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Height Estimation from Foot and Shoeprint Length

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ABSTRACT: Foot length displays a biological correlation with height that suggests the latter might be estimated from foot- or shoeprints when such evidence provides an investigator the best or only opportunity to gauge that aspect of a suspect's physical description. Previous utilization of percentages and linear regressions of foot length to make height estimates is reviewed and appraised, as is such use of shoeprints. Newly determined percentages and linear regressions for determining height from foot length for young adult males and females based upon very large U.S. Army anthropometric databases are presented and evaluated. Suggestions are made for the practical employment of shoeprint length, preferably as a direct measurement but also indirectly as a shoe size indicator, for height assessment.

KEYWORDS: physical anthropology, human identification, height estimation, footprints, stature, foot length, shoeprints

> "Yes," he reported, after a short examination of the grass bed, "a number twelve shoe, I should say. If he was all on the same scale as his foot he must certainly have been a giant."
>
> Sherlock Holmes, in *The Adventure of Wisteria Lodge*

Police officers many times cannot accept as accurate or do not have eyewitness height estimates for suspects in crime scene investigations. If present, footprints, either of the bare foot or more commonly as shoeprints, provide an opportunity for estimating height as one characteristic helping to identify or eliminate a suspect.

Addressing this task would seem to be a relatively simple, desirable goal of forensic anthropology. We found only one recent forensic anthropology textbook, however, that offered any assistance in this: the comprehensive second edition of *The Human Skeleton in Forensic Medicine* [*1*]. There the sole reference was to an article published in 1902 [*2*].

A study on determining height from footprint length by the late Louise M. Robbins [*3*], published in the same year (1986) and thus not available to the authors of the text mentioned above, used a modern U.S. sample, but incorporated several idiosyncratic views, described later, that in our opinion lessen its value. Consequently, we decided to undertake our own research with the aim of providing a statistically sound and useful means for estimating the height of modern Americans from measures of their feet and shoes.

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Previous Research

The first study in this century of the relationship between height and foot length utilized a sample of 3000 male prisoners. "The majority of the prisoners were English and Welsh, many were Irish, and only a few Scotch; no foreigners or youths under 21 were included" [*2*]. At the time of publication, correlation and linear regression were two quite new statistical techniques; their use in that research foreshadowed the analytic approach that—along with the simple percentage determined by foot length divided by height—continues to the present day. Even in 1902, Macdonell [*2*] recognized that population variation might complicate the relationship between foot length and height, since he was concerned that his sample of prisoners had an average height 8.4 cm (3⅓ in.) less than a sample of 1000 Cambridge University students.

Since 1902 there have been relatively few foot length/height studies made for either anthropological or forensic purposes. Reference works in physical anthropology generally have preferred to use the foot length/height percentage. The famous textbook *L'Anthropologie* [*4*] by the French anthropologist Paul Topinard, first published in 1876, for example, provides a number of foot length/height percentages for various populations ranging from 14.9 to 18.1. Topinard does not here, nor in subsequent editions, including the English language one [*5*], offer an overall or average percentage of 15%, contrary to the claim by Robbins [*3*].

In the German language, and generally for the first half of this century in the United States, Rudolf Martin's *Lehrbuch der Anthropologie* has been recognized as a standard reference by physical anthropologists. In the three editions [*6*] published in 1914, 1928, and 1959, Martin states: "Die Fuβlänge relativ zur Körpergröβe zeigt innerhalb der menschlichen Rassen keine groβen Schwankungen, sie beträgt im Mittel 15 Prozent derselben" (Foot length relative to height within human races shows no great variation, amounting on average to 15 percent). The 15% value was accepted by the late dean of French physical anthropologists, Henri Vallois [*7*], but not by his successor, Georges Olivier [*8*], who recommended a value of 15.5%. (The difference is substantial: the calculated height of an individual with a foot length of 28 cm [11 in.] would vary by 6 cm [2⅜ in.].)

Robbins [*3*] incorrectly alleged that the French anthropologist Léon Pales accepted 15% as an appropriate foot length/height ratio in his research on the Niaux caves in France [*9*]. On the contrary, Pales referenced Olivier's 15.5% value favorably and, because he considered the footprints to be of children 8.5 to 11.5 years of age, used 16% and wondered if he should perhaps use 17%. As for the 15% figure, he said "elle surestime la stature de l'adulte et plus encore celle de l'enfant" (it overestimates the height of the adult and even more that of the child). There are authoritative advocates of 15% as the basic foot-length-to-height ratio, but it is by no means generally accepted by European researchers, past or present, as Robbins [*3*] claimed.

Populations previously investigated for foot length-height relationships include those essentially worldwide ones listed in the older studies of Topinard [*4,5*] and Martin [*6*], culled from even earlier research. Pales et al. [*10*] provide data for Pacific area groups, as does Hrdlička [*11–13*] for U.S. whites, blacks, and Indians. Dahlberg and Lander [*14*] report in detail on a study of 8200 Swedish men prompted by the equipment needs of the military. Their study is so foot-focused, however, that the regression equation they provide is for estimating foot length from height rather than the other way around. In recent years, Indian anthropologists have undertaken a number of specific studies [*15–17*] examining height and foot length relationships in various Indian populations, of which that by Philip [*18*] is the most recent and detailed. Finally, Klementa and his colleagues [*19*] have argued that their measurements of Czech male and female 17-year olds are tantamount to adult data and provide a table for determining height from 1-cm increments of foot length (corrected versions of the table have been published [*20,21*]. Their sample sizes, however, are small (about 30 of each sex) and their males appear uncharacteristically tall.

As mentioned above, Robbins provided a recent U.S., forensically oriented examination of the relationship between foot length and height. Both her paper [*3*] and her book *Footprints* [*22*] have been critically reviewed elsewhere (for example, Refs *23* and *24*); it is necessary here only to make a few observations directly related to her height-foot length research. Robbins measured foot length two ways: from an inked print made by an individual standing on paper on a hard flat surface, and from a pencil tracing around the foot on the paper. The average difference between them is about 14 mm (9/16 in.). Foot length measured the usual way by calipers would lie between these two length measures, but much closer to that from the outline (Steggerda, in Ref *25* found traced versus caliper foot lengths differ by 2 to 3 mm).

Robbins [*3*] argued that estimating height by means other than foot length as a percentage of height was "unduly complicated," and recommended 15% as a suitable figure for both sexes when using the "length of the foot outline or fleshed foot," allowing a "margin of variation of ±25.4 mm (1 in.)" for the result. She appears not to have realized that by using 15% rather than her own figure for the ratio of foot outline length to height for females over 14 years of age, 14.738% (right and left values averaged), a female with an average foot length would have her height underestimated by 29 mm (1⅛ in.). It is not clear how Robbins could have advocated using a ratio that exceeded her "margin of variation" when applied to her own database, at least for females, and when she believed that sex is determinable from footprints [*22,26*]. If Robbins's published data [*3*] are used to calculate height, the best approach might be to apply the average of the left and right percentages of height represented by bare footprint length for her sample of males over age 14 (14.35%) and females over age 14 (13.93%) and, similarly, by outline foot length for males (15.16%) and for females (14.74%), each based on samples of 223 to 292 individuals.

Robbins provided two other means of relating height and foot length. She [*3*] reprinted regression equations for right and left feet of males from Pales [*9*], indicating that details of the sample from which they were derived were not provided. (In Pales's original publication [*10*] on these data they are 51 young French soldiers.) And in Robbins's book *Footprints* [*22*], Fig. 10.4 is a scattergram of her bare footprint and height data from 550 individuals of both sexes and ages ranging from 3 to 79 [*3*]. A regression line has been fitted to these data, allowing the diagram to be used to determine height by finding a given footprint length on the ordinate and reading height on the abscissa. Unfortunately, the scales are so designed (14-mm units for foot length, 98-mm units for height) that interpolation is difficult (Robbins's own example errs by 6 mm [¼ in.]).

Materials and Methods

The relationship between height and foot length is not necessarily constant throughout the life cycle. Although various studies produce somewhat differing results, the persuasive research of Friedlaender and associates [*27*] suggests that a decline in height does not commence until the fifth decade of life. At the other end of the scale, the relationship between foot length and height, or total body length as it is called in the newborn, varies but perhaps not as much as might be imagined. Merlob et al. [*28,29*] found that the foot length/total body length ratio at 27 gestational weeks is about 14.3% and slowly increases to about 16% at 41 gestational weeks. James et al. [*30*] provide a regression formula to determine total body length from foot length in the newborn.

Meredith [*31*] assembled a large amount of foot length data on children, but little is related to height. And while Rutishauser's [*32*] study of African children six years of age or younger is specifically aimed at estimating height from foot length, her measure of foot length is the bare footprint on a hard surface, which makes her results difficult to compare with those of more conventionally measured foot length. The research reported by Anderson and colleagues [*33*], however, found that "the relation of the length of the foot to stature showed little change with increasing age. In both boys and girls, the length of the foot consistently represented about 16% of stature, with a range at each age of less than 2%." They also found that girls' feet seem to grow less after age 12 than boys'. It should be kept in mind that, despite their statement, their Table 3 indicates that at age 18, the end point of the study, the figure is closer to 15 than 16%, and that in their sample of children, all of whom were afflicted by polio, they do not seem to have rigorously determined that the specific limb and measurements used were truly unaffected by the disease. Klementa et al. [*19*] also provide extensive data on children 4 to 17 years of age.

According to Roche [*34*], "generally, stature at 18 years is accepted as adult, although there are small increments in stature after this." The sex difference in reaching adult height is considerable: the median age for attaining adult height in males is 21.2 years, in females 17.3 years, with growth continuing in 10% of males until 23.5 years and in 10% of females until 21.1 years [*35*].

The present study, by using U.S. Army data, is not affected by height reduction incident to age, but because the Army sample is weighted toward young adults (for example, 58% of the males are ages 17, 18, or 19), some portion has not achieved final adult height. To eliminate all men, for example, under age 23.5 years would not only virtually eliminate the sample itself, but would also be contrary to a principal aim of the study, which is to provide a practical forensic tool. Determining the height from measures of foot length in young men is an advantage of the demographics of the Army sample which has for that reason been used in its entirety. Application of our results, however, to persons under 17 or the elderly should be approached with caution.

U.S. Army studies choose anthropometric measures on the right side. Whether to measure the right or the left foot or both is a question of technique that has been variably answered in studies of the relationship between height and foot length. Some authors [*32*] have measured only the left foot, others [*29*] only the right, still others [*3,10*] both. Traditional anthropometrists, such as Hrdlička [*36*] and Olivier [*37*], seem to favor measuring the left side, as is recommended in old anthropometric efforts at standardization (for example, the 1912 "Geneva Convention" [*36*]. It may be possible to make a case for any of these options, but if the laterality issue is limited, as it is in this paper, to foot length, there seems no good reason not simply to measure one side as representative of this body dimension. Although there are certainly reports to the contrary [*38,39*], many studies [*40–42*] have found no significant difference between the number of people whose right foot was longer than their left and vice versa. Klementa [*19*] examined over 3500 young men and women and found no difference in the females and a left-over-right difference of 1 mm, which he considered insignificant, in the males. In a study of some 6800 U.S. shoe store patrons, Rossi [*43*] found that the longer foot is "roughly divided equally between left and right."

Any statistical product for forensic use is only as good as the underlying data. Army anthropologists have made conscientious and explicit efforts to standardize anthropometric techniques, minimize interobserver variation, and detect data-processing errors. Undoubtedly, they have the motivation and resources to do so. Anecdotally, Snow and Williams [*44*], who found and reported on a single individual measured some 19 times over a 20-year period, believed that military surveys were more accurate than police or medical records. Among the dozens of anthropometric measurements possible, the two—height and foot length—used in this paper are fortunately among the most reliable. Steggerda [*25*], for example, measured the same person (Mrs. Steggerda) 50 times to determine *intra*observer variability. Height had the lowest coefficient of variation of any measurement, and he concluded that from the size of the coefficient of variation for foot length it must be regarded as an "essentially accurate measurement" [25]. Much more recently, Bennett and Osborne [45] examined *inter*observer measurement reliability using eight observers trained by the same person to take 63 measurements on eight males and eight females. Only 8 of the 63 measurements had nonsignificant between-observer F-ratios in both sexes. Height and foot length were two of these. Our conclusion is that height and foot length dimensions obtained from military surveys such as the two used in this research [46–48] should be presumed to be as accurate as such information from large anthropometric surveys is ever likely to be.

Additional characteristics and advantages of the U.S. Army 1966 survey of men and 1977 survey of women are discussed in the reports themselves [46,47] and by Giles and Hutchinson [49]. Briefly, they include very large sample sizes—6682 men and 1330 women—and a representative, healthy, young (mean age/standard deviation for the men of 22.2 ± 4.6 years and 23.1 ± 5.4 years for the women) sample of the U.S. population. Blacks are overrepresented, but not excessively, in proportion to whites in terms of U.S. population proportions. The range of height, 151.9 to 199.1 cm (59¾ to 78⅜ in.) for men and 142.6 to 183.8 cm (56¼ to 72⅜ in.) for women, compares favorably with that found by the most recent U.S. Public Health Service's National Health and Nutrition Examination Survey (NHANES II) of the U.S. population. Since the NHANES II measure of height included upward traction on the mastoid processes and was taken against an upright, however, it is not precisely comparable to the U.S. Army's.

Height in the U.S. Army surveys was obtained in millimetres using an anthropometer with a freestanding subject erect, without shoes and with heels together and head level. Foot length was measured to the tip of the longest toe in a measuring box with the heel against the rear of the box and the long axis of the foot parallel to the side of the box. The two measures display product-moment coefficients of correlation r of 0.678 for the men and 0.693 for the women.

Results

The simplest way to estimate height, as Robbins [3] pointed out, is to determine the fraction or percentage that foot length is of height. We have done that for both sets of soldiers [46–48] by summing the foot length divided by height value for each person in the sample and dividing that sum by the sample size. The result is the average of foot length/height percentages for the 6682 males and 1330 females; it is not the percentage formed from the average foot length and average height. The figure for males is 15.346% and for females 14.926%. The height of a man with a foot length of 28 cm would be estimated as $28 \div 0.15346 = 182.5$ cm. A recent study by Davis[3] suggests that such average percentages for the population in the United States may result in overestimating the height of young black men and women by an average of 3 to 4 cm, while underestimating the height of young white men and women by an average of 1 to 4 cm.

More importantly, linear regressions of height on foot length calculated by the least squares method were obtained for both samples. These two regression equations and the accompanying statistics are as follows:

Men *(metric system):*
Height (cm) $= 3.447 \times$ foot length (cm) $+ 82.206$
Sample size $= 6682$
Mean height (cm) $= 174.516$
Standard deviation of height (cm): 6.610

[3]Davis, K. T., "The Foot Length to Stature Ratio: A Study of Racial Variance," M.A. thesis, Texas Tech University, Lubbock, TX, 1990.

Mean foot length (cm): 26.776
Standard deviation of foot length (cm): 1.301
Standard error of the estimate (cm): 4.856

Men *(English system):*
Height (in.) = 3.447 × foot length (in.) + 32.364
Sample size = 6682
Mean height (in.) = 68.707
Standard deviation of height (in.): 2.602
Mean foot length (in.): 10.542
Standard deviation of foot length (in.): 0.512
Standard error of the estimate (in.): 1.912

Women *(Metric system):*
Height (cm) = 3.614 × foot length (cm) + 75.065
Sample size = 1330
Mean height (cm) = 162.951
Standard deviation of height (cm): 6.520
Mean foot length (cm): 24.318
Standard deviation of foot length (cm): 1.251
Standard error of the estimate (cm): 4.700

Women *(English system):*
Height (in.) = 3.614 × foot length (in.) + 29.553
Sample size = 1330
Mean height (in.) = 64.154
Standard deviation of height (in.): 2.567
Mean foot length (in.) = 9.574
Standard deviation of foot length (in.): 0.493
Standard error of the estimate (in.): 1.850

Putting the equations to use is simple: a man with a foot length of 28 cm would have an estimated height of $3.447 \times 28 + 82.206 = 178.7$ cm (or, equivalently, a man with a foot length of 11 in. would have an estimated height of $3.447 \times 11 + 32.364 = 70\frac{1}{4}$ in.).

It should be noted that we tested the effect of applying the male regression to females and vice versa. When height for the 1330 women was estimated by the regression for men, it overestimated the women's height by an average 3.09 cm ($1\frac{3}{16}$ in.). On the other hand, estimating the height of the men by the women's regression produced results that made the men an average 1.69 cm ($\frac{2}{3}$ in.) too short.

The size of the Army samples is statistically advantageous in determining confidence limits for a single predicted height value using the regression equations because the problem in such estimates that Giles and Klepinger [*50*] discuss turns out to be negligible. In effect, the 95% confidence interval, where the expectation is that 19 out of 20 individuals will fall between its upper and lower values, can simply be formed as 1.96 times the standard error of the estimate, in centimetres or inches, for each regression equation.

The standard errors of estimate given with the regression equations can be used to form whatever limits are deemed appropriate. For example, about two out of three individuals would be expected to fall within limits set as plus or minus one standard error on either side of the predicted value for stature. Seventy percent limits, comparable to those chosen for the height estimates from shoeprints in Table 2, would be, for males, ± 5 cm (± 2 in.) or, for females, ± 4.9 cm ($\pm 1\frac{15}{16}$ in.). For example, the man whose height was predicted as 178.7 cm from his 28-cm foot length should in fact have a true height that falls 70% of the time between 173.7 and 183.7 cm. Alternatively, a man's height estimated as $70\frac{1}{4}$ in. from his 11-in. foot length should in fact have a true height that falls 70% of the time between $68\frac{1}{4}$ in. and $72\frac{1}{4}$ in.

Evaluation

One of the more satisfying ways to evaluate predictive statistical results is to apply them to an independent (that is, not used in calculating the statistics) sample in which the predicted values can be compared to known values. The 1977 U.S. Army anthropometric survey of women also gathered similar data on a group of young men [*51*]. These 287 men, with one exception, were trainees with a median age of 19 years who had been in the Army less than a month. One third was black, two thirds white. Their range of height, 153.0 to 197.4 cm (60¼ to 77¾ in.) was almost as great as in the database male sample.

In order to compare procedures, we have estimated the heights of these 287 men from their foot lengths in three ways: with Robbins's [*3*] suggested 15% for the "fleshed foot," with our 15.346% for men, and with our male regression equation (3.447 × foot length [cm] + 82.206 = height [cm]). As a further indication of the accuracy of Robbins's 15% recommendation, we also applied it to our primary sample of 6682 men and 1330 women, but did not do so with our percentage and regression since for us those samples are not independent but are rather the ones from which our equations were derived. In this latter exercise, Robbins's suggested 15% overestimated the men's height by an average of 3.991 cm (1$\frac{9}{16}$ in.) and underestimated the women's height by an average of 0.832 cm (⅓ in.).

For each man in the test sample of 287, we subtracted his measured height from his estimated height and determined the average difference for the whole sample. Robbins's 15% overestimated height in this sample by an average of 4.31 cm (1$\frac{11}{16}$ in.). Our percentage, 15.346, overestimated height by an average of 0.29 cm (⅛ in.). The male regression equation overestimated height by an average of 0.37 cm (⅛ in.). Although the amount of overestimation is very small and does not really detract from the demonstration of the percentage's or equation's accuracy, it is nevertheless possibly attributable, at least in part, to the fact that the test sample was sufficiently younger than the database sample that a larger fraction may not have reached full adult height and thus reflects the general children's tendency toward foot length being a slightly larger percentage of height.

On the face of it, it appears that Robbins's [*3*] view that any approach for estimating height beyond using a percentage (although not *her* recommended percentage!) is "unduly complicated" might be vindicated. If one looks beyond the similar *averages* of the estimated height values determined the two ways to the *variance* of those two sets of estimated height values, this turns out not to be so. The difference in average predictive accuracy (estimated height minus measured height) between our percentage and our regression equation (0.29 versus 0.37 cm, respectively) is statistically nonsignificant (Ref *52*, p. 154). But the difference between the variances (35.04 versus 21.71, respectively) in our test is highly significant ($P < 0.001$) (Ref *52*, p. 190) and favors height determined by the regression equation. Therefore, although the average accuracy for predicting height by our percentage and by our regression equation on this test sample is statistically the same, that average comes from individual results which do not fluctuate as widely when determined by regression as when determined by percentage.

Shoeprint Length and Estimated Height

The underpinning of any predictive relationship between shoeprint length and height is the correlation, such as that established above, between foot length and height: it cannot be better, and it may well be substantially worse. Nevertheless, the forensic science utility of height information from shoeprint data prompts a "best-effort" approach to the problem despite well-taken caveats (for example, Ref *53*).

The Indirect Method: Shoe Size

The standard forensic science reference in North America for assessing height from shoeprint data is Michael J. Cassidy's *Footwear Identification* manual [*54*]. Cassidy interposes the shoe size of four types of footwear between the "impression measurement" and "approximate height (80% or better)" based upon a survey of 1800 male employees of the Royal Canadian Mounted Police and some members of the Canadian Armed Forces. As Cassidy points out, some shoe styles have the size molded into the sole, and although this information may be discernable in the trace (for example, Ref *55*), such instances must be rare. Otherwise, however, inserting shoe size between the shoeprint length measurement and the estimate of height adds another potential source of variability.

U.S. shoe sizing makes a good argument for conversion to the metric system. In principle, one whole size, both in children's and adults' shoes, equals ⅓ in., with the beginning, size 0, equaling 3¹¹⁄₁₂ in. (in England, size 0 equals 4 in.). Adult size 1 begins where one might expect size 14 in children's sizes, if it existed. By this declension an adult size 9 shoe, for example, is 11¼ in., a size 9½ is 11⁵⁄₁₂ in., and so on [*56*]. Half-sizes continue by ⅙ in. increments on up to at least size 21½, said to be the largest sneaker made by Converse [*57*].

In the U.S. system, a size 12 shoe should be 42.3 mm (1⅔ in.) longer than a size 7 shoe, for example. Data from VanHoven's [*58*] investigation of the relation between shoeprint and sneaker size shows the average of the length differences for four brands (Converse All Star®, Puma, Adidas, and Nike) between sizes 7 and 12 to be 41.7 mm, very close to expected. For the three brands other than Nike, the standard deviation of the within-size variation is about 1.1 mm (about 1.5 mm for Nike). VanHoven's data demonstrate close manufacturing control relative to sizing for these shoes (incomplete data suggested that perhaps more variation occurs in foreign brands of sneakers).

Since shoeprint length is highly correlated with shoe size and increases linearly, in principle shoe size should yield an estimation of height. There are two main difficulties. One is variation in the style of sole and heel, which substantially increases the variability of the imprint left by shoes of the same shoe size. VanHoven [*58*] estimates from the sneakers he examined that, for a given shoeprint length, these style differences give rise to a ± 1 shoe size spread in determining the shoe size of the shoe that made the print. Another way of expressing VanHoven's data is that the average between-brand, within-size difference in the range of whole sizes 7 to 12 is from 1.2 mm (¹⁄₁₆ in.) (Converse All Star/Puma) to 10.4 mm (⅜ in.) (Converse All Star/Nike). If additional shoe types are included (the shoeprint length of some cowboy boots is actually less than the foot length), the problem only increases.

The other difficulty lies in the fit, or lack of it, of the shoe to the foot. Gordon et al. [*53*] report a good correlation between height and combat boot size in a U.S. Army series. But, as they point out, the boots are one style, from a single manufacturer, and professionally fitted. Even with professional fitting there is substantial variation in lengths of feet shod with one size of combat boot. For example, a sample of 27 male soldiers fitted to a size 9 combat boot had an average foot length of 265.7 mm (10½ in.) but a range of 20 mm (¾ in.).[4] Unfortunately, it seems possible that an increasing number of shoes are obtained without professional fitting, leading to a much greater variation in shoe sizes worn by persons with a given foot length.

Our observation in measuring shoes is that length and width are no more important than height of arch to the wearer. One person examined was 179 cm (70½ in.) tall and wore a sneaker that was 6.7 cm (2⅝ in.) longer than his foot length! We also found that

[4]Buikstra, J. E. and Gordon, C. C., personal communication, 20 Aug. 1990.

cheaper brands of sneakers are not made in widths greater than D, and that the wearer compensates for lack of width by buying a longer shoe. The longer shoe displaces the width of the shoe forward from the base to the middle of the little toe, thereby relieving the pinching sensation on the little toe. Thus the wearer accommodates the width of the foot at the ball by using material on the sides of the shoe at the arch and relieves the pressure on the arch of the foot by adjusting the lacing. This bulging of the sides of the sneaker is readily seen, as is the wider-than-normal lacing. In soft soils, mud, or wet sand, the bulging is also apparent in the impression left by the shoe.

Cassidy [*54*] measured a total of 600 shoes in four different style groups (welted boots/normal heels, work boots/snow boots, cowboy boots, and running shoes/flat bottom casuals) to compile his Table 5 for estimating shoe size from shoeprint length. This helpful conversion table is reprinted as Fig. 1 with permission of the Royal Canadian Mounted Police. If shoe size information, however determined, is used for height calculation, one way of coupling it with our regression equations for estimating male and female height (Cassidy [*54*] provides only male height equivalents) is to establish an average foot length for each shoe half-size.

Ascertaining foot length-shoe size equivalencies is certainly not without its hazards, which of course apply to Cassidy's [*54*] procedure as well as to ours. For a number of reasons, including variations of style, heel height, materials, patterns, lasts, construction, and manufacturers, different shoes in identical sizes will measure and fit differently [*56*]. In turn, those variations are compounded because fitting involves comfortably sheathing an object, the foot, whose dimensions vary in ways not necessarily proportional to length. Nevertheless, to relate shoe size to foot length, we suggest assuming that the average foot's length is 19 mm (¾ in.) shorter than the standard length of the shoe size to which it is fitted. That figure reflects that (1) professional fitting is said on average to leave 12.7 mm (½ in.) to 15.9 mm (⅝ in.) "between the toe and the end of the shoe" [*56*], (2) the Brannock Device® for men, an apparatus commonly used in shoe stores for fitting, designates a given standard shoe size 23.3 mm (11/12 in.) longer than foot length, and (3) the 27 male U.S. Army soldiers mentioned earlier whose feet were fitted to size 9 combat boots had an average foot length 20 mm (⅘ in.) shorter[5] than the presumed length for that size boot.

The Brannock Device for women designates one shoe size larger for the same length foot then the companion equipment for men [*56*], but a sample of 33 female U.S. soldiers fitted to size 5 combat boots had an average foot length 16 mm (⅝ in.) shorter[6] than the presumed length for that size boot, less than the same study's differential for men. In view of these conflicting data, the same relation between foot length and shoe size has provisionally been used for women as was used for men.

In Table 1, estimated heights are provided for shoe sizes ranging from 4 to 12 for women and from 6 to 14 for men. The height estimates are based upon the regression equations derived earlier for men and for women applied to a foot length calculated as the length equivalent of that shoe size less 19 mm (¾ in.).

In general, our predicted height for men runs somewhat less than the estimates found in Cassidy's [*54*] Table 6. Although we prefer the direct method described below for utilizing shoeprint length, in our opinion the height values in Table 1 are the best estimates currently available from shoe size information because the underlying foot length/height relationship is derived from linear regressions on statistically well-described, very large U.S. Army samples with stated standard errors of estimate. Our data do not permit the calculation of confidence limits for the estimates from shoe sizes; Cassidy [*54*] believes 80% of men's true height to fall within ± 2 in. (± 5 cm) of his height estimates in our range of shoe sizes.

[5]See Footnote 4.
[6]See Footnote 4.

WELTED BOOTS NORMAL HEEL — SHOE SIZE							5	5½	6	6½	7	7	7½	8	8	8½	9	9½	10	10½	10½	11	11½	12	12½	13	13	13½	14	14	14½
							3½	4	4½	5	5½	5½	6	6½	6½	7	7½	8	8½	9	9	9½	10	10½	11	11½	11½	12	12½	12½	13
WORK BOOTS & SNOW BOOTS — SHOE SIZE			5	5	5½	6	6	6½	6½	7	7½	7½	8	8½	9	9	9½	9½	10	10	10½	10½	11	11½	11½	12	12½	12½	13		
			3	3	3½	4	4	4½	4½	5	5½	5½	6	6½	7	7	7½	7½	8	8	8½	8½	9	9½	9½	10	10½	10½	11		
COWBOY BOOTS — SHOE SIZE	6	6	6½	7	7½	7½	8	8½	9	9	9½	10	10½	10½	11	11½	12	12	12½	13	13½	13½	14								
	4	4	4½	5	5½	5½	6	6½	7	7	7½	8	8½	8½	9	9½	10	10	10½	11	11½	11½	12								
RUNNING SHOES & FLAT BOTTOM CASUALS — SHOE SIZE		6	6½	6½	7	7½	8	8	8½	9	9	9½	10	10½	10½	11	11	11½	12	12½	13	13	13½								
		4½	5	5	5½	6	6½	6½	7	7½	7½	8	8½	9	9	9½	9½	10	10½	11	11½	11½	12								
	9¾	9⅞	10	10⅛	10¼	10⅜	10½	10⅝	10¾	10⅞	11	11⅛	11¼	11⅜	11½	11⅝	11¾	11⅞	12	12⅛	12¼	12⅜	12½	12⅝	12¾	12⅞	13	13⅛	13¼	13⅜	13½

FIG. 1—*Shoe size determination from shoeprint length. Shoeprint length measurements from 9¾ to 13½ in. are provided in the bottom row. Above each measurement is the expected spread of shoe sizes for that shoeprint length in each of four shoe style groups. Reprinted by permission from Michael J. Cassidy,* Footwear Identification, *Table 5 (Ref 54, p. 114).*

TABLE 1—*Height estimates for women and men from shoe size and percentages of basic shoes sold in each half-size. See text for derivation of height estimate.*

	Women			Men		
Shoe Size[a]	Estimated Height, cm	Estimated Height, in.	% in Size[b]	Estimated Height, cm	Estimated Height, in.	% in Size[b]
4	156.2	61½	. . .			
4½	157.7	62⅛	0.7			
5	159.2	62¾	2.1			
5½	160.8	63¼	4.7			
6	162.3	63⅞	6.5	165.4	65⅛	. . .
6½	163.8	64½	11.4	166.9	65¾	4.6
7	165.4	65⅛	13.9	168.3	66¼	7.6
7½	166.9	65¾	15.1	169.8	66⅞	9.7
8	168.4	66¼	13.6	171.2	67⅜	11.8
8½	169.9	66⅞	11.7	172.7	68	13.0
9	171.5	67½	9.6	174.2	68⅝	13.2
9½	173.0	68⅛	3.8	175.6	69⅛	11.9
10	174.5	68¾	4.0	177.1	69¾	10.3
10½	176.1	69⅜	1.1	178.5	70¼	7.3
11	177.6	69⅞	1.4	180.0	70⅞	6.0
11½	179.1	70½	0.3	181.4	71⅜	0.6
12	180.6	71⅛	0.3	182.9	72	2.3
12½				184.4	72⅝	. . .
13				185.8	73⅛	. . .
13½				187.3	73¾	. . .
14				188.7	74¼	. . .

[a] U.S. shoe size. A French or Continental shoe size (where size 0 equals zero length and each size increment is ⅔ cm) [56] can be converted by the following equation: (size − 31.43) ÷ 1.27 = U.S. (adult) size. In the Mondopoint system ([59], SATRA Footwear Technology Centre, and W. A. Rossi, personal communication, 13 Aug. 1990), designed for eventual worldwide adoption but currently only used selectively in some European countries and NATO, a conversion equation is (Mondopoint size − 191.70) ÷ 8.47 = U.S. (adult) size.

[b] Data from Rossi and Tennant [56].

The Direct Method: Shoeprint Length

The use of a direct approximation of foot length ought to be at least as accurate in estimating height as the same measurement first interpreted as a shoe size, and, by eliminating one source of variation, in principle provide greater accuracy. Relating shoeprint length to foot length, however, is susceptible to the problem of variations in fit and style discussed above. We decided to make a small direct investigation of this relationship. VanHoven [*58*] reported that sneaker prints made in dust, on paper or cardboard, or in fresh wet snow, for example, have virtually the same measurement as sneaker length measurements (casts of prints present some variation); consequently, we believe shoe length to be an accurate proxy for shoeprint length.

In the course of four special training sessions in tracking given by one of us (PHV) in 1986 to 1987 at the University of Illinois Police Training Institute in Urbana, the opportunity was taken to obtain the foot length, shoe length, and height of 84 male Illinois police officers enrolled. These officers, with an average age/standard deviation of 32.7 ± 6.1 years, had no knowledge prior to attending the sessions that could have led to any relevant selection of the casual street clothing they wore.

Height was measured with the subjects against a wall in stocking feet; foot and shoe lengths were measured in a box constructed for the purpose. The officers' average height/standard deviation were 178.9 ± 6.5 cm (70$\frac{7}{16}$ ± 2$\frac{9}{16}$ in.) and similarly for foot length 27.0 ± 1.3 cm (10$\frac{5}{8}$ ± $\frac{1}{2}$ in.).

As a practical matter in regard to the identification by nonspecialist police investigators of shoe type from shoeprints, the variety of shoes worn by the officers was divided into only two classes: "flats," worn by 49 officers, which includes loafers, tennis shoes, and running or jogging shoes (sneakers), and "heels," worn by 35 officers, which includes oxfords, heeled loafers, combat or lug-soled boots, work boots, and cowboy boots.

Forensic tracking specialists can, and would be expected to, further identify footwear based on track impressions. The shape of the sole and heel, the presence of any tread patterns in the impression, and evidence of a welt are keys to identifying particular shoes, boots, or sandals [*60*].

In addition, weather conditions at the time the track is made will suggest boots or overshoes. These necessarily add length to the estimated difference between shoe length and foot length. Temperature, area of the country, and topography will further suggest the type of footwear. A border patrol tracker working along the U.S.-Mexican border in July would hardly expect to find tracks from a snowboot: sandals and tennis shoes are the norm, with an occasional Durango-style boot [*60*]. Weathering and aging factors can also distort the physical dimensions of a foot or shoe impression. Understanding these conditions is an acquired skill (Ref *61*, p. 230).

The average excess of length of shoe over length of foot for the sample wearing flats was 2.62 cm (1 in.), while that of the sample wearing heels was slightly greater, 2.87 cm (1$\frac{1}{8}$ in.). These average differences are somewhat less than the excess of shoe length over foot length reported in some human engineering literature, for example, 3.05 cm (1.2 in.) for "men's street shoes" [*62*], 4.06 cm (1.6 in.) for military boots [*62,63*]. Nevertheless, we have used our data to form Table 2, which provides an estimate for male height directly from shoeprint length. Table 2 estimates height by use of our regression equation for men calculated on a length 25.4 mm (1 in.) less than the shoeprint length given in the table. Table 2 is thus constructed for use with shoeprints made by flats in our definition; to apply it to shoeprints made by heels in our definition, one should use the *next smaller* measurement, allowing in effect an additional 2.5 mm ($\frac{1}{8}$ in.) to compensate for the slightly longer print on average made by heels. The figures in parentheses following each estimated height in Table 2 are ±6.35 cm (±2$\frac{1}{2}$ in.), representing the height spread expected to include 70% of men, based on our survey, for that shoe length.

No equivalent to Table 2 has been prepared for women since we have no data relating

TABLE 2—*Height estimates for men based on shoeprint lengths for "flats." Use* next smaller *entry for "heels." Figures in parentheses are estimated height spreads expected to incorporate 70% or more of subjects. See text for explanation of shoe style terms, derivation of height estimates, and calculation of 70% expectation limits.*

Centimetres		Inches	
Shoeprint Length	Estimated Height (70% Limits)	Shoeprint Length	Estimated Height (70% Limits)
24	156.2 (150–163)	9½	61⅝ (59–64)
24.25	157.0 (151–163)	9⅝	62 (59½–64½)
24.5	157.9 (152–164)	9¾	62½ (60–65)
24.75	158.8 (152–165)	9⅞	63 (60½–65½)
25	159.6 (153–166)	10	63⅜ (61–66)
25.25	160.5 (154–167)	10⅛	63⅞ (61½–66½)
25.5	161.3 (155–168)	10¼	64¼ (62–67)
25.75	162.2 (156–169)	10⅜	64⅝ (62–67)
26	163.1 (157–169)	10½	65⅛ (62½–67½)
26.25	163.9 (158–170)	10⅝	65½ (63–68)
26.5	164.8 (158–171)	10¾	66 (63½–68½)
26.75	165.7 (159–172)	10⅞	66⅜ (64–69)
27	166.5 (160–173)	11	66⅞ (64½–69½)
27.25	167.4 (161–174)	11⅛	67¼ (65–70)
27.5	168.2 (162–175)	11¼	67¾ (65½–70½)
27.75	169.1 (163–175)	11⅜	68⅛ (65½–70½)
28	170.0 (164–176)	11½	68½ (66–71)
28.25	170.8 (164–177)	11⅝	69 (66½–71½)
28.5	171.7 (165–178)	11¾	69⅜ (67–72)
28.75	172.6 (166–179)	11⅞	69⅞ (67½–72½)
29	173.4 (167–180)	12	70¼ (68–73)
29.25	174.3 (168–181)	12⅛	70¾ (68½–73½)
29.5	175.1 (169–181)	12¼	71⅛ (68½–73½)
29.75	176.0 (170–182)	12⅜	71⅝ (69–74)
30	176.9 (171–183)	12½	72 (69½–74½)
30.25	177.7 (171–184)	12⅝	72⅜ (70–75)
30.5	178.6 (172–185)	12¾	72⅞ (70½–75½)
30.75	179.4 (173–186)	12⅞	73¼ (71–76)
31	180.3 (174–187)	13	73¾ (71½–76½)
31.25	181.2 (175–188)	13⅛	74⅛ (71½–76½)
31.5	182.0 (176–188)	13¼	74⅝ (72–77)
31.75	182.9 (177–189)	13⅜	75 (72½–77½)
32	183.8 (177–190)	13½	75½ (73–78)
32.25	184.6 (178–191)		
32.5	185.5 (179–192)		
32.75	186.3 (180–193)		
33	187.2 (181–194)		
33.25	188.1 (182–194)		
33.5	188.9 (183–195)		
33.75	189.8 (183–196)		
34	190.6 (184–197)		

women's shoe length to foot length. One wishing to assume a relationship similar to that for men, particularly for flats, between foot length and shoeprint length can utilize the regression equation for women given above to estimate height for a particular case from a shoeprint length reduced by the amount used for men.

While the spread of 12.7 cm (5 in.) may not sound too helpful, it should be kept in mind that the search for criminal suspects often involves viewing people walking on sidewalks at varying distances by officers whose capability to estimate height accurately is unknown. Our height estimate may be more accurate than that given by eyewitness descriptions. Cassidy [*54*] concluded that shoe length can only indicate that the suspect is small, medium, or large. While generally agreeing, we believe our regression approach should produce a better outcome. In an actual case [*64*], one of us (PHV) estimated the heights of two unknown suspects whose tracks were observed leaving the site where a vehicle was abandoned. The owner was later found murdered, and the two men were arrested for the crime. Estimated heights were both accurate to less than an inch.

For a forensic tracking specialist, foot length and shoe length are only two factors to consider in determining height. Others include foot width, length of stride, trail width, pitch angle, and pressure releases [*61*]. A forensic tracking specialist can often give a very good description of a suspect based on track impressions, including sex, height, weight, age, whether the suspect is right- or left-handed, what, if anything, the suspect is carrying and how that weight is carried, the presence of injuries, their nature and location, and the mental and physical condition of the suspect.

As a final comment, we might reflect on a shoeprint in one of the best known cases in the history of U.S. crime [*65*]. It was found outside the nursery window of the country home of the famous aviator Charles A. Lindbergh after the kidnapping of his baby son in 1932. It was of a shoe or boot and was measured by a New Jersey State Police detective (surprisingly, against the handle of his flashlight!) as being between 12 and 12¼ in. (30.5 to 31.1 cm) long.[7] From Table 2 it is seen that a shoeprint of 12⅛ in. yields an estimated height of 70¼ in. (178.4 cm) when using the next smaller length, 12 in., because the shoe involved was apparently a heel in our usage. The man eventually convicted for the kidnapping, Bruno Richard Hauptmann, gave his height as 5 ft 10 in. (177.8 cm) on a driver's license renewal application, apparently now the only written record of his height. Although this is reassuring, unfortunately the accuracy of self-reported height is another story [*49*].

Discussion and Conclusions

The common-sense supposition that foot or shoeprint length correlates with a person's height is borne out by results reported in the anthropological literature for more than a century. Suggestions made over the years for putting that interdependence to practical forensic use have been reviewed in the context of an examination of the foot length and height of over 8000 U.S. Army personnel and a determination of the relationship between foot length and shoe length in a sample of male police officers. This inquiry has led to several conclusions and recommendations:

1. *Variation in foot length-height percentage.* The relationship between foot length and height varies perhaps between 14 and 17% from birth to death, by sex, and among the world's populations, usually tending toward a larger percentage in children generally, men and tall people of both sexes, and a smaller percentage in women and short people of both sexes. Our examination has focused on adult U.S. men and women.

2. *Variation in measures of foot length.* Using the correlation between height and foot length for forensic science goals is complicated by differing ways of measuring the latter. For our purposes we have grouped and employed these as follows: length of bare footprint on a hard surface; foot length measured from the footprint traced on paper, directly from the foot, and from a footprint in a medium yielding enough to reveal the foot's length; shoeprint length and shoe size; and shoeprint length and foot length.

3. *Variation in foot and shoe impressions.* Many characteristics of foot- and shoeprints in addition to length, such as width, pitch angles, length of stride, and pressure releases, provide a forensic tracking specialist means for completing a picture of the person who made them.

[7]Fisher, J., personal communication, 3 Feb. 1988.

4. *Bare footprint on a hard surface.* Data provided by Robbins [*3*] suggest a bare footprint on a hard surface represents 14.35% of a man's height, 13.93% of a woman's.

5. *Foot length.* Analysis of our U.S. Army database indicates a quick estimate of height may be made by presuming foot length to be 15.346% in men, 14.926% in women. But from the same database, the regression equation for men *height (cm)* = *3.447* × *foot length (cm)* + *82.206 (height* [*in.*] = *3.447* × *foot length* [*in.*] + *32.364)* or for women *height (cm)* = *3.614* × *foot length (cm)* + *75.065 (height* [*in.*] = *3.614* × *foot length* [*in.*] + *29.553)* provides the same average accuracy of prediction with less variation among score errors. A 70% confidence interval is formed by ±5 cm (±2 in.) for men, ±4.9 cm (±1 15⁄16 in.) for women. The unisex 15% figure recommended by Robbins [*3*] on the average produces substantial overestimation in men and some underestimation in women.

6. *Shoeprint length and height: shoe size.* The correlation between foot length and height underlies estimating height from shoeprint length, but complications arise from variations in shoe style, fit, and the relationship of shoe size to shoeprint length. Cassidy [*54*] uses shoe size for height estimations for men; Table 1 provides an alternative from our U.S. Army regression equations for estimating height for both sexes if shoe size is established.

7. *Shoeprint length and height: direct determination.* Table 2 is an alternative we prefer to the use of shoe size. It provides height estimates based on our regression equation for men directly from shoeprint lengths categorized as either "flats" or "heels" and modified by results from our sample survey of the relation between shoe length and foot length. From our sample survey, it also includes for each shoe length entry the spread, 6.35 cm (2½ in.), expected to include 70% of cases.

We end with the reminder that scientifically estimating height in humans by means of some component of their bodies, whether femur length [*66*], finger length [*2*], or foot length, can never provide exact results nor be properly discussed except in statistical terms. For foot length and within those limits, we have attempted to be as clear, as candid, and as forensically useful as possible.

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