board (about eighteen feet long and eighteen inches wide) ... This was covered in order by a wide strip of inked fabric, similar in texture to typewriting ribbon, a corresponding stretch of paper, and a narrow sheet of muslin." The footprints obtained in this way are of course reverse images, but were apparently of adequate quality. It is unclear where an inked fabric runner could be obtained, nowadays, and its storage might be problematic. The "kinetographic board" may have been difficult to carry from one study location to another, but a similar device would probably work very well in the laboratory. More recently and with greater technology, Tuttle *et al.* (Tuttle, Webb 1989, Tuttle *et al.* 1991) used a multi-layered carbon paper runner made by Moore Business Forms, Inc., and called Shutrak. This product provides excellent prints which are well-preserved and can be marked on more than once with a grease pencil, because a clear plastic layer is placed over the prints after they are made. Shutrak is wide enough for most people, but is only 15 inches (38 cm) wide, thereby constraining some subjects who might normally walk with wider steps because of neurological or anatomical disorders. Unfortunately, Moore Business Forms has discontinued the manufacture of Shutrak. A readily available and inexpensive alternative was used by Uetake (1992). He had his subjects wear paint-soaked socks and walk on a 50 m paper trackway which measured 80 cm in width. This was much less constraining and allowed his subjects to "meander" as they walked. Because socks used this way are resoaked and depleted with each trail, this technique is useful over a limited distance and the prints may be somewhat "heavy" at the beginning. Note, however, that Uetake obtained usable results over a distance of 50 m, in most cases.

Finally, excellent quality prints can also be obtained with a large inkpad and a sheet of plain white paper. The inkpad must generally be "homemade", since it should be larger than any foot which is to be printed. The inkpad used in the present study was made with a shallow, plastic, lidded food storage container, lined with a thin layer of foam rubber which was then soaked in stamp pad ink. The extra-large inkpad thus made and a packet of letter-sized paper are easily portable and quick to use, and the lid on the container prevents the ink from drying out. A serious drawback to this method is that it is useful only for static or single footprints, not for making footprint trails. Furthermore, the feet of the subjects should be cleaned after making prints, a messy and sometimes time-consuming chore. However, to avoid the need for clean-up, Kennedy *et al.* (2003) used an "inkless pad" and special chemically-treated paper with excellent results.

MEASURING FOOTPRINTS

Foot angle

In the literature on angle of gait, there are basically two methods of determining foot angle: along the medial border of the foot, or using the longitudinal axis of the foot (variously defined). Tuttle (1987) used both methods and reported both types of results. Morton (1932) also used both methods, and may have reported both types of results, but he did not specify which method produced which sets of results. When measuring foot angle along the medial border of the footprint, the medial most points of the ball and the heel determine one line and the line of progression determines the other line between which the angle is measured. This technique has been used by many authors, including one of us (Webb 1989, 1990, Tuttle 1987, Morton 1932, Hoffman 1905). It is preferable to using the lateral border, since the lateral margin of the footprint is more variable in general form and less closely tied to underlying skeletal structures than the medial border. However, if the narrowing of the feet that occurs with habitual wearing of shoes (Webb 1990, Hoffman 1905) is accomplished in part by movement of the hallucal ray toward the midline of the foot, then shod and unshod peoples may have different measured foot angles merely because of the width of their balls.

A better indicator of foot angle may be the longitudinal axis, since it is less likely to be affected by variations in ball width. However, there are several methods of determining the longitudinal axis of the foot. In some cases, the method

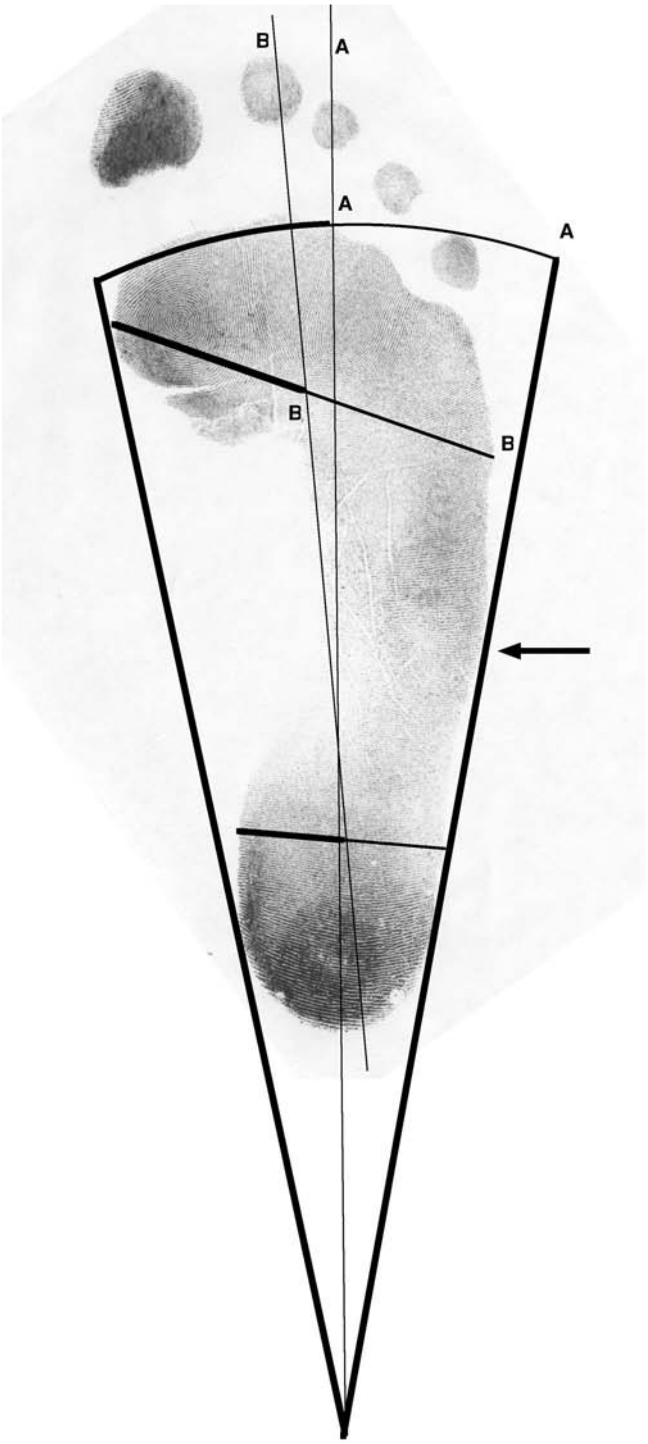

FIGURE 1. Two techniques for drawing the longitudinal axis of the footprint. The footprint shown was chosen for the fact that it shows a bulge in the lateral midfoot (arrow), a condition that is fairly common. The longitudinal axis defined by the angular bisector of tangents to the medial and lateral borders of the foot (A), can be altered significantly by irregularities in the midfoot. On the other hand, a longitudinal axis defined by the midpoints of ball and heel (B) is likely to produce a more consistent anatomical position of the axis. Note that the placement of the longitudinal axis in method A is through the third digit, but through the second digit in method B. If the bulge in the lateral midfoot were absent, as it is in most prints, the axis in method A would be much closer to that drawn by method B.

of drawing the longitudinal axis appears to have been "by eye" (Shores 1980, Tuttle 1987), such that the axis passes near the middles of the ball and heel. Morton (1932) drew a line from the posterior most point of the heel to a point midway between the first and second toes. More recently, Barker and Scheuer (1998) used the same technique, but only when it was not possible to draw the line through the base of the concavity of the ball print between the first and second toes. Obviously, in either case, this would be affected by the shape and orientation of the hallux which in turn is affected by the wearing of shoes. Uetake (1992) defined the longitudinal axis as the line "that equally divides the angle made by the inner and outer tangential lines of a footprint". The resulting line is greatly affected by the fleshy parts of the foot, especially the lateral midfoot, but is otherwise a reasonable indicator of the "middle" of the footprint and has been used by several authors (Kennedy *et al.* 2003, Urry, Wearing 2001). However, there are problems of consistency among different subjects with regard to the lateral border of the print. In particular, the tangent line on the lateral side can be greatly affected by the soft anatomy of the midpart of the foot. Hence, the resulting bisector used as the longitudinal axis may not pass through comparable parts of the foot in differently shaped individuals (*Figure 1*). Nevertheless, Selby-Silverstein (1994) used a version of this technique in a rather complicated way. With digitally imaged footprints, she began as have others (Kennedy *et al.* 2003, Urry, Wearing 2001, Uetake 1992) with lines tangent to the medial and lateral borders of the foot. Line segments perpendicular to the medial borderline were drawn across the print to the lateral borderline in four places: the anterior most projection of the toes/shoe, the posterior most point of the heel, and at one-third and two-thirds of the distance along the medial borderline from the heel line to the toe line. The midpoints of these one-third and two-thirds lines were then used to draw the longitudinal axis. In addition to the problems associated with the irregular anatomy of the lateral border of the footprint, it is unlikely that arbitrarily dividing the footprint into thirds has any functional meaning, and we do not recommend Selby-Silverstein's (1994) technique.

An alternate method may provide more consistent results. Tuttle (1987) initially used short sections of twine, placed by eye, to demarcate the mid longitudinal axis. However, in later publications, he and his colleagues and others (Tuttle *et al.* 1991, Musiba *et al.* 1997, Manley-Buser *et al.* 2001) drew lines across the widest points of the heel and ball, then drew the axis through the midpoints of those lines. This kind of technique, involving the midpoint of a line across the foot, has the advantage of halving any variation in the outline of a footprint or error in placement of the line. Unfortunately, once again there is a problem involving the lateral part of the print, since it is difficult to determine how far along the lateral margin of a footprint to place the lateral end of the line across the ball (see Results below). One minor advantage of using the midpoints of the ball and heel to draw the longitudinal axis is that the piece of paper can be much smaller than that used if the tangents to the medial and lateral borders must be extended until they meet, somewhere behind the heel.

Finally, some authors have attempted to reduce the measurement error by marking the shoes of subjects with easily visible point or line markers. Patek (1926), using gaiters, put hobnails near the posterior middle of the heel and the middle of the sole. A line extended through these points on the footprint was taken as the longitudinal axis. Boenig (1977) also put markers on shoes, at the toe and heel, to make measurements from footprints easier. Murray *et al.* (1964) placed reflective strips on the vamps of shoes and photographed the shoes from above, measuring gait angle from the photos. All of these methods suffer from the use of shoes and an apparently arbitrary placement of markers.

Foot length

Once foot length is consistently defined, it can be used by itself in developmental studies and in conjunction with step length in clinical biomechanical studies to assess relative step length and, thereby, walking effectiveness. While foot length may seem like a parameter with an obvious methodology, there are nevertheless several techniques that have been used. Tuttle (1987) measured "between the mid-tip of the hallux and mid-posterior extremity of the heel," and Davenport (1932) measured from the heel to the tip of the second toe. However, it has become most common to measure along the longitudinal axis of the foot. Hence, Shores (1980) used the longitudinal axis defined by eye. Selby-Silverstein (1994) measured foot length along the longitudinal axis also, but defined the axis in an unusual manner (*vide supra*). As described above, Manley-Buser *et al.* (2001) used the longitudinal axis defined by the midpoints of the ball and heel, and Kennedy *et al.* (2003) defined it by the angular bisector of the tangents to the medial and lateral borders. Appropriately, when using the longitudinal axis, foot length is nearly always measured between the anteriormost and posteriormost projections of the toes and heel.

Toe length

Toe length is useful in developmental studies since, during the growth period, it appears to change relative to the rest of the foot. And, when defined by the centres of the metatarso-phalangeal joints, toe length is relevant in biomechanical research and in orthotics and footwear design. Several methods of measuring toe length have been described in the literature. However, many of these appear to be ad hoc, untested methods developed for specific studies.

One technique measures the length of the toes from the gap between the first and second toe prints. This is likely to be quite variable, because the flesh of the foot will move forward slightly when greater pressure is applied to the foot. Hence, the length of the toe will vary depending on the amount of weight placed on the foot. Also, subjects with slightly different musculature or fat placement might have very different measured toe lengths, even when their phalanges are virtually the same length.

Another technique measures toe length of the first toe only, from the crease which is often found under the big toe (McFadden, Shubel 2002). This crease may show up in the footprint, but too often it does not, making many footprints immeasurable. It is also unclear that the hallux, which is not always the longest toe (see McFadden, Shubel 2002, and citations therein; Mukherjee, Raghavendra 1977, and citations therein), is the most appropriate digit from which to measure "toe length". However, Barker and Scheuer (1998) also measured only the big toe, using its projection beyond the anterior most point of the ball print. This technique presents additional problems in that the fleshy portion of the ball will be compressed more or less, depending on the amount and distribution of weight placed on the foot, and the shape of the ball will vary according to the position and amount of subcutaneous fat.

It appears that the most promising techniques, those of Tuttle *et al.* (1990) and Manley-Buser *et al.* (2001), use a line drawn across the ball of the foot. The greatest projection of any toe beyond this line is considered "toe length". This has the advantage of not changing with foot pressure and of being found on every well-made footprint. It also coincides fairly closely with the centre of the joint at the base of the hallux. However, the technique for placing the line across the ball of the foot seemed quite variable when the results of different observers were compared (see below), and even when the same observer measured identical photocopies of one print. To develop an accurate method of estimating age from footprints, a very consistent method of measurement must be used. Furthermore, a preliminary study of X-rays of the foot (radiographs and footprints being supplied by ten volunteers with their written permission) suggested that the line across the ball does not always pass near the metatarso-phalangeal joints of the lateral toes, making the line less meaningful in a functional sense (*Figure 2*).

Thus, the literature on footprint analysis contains a number of different methods of measurement. However, some methods are used without description (Chodera 1974) or are described or depicted in conflicting ways within one report (Morton 1932). Indeed, the literature on footprint measuring seems to have been plagued for many decades by a lack of precise descriptions of techniques, and even more so by a lack of testing of those techniques.

Unfortunately, many early studies often do not justify or even describe their techniques adequately. More recently, some authors have described their methods in sufficient detail that they may be reproduced by others. Hence, although their consistency may not have been tested, these techniques can at least be tested in the future. Finally, a number of techniques are presented in the literature along with attempts to validate their efficacy. In an early attempt at validation, Boenig (1977) compared her results for stride length, step width, foot angle and cadence with those from Murray *et al.*'s (1970) earlier study, and found them comparable, although her technique was different. She also compared a second trial of each subject one week after the initial trial, then compared the results of the two trials.

FIGURE 2. Footprint and measurement lines overlain on a radiograph. The footprint of one subject is superimposed on the radiograph of the same subject’s foot. The lines drawn on the footprint are those used by Tuttle *et al.* (1990) and Manley-Buser *et al.* (2001), with two new lines added as described in the new method developed here. Note that the line across the entire ball of the foot (as suggested by previous authors) is proximal to the metatarso-phalangeal joint centres of all but the first and fifth rays.

For foot angle, Boenig (1977) found a Pearson's product coefficient (r) of 0.694 ($p<0.05$), between the two trials. She took this to be a good indicator of technical reliability. More recently, Urry and Wearing (2001) compared foot contact area, arch index and "long plantar angle" between traditional ink footprints and those made electronically. They found that, although significantly different results were obtained for foot contact area and arch index, the long plantar angle (angle between the medial and lateral borders of the print) was very similar in the two methods. In addition, work by Menz (1998) evaluated the clinical use of footprints in determining foot pronation. Menz (1998) found that techniques using three-dimensional measurements of the whole foot might be valid, but footprint analysis is generally not useful in determining foot pronation. These three papers described attempts to develop clinical evaluation tools, and this seems to be where most of the effort in methodological advancement is directed (see, for example, the references in Urry, Wearing 2001, Menz 1998).

Another application is in forensics where Kennedy *et al.* (2003) performed a statistical analysis of several hundred footprints, including repeated prints of the same individuals. They found considerable variation among different subjects' prints, but very little variation among the prints of one individual. More relevantly, they found that, using their methods, even one degree of rotation of the digitally scanned footprint yielded slightly different measurements of length, width and other parameters. Unfortunately, the authors did not attempt to validate their measurement techniques. However, Barker and Scheuer (1998) evaluated the use of footprints and partial prints in estimating shoe size and stature. They present intra-observer and inter-observer errors for a series of linear measurements, though they do not associate particular errors with particular parameters. They did note much greater inter-observer errors than intra-observer errors, as may be expected.

MATERIALS AND METHODS

In this study, we have chosen one set of methods which showed the greatest promise, that of Tuttle *et al.* (1990) and Manley-Buser *et al.* (2001). These very similar techniques are likely to yield the best results, because they are based on direct footprints rather than shoes or arbitrarily placed markers, they are defined by a longitudinal axis, and they rely on anatomical structures which are usually readily observed. We therefore began with their method, then tested it, improved on it, and tested the new method, in an effort to provide ourselves and others with a valid set of measuring techniques for further research. In contrast to those authors mentioned above, our aim was not to develop methods that associate footprint measurements with clinical diagnoses or body parameters of forensic value. Instead, we considered the validity and reproducibility of the measurement techniques themselves. It is our hope that other scientists, using other techniques, will test their own methods and justify their use before presenting results based upon them. Eventually, this will lead to a series of tested, valid methods of footprint analysis from which we will all benefit.

Our examination of X-rays from ten individuals and comparison of those X-rays with the footprints of the same individuals suggested to us that the ball of the foot as indicated by the footprint is an important structural and functional region which is directly related to the length of the toes and the point at which they bend (the joint centres). Experimentation with a series of identical copies of footprints and several lines drawn between various points on the prints led us to the conclusion that we could improve on the techniques of Tuttle *et al.* (1990) and Manley-Buser *et al.* (2001). Specifically, we could improve the consistency with which observers place the relevant lines by eliminating one point that is particularly difficult to define, and by drawing an additional line to help the observer locate the best place to draw the line across the ball of the foot.

With the refined methodology, we hope to expand on Manley-Buser *et al.*'s (2001) study of foot ontogeny, in part to determine if "ontogeny recapitulates phylogeny" in the case of toe growth. We also hope to be able to apply our findings to the footprints of earlier hominids, perhaps to estimate relative age, and to assist others who use foot angle in locomotion studies and assessment of rehabilitation procedures.

TESTING THE OLD METHOD

Description

The original method of Tuttle *et al.* (1990) relies on several lines determined by anatomical points on the footprint (*Figure 3*). We term these points "critical points". The method begins by marking the medial-most point of the heel on the medial side and the lateral-most point on the lateral side (points E and G, *Figure 3*). A line is then drawn connecting these two points, and the midpoint, F, is determined with a ruler and simple division of the distance between them. The same is done for the medial- and lateral-most points of the ball, producing points B and D, with the midpoint at C. Then, the longitudinal axis of the footprint is defined by the line, CF, passing through the midpoints of the ball and heel. Two more lines are drawn perpendicular to this axis; one marking the anterior-most projection of the toes (at point A), the other marking the posterior-most portion of the heel (at point H). Finally, footprint length is measured from A to H and toe length from A to C. Toe index, the proportion of the foot made up by the toes, is defined mathematically as ($100 \times AC/AH$) and is expressed as a percent.

Intra-observer error

To improve the older method used by Tuttle *et al.* (1990), we subjected it to extensive testing. This allowed us

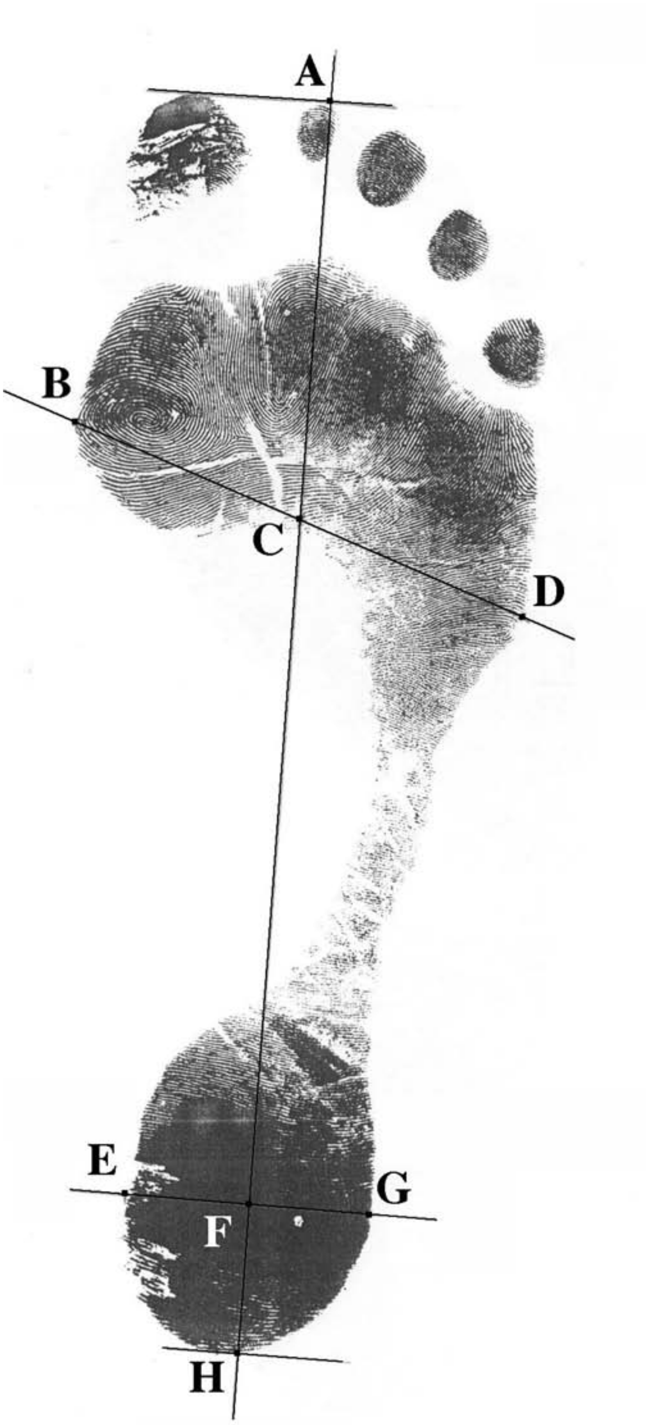

FIGURE 3. Method of Tuttle *et al.* (1990) and Manley-Buser *et al.* (2001). See text for definition of the critical points, A through H.

to identify those areas where errors were greatest and therefore helped us to devise a new technique targeting specific areas for improvement. We tested intra-observer error with two observers, each observer measuring ten photocopies of the same two footprints provided by two volunteers with their written consent. This made a total of four sets of ten footprints and 40 sets of measurements. Each measured footprint was scanned with a Hewlett-Packard Scanjet 6300C flatbed scanner, at a resolution of 600 dpi. Then, the critical points (A through H) were digitized using Lemke Software's GraphicConverter v.4.0.2. [To ensure the reliability of the digital measurements, a 30 cm plastic ruler (marked in mm) was scanned and measured in GraphicConverter. The congruence between the digital measurements and the marked distances on the ruler was excellent.] The variation of the critical points in two directions, antero-posteriorly and medio-laterally, and the associations of these errors with foot length, toe length and toe index were used as indicators of the precision and accuracy of the technique. Variation in foot length, toe length and toe index was also calculated. An additional measure of the reliability and consistency of the method was the variation in orientation of the longitudinal axis of the print. Since every print in each set was an identical photocopy of the original, two very precisely marked features of the footprint were used to orient it on the computer screen, in exactly the same direction every time. In this standardized orientation, the angle of the longitudinal axis relative to the horizontal could be measured consistently.

Inter-observer error

We determined inter-observer error with the assistance of several members of the Laboratório de Estudos Evolutivos Humanos (LEEH), of the Universidade de São Paulo, Brazil. A total of ten observers used the method of Tuttle *et al.* (1990) to measure the same photocopied footprint, thus producing one set of ten prints for our analysis.

RESULTS

Intra-observer error

The results of our evaluation (*Tables 1* and *2*) showed that, among the measurements of one observer, the longitudinal axis determined by the line AH was very stable, even though the points used to draw it (B through G) varied, sometimes considerably, in the antero-posterior direction. Indeed, the stability of the axis is indicated by the facts that the standard deviation in the angle of the longitudinal axis relative to the footprint was between 0.19 and 0.30 degrees, and the range through which the longitudinal axis varied was between 0.56 and 1.13 degrees. Furthermore, points A and H which determine the length of the print were also quite stable, showing little variation within each set of footprints. As might be expected, points B and D were closely associated with variation in toe index, since they determine point C from which toe length is measured.

Inter-observer error

The results of our inter-observer study (*Tables 3* and *4*) show once again that the variation in the medio-lateral dimension was less than that in the antero-posterior dimension, and the points B through G were most variable. Since D partly determines C, C too was rather variable in

TABLE 1. Results of intra-observer analysis of the method of Tuttle *et al.* (1990). Length measurements are in centimetres; toe index is in percent; foot angle is in degrees from the horizontal.

	Print C						**Print J**					
	Observer 1			**Observer 2**			**Observer 1**			**Observer 2**		
	x	**s.d.**	**range**	**x**	**s.d.**	**range**	**x**	**s.d.**	**range**	**x**	**s.d.**	**range**
Foot length	12.23	0.08	0.23	12.22	0.10	0.31	21.01	0.14	0.45	21.01	0.18	0.50
Toe length	4.61	0.08	0.24	4.69	0.09	0.30	6.99	0.07	0.19	6.97	0.09	0.28
Toe index	37.72	0.51	1.68	38.40	0.58	1.46	33.29	0.24	0.84	33.17	0.41	1.54
Foot angle	91.95	0.24	0.65	91.80	0.30	1.13	92.48	0.19	0.56	92.44	0.21	0.66

TABLE 2. Intra-observer variations in placement of critical points. Standard deviations (in cm) of the placement of critical points are averaged for Observers 1 and 2, and Prints C and J. Fisher's r to z scores are also averaged for both observers and both footprints. They show the correlation between the placement of each critical point and the calculated toe index, and the probability (p-value) that the correlation coefficient is equal to zero. Fisher's r to z scores are for antero-posterior variations only, since the correlations were generally low and the p-values generally high for variations in the medio-lateral direction. Only those values with consistently high correlations and p-values below 0.05 are reported.

	Standard deviations		**Fisher's r to z for toe index**	
Point	**Medio-lateral**	**Antero-posterior**	**Correlation**	**P-value**
A	0.073	0.103	–	–
B	0.043	0.118	–	–
C	0.038	0.083	–0.687	.034
D	0.028	0.100	–0.800	.007
E	0.050	0.333	–	–
F	0.050	0.233	–	–
G	0.040	0.185	–	–
H	0.058	0.038	–	–

this case, since D was extremely variable in the antero-posterior dimension. The antero-posterior positions of points B and D were highly correlated with the variation in foot index, as was the position of C, of course. As with the intra-observer analysis, points A and H were very consistent in both directions and the position of the longitudinal axis was also very consistent. Indeed, inter-observer standard deviation of foot angle (the position of the longitudinal axis) was as good as the standard deviation for intra-observer trials (*Tables 1* and *3*).

TABLE 3. Results of inter-observer analysis of the method of Tuttle *et al.* (1990). Length measurements are in centimetres; toe index is in percent; foot angle is in degrees from the horizontal. Only Print J was used in this analysis, and only one group of observers.

		s.d.	**Range**
Foot length	21.33	0.06	0.19
Toe length	6.85	0.34	0.81
Toe index	32.11	1.63	3.89
Foot angle	92.54	0.21	0.72

TABLE 4. Inter-observer variations in placement of critical points. Fisher's r to z scores show the correlation between the placement of each critical point and the calculated toe index, and the probability (p-value) that the correlation coefficient is equal to zero. Only those correlations with p-values below 0.05 are reported.

	Standard deviations		**Fisher's r to z for toe index**			
Point	**Medio-lateral**	**Antero-posterior**	**Medio-lateral**		**Antero-posterior**	
			Correlation	**P-value**	**Correlation**	**P-value**
A	0.11	0.04	–	–	–	–
B	0.03	0.16	-0.813	.0026	0.816	.0025
C	0.07	0.37	–	–	-0.998	<.0001
D	0.04	0.85	0.920	<.0001	-0.995	<.0001
E	0.02	0.34	–	–	–	–
F	0.07	0.24	–	–	–	–
G	0.02	0.18	–	–	–	–
H	0.07	0.04	–	–	–	–

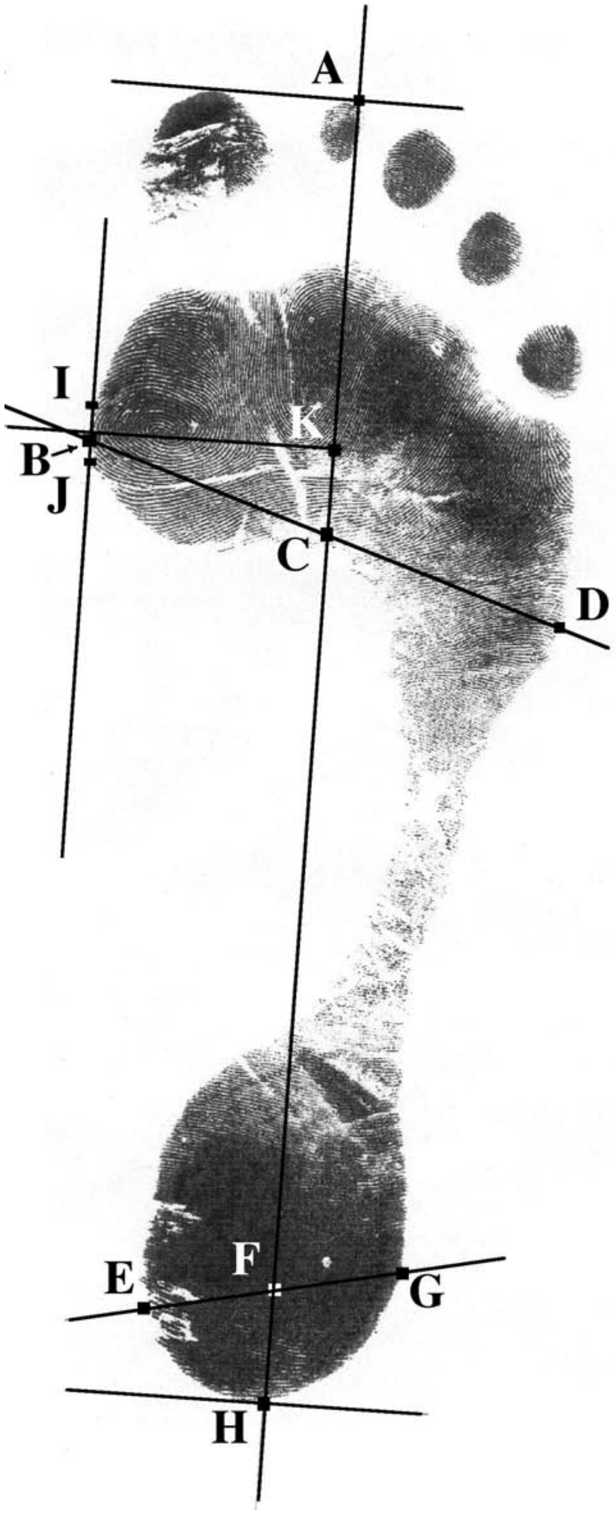

FIGURE 4. New method. After the original eight critical points (A through H) are drawn, the new points I, J and K are added, to improve the reliability of the point from which toe length is measured. Hence, the line segment AK is taken as toe length, replacing AC. An additional point, B’ (not shown), is drawn at the midpoint of the line segment between I and J.

TESTING THE NEW METHOD

Description

Because the longitudinal axis of the footprint was so stable in our intra-observer and inter-observer trials, we chose to retain it when developing a better method. However, from the amount of error in points B and D, it was clear that we needed to draw the line across the ball of the foot in a different way. Since the antero-posterior error of point D was so great, we decided to eliminate it from further use, once the longitudinal axis was drawn. We also chose to constrain the position of the line across the ball by using a visual aid. Specifically, a ruler was held against the medial side of the ball, parallel to the longitudinal axis and approximately tangent to the edge of the print. With the ruler as a guide, the most anterior and most posterior points which could reasonably be chosen by any observer were marked on the medial side of the ball (I and J, *Figure 4*). Then, the midpoint of those two new points (B', not labelled) was used to draw a line perpendicular to the longitudinal axis. This new point, K, at the junction of the longitudinal axis and the perpendicular line to B', was then used to measure the length of the toes. Using X-ray photographs and footprints of the same ten subjects (*Figure 2*), we determined that the new ball line lay very close to the middles of the joints between the first, second and third metatarsals and their proximal phalanges. In other words, the line was very close to the joint centres where the toes bend relative to the rest of the foot. Therefore, the new ball line (B'K) and new point K will have functional significance.

To assess intra-observer error, a set of photocopies of the same footprint were marked and measured by one observer, using Tuttle *et al.*'s (1990) method, and the newly devised method. Comparisons between the variability of the original critical points and the new point, K, were made. The variability of toe index was also compared, using points C and K. For inter-observer error, the same technique was used, and once again errors were calculated from the results of ten members of the LEEH.

RESULTS

Intra-observer error

Analysis of variation among footprints measured by the same observer showed a slight improvement in the positioning of several points in both medio-lateral and antero-posterior directions (*Table 5*). The standard deviation of toe index also decreased slightly (from 0.956% to 0.899%) using the new method. However, point K, which replaced point C for toe measurement, showed a standard deviation of its position exactly equal to the deviation of point C under the older method of Tuttle *et al.* (1990).

Inter-observer error

In this case, we found a substantial improvement in the consistency of toe index, because point K was far more

TABLE 5. Comparison of intra-observer errors. Using the original method of Tuttle *et al.* (1990) and the critical point C, and the new method with the critical point K, toe length and toe index show less variation with the new method. However, the medio-lateral and antero-posterior variation in points C and K are identical. Standard deviations are in parentheses.

	Point C	**Point K**
Toe length	5.23 cm (0.155)	4.04 cm (0.146)
Toe index	32.78% (0.956)	25.32% (0.899)
Medio-lateral variation	(0.06 cm)	(0.06 cm)
Antero-posterior variation	(0.15 cm)	(0.15 cm)

TABLE 6. Comparison of inter-observer errors. Using the original method of Tuttle *et al.* (1990) and the critical point C, and the new method with the critical point K, toe length and toe index show about one-fifth the variation with the new method. The medio-lateral variation in points C and K are similar, but there is a considerable reduction in antero-posterior variation when using point K and the new method. Standard deviations are in parentheses.

	Point C	**Point K**
Toe length	6.60 cm (0.45)	5.66 cm (0.09)
Toe index	31.48% (2.105)	27.02% (0.384)
Medio-lateral variation	(0.06 cm)	(0.05 cm)
Antero-posterior variation	(0.43 cm)	(0.10 cm)

stable than point C (*Table 6*). The standard deviation of point K was less than one-fourth of that for point C, in the antero-posterior dimension. The standard deviation in toe index was 2.11% of average toe index using point C, but only 0.38% using point K, a reduction of 82%. Therefore, inter-observer error was reduced by a factor of about five, as compared to the original method.

DISCUSSION AND CONCLUSIONS

The small reduction in intra-observer error and the dramatic reduction in inter-observer error are an indication that the new method is a considerable improvement over the original method. It may be, in fact, that the intra-observer error was so small to begin with that a large reduction was impossible, if pencil and ruler are used. Indeed, when analyzing the measured footprints with a digital scanner and computer, the resolution of the image was such that the thickness of a pencil line was measurable. This suggests that the limits of traditional measuring devices have been reached, and that more detailed studies of footprints should rely on digitized images. However, variation in footprints of the same subject may be of the same order as errors made by pencil and ruler. If so, the most stable parts of the original method (such as points A and H, and the longitudinal axis) are reliable enough that no improvement is necessary. Hence, reduction of variation among different observers is likely to be a major benefit of the new method. In fact, a good technique will have approximately the same (small) amount of error among observers as among the measurements of one observer. This and more is achieved with the new method (*Tables 5* and *6*).

The other major benefit of the new method tested here is the positioning of the ball line relative to underlying skeletal features. As shown in *Figure 2*, the new line, B'K, is a better indicator of the joint centres of the first through third rays. It is these rays, especially the first and perhaps second, that are used at toe-off during normal human walking. Therefore, measurement of toe length from this point forward is probably a better measure of the functional length of the toes.

We have also validated the longitudinal axis as a consistent method of determining foot angle, at least when it is defined as described above. The longitudinal axis, when defined by dividing some dimension in half, will generally reduce human error and the vagaries of ink and substrate by half, as well. It therefore provides a good standard by which to orient the foot for other measurements. The longitudinal axis is also useful in dynamic footprints where gait parameters are measured. Thus, a well-tested method such as that provided here will be useful in a variety of studies.

Future research on footprints should involve more testing of methods and validation of their accuracy and precision. The work presented here is a beginning which we hope will encourage others to be more careful in choosing their techniques. Once a technique is properly validated, it can be used with confidence in clinical, forensic, biomechanical and evolutionary contexts. The work presented here will aid in the identification of patterns of toe growth in modern humans, and in comparison of humans and earlier hominids. It will also facilitate studies of locomotion in which foot orientation is a critical parameter (e.g. Webb 1990).

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