2021

Finger ridge-counts correlate with the second to fourth digit ratio [pre-print]

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Running Title: Digit ratio and finger ridge-counts

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Abstract

Objectives

This study examined the relationship of finger ridge-counts to second to fourth digit ratio, which has not yet been definitively demonstrated. The related question of sex dimorphism in finger ridge-counts was further elucidated.

Methods

A sample of Germans, including 1,134 males and 1,031 females, was examined for sex dimorphism in the finger ridge-counts. Second and fourth digit lengths were measured in a sub-sample of 80 males and 86 females to compute second to fourth digit ratio. Principal component scores were obtained to investigate sex dimorphism and the correlation between ridge-counts and digit ratio. Regression and analysis of covariance were used to investigate relationships.

Results

Males generally have higher ridge-counts than females. Subtle dimorphic features emerged from the principal components, like a contrast between digits 2 and 4, suggesting a ratio analogous to the digit ratio. The most dimorphic feature was digit 1 asymmetry, males exhibiting a stronger right bias than females. Digit ratio was significantly related to four principal components, expressing various contrasts among digits. Other relationships involved contrast between digits 3 and 5 and asymmetry on digits 1 and 2.

Conclusions

This paper provides definitive evidence that finger ridge-counts correlate with second to fourth digit ratio. The most important finding was associations of ridge-counts with digit ratio did not involve commonly used summary counts over all digits. Rather, associations acted more locally, in ways paralleling the digit ratio, in others reflecting asymmetry. The results strongly support the idea that sex hormones affect finger ridge-counts.

Key Words: Finger ridge-counts, prenatal hormones, digit ratio, sex dimorphism, asymmetry

1 INTRODUCTION

The second to fourth digit ratio, hereafter 2d:4d, has been extensively used as a marker of exposure to prenatal sex hormones and has been linked to a wide variety of postnatal morphologies and behaviors. Much of this work has been summarized in Manning (2002). Manning (2002, p. 11) reported a significant relationship between the ridge-count on right digit 4 and 2d:4d on the right hand in a sample of very low birth weight individuals. However, attempts to demonstrate correlation between 2d:4d and ridge-counts using variables such as summations of ridges over digits have been unsuccessful (Dressler and Voracek 2011; Klimek. Galbarczyk, Nenko, & Jasienska (2021), leaving the relationship unresolved.

There are good reasons to expect a relationship between 2d:4d and finger ridge-counts. Adult finger length ratios are established early in prenatal development, by the seventh intrauterine week (Garn, Burdi, Babler, & Stinson, 1975). Apical volar pads emerge by 7.5 weeks *in-utero* and begin to regress by 10.5 weeks *in-utero* (Babler, 1991). During this time, dermal ridges form on the distal digit segments. Babler (1987) has shown a relationship between the shape of the distal phalanx and pattern type. That finger ridge-counts respond to fetal hormones comes from several lines of evidence. Perhaps the most obvious indirect indicator is sex dimorphism, such that females generally have lower ridge-counts than males (e.g. Holt, 1968). Polani and Polani (1979) found individuals with complete androgen insensitivity syndrome showed the female pattern, such as ulnar loop ridge-counts more in line with females than males. Jamison, Meier, and Campbell (1993) found a relationship between testosterone levels in adults and several dermatoglyphic asymmetry variables, including both finger and palmar variables.

Association of 2d:4d with a wide variety of behavioral traits suggests prenatal hormone involvement in brain organization (Wacker, Mueller, & Stemmler, 2013; McFadden, Loehlin, Breedlove, Lippa, Manning, & Rahman 2005; Hampson, Ellis, & Tenk, 2008; Schwerdtfeger, Heims, & Heer, 2010). However, examples of correlation between dermatoglyphic variables and morphological and behavioral phenotypes are many fewer than those found for 2d:4d. This may in part be because collecting and analyzing dermatoglyphic data are more labor-intensive and time-consuming than collecting 2d:4d data, and possibly because fewer such associations exist, or the correlations are weaker.

One underappreciated line of reasoning in studies of finger ridge-counts is the failure of summed variables such as total ridge-count (TRC, the sum of the larger count for each digit) and absolute ridge-count (ARC, the sum of the radial and ulnar count for each digit) to reveal the relevant variation behind many questions of population variation. Early work on TRC focused on its heritability, estimated at 0.95 (Holt, 1968). Different digits contribute differently to TRC, despite the high correlation between digits in an individual (Jantz, Hawkinson, Brehme & Hitzeroth 1982). Consequently, using TRC or ARC may obscure possible relationships individual digits have with 2d:4d. That Manning (2002) observed a relationship between 2d:4d and ridge-counts for right digit 4 supports utilization of individual digit ridge-counts rather than summed variables like TRC or ARC.

This same argument can be extended to sex dimorphism in ridge-counts. Sex dimorphism does not appear to have been examined in a detailed manner. The usual finding for Europeanderived populations is males have higher TRC and ARC values, and this is also the case for most individual digits (e.g. Andreenko & Baltova, 2017). But the way digits interact to produce multidimensional sex difference is inadequately understood.

The goals of this study are to elucidate the nature of sex dimorphism in ridge-counts and to use 2d:4d to explore the role of hormones in ridge-count variation.

2 MATERIALS AND METHODS

The study sample, consisting of Germans from the Freiburg area, was printed and analyzed by the late H. Brehme of Freiburg University. The prints were collected as part of several morphological and morphoscopic traits used by the Institute of Human Genetics and Anthropology in connection with paternity investigations prior to the widespread use of genetic markers for that purpose (Asen, 2019). The prints were collected in the late 1950s and 1960s and as such can be regarded as an historical sample. The full sample consisted of 1,133 males and 1,031 females, complete for all ridge-counts. The full sample was used to examine sex dimorphism. A sub-sample of 80 males and 86 females was selected to evaluate the relationship to 2d:4d. Paternity cases obviously do not constitute a random sample, if for no other reason than they consist of individuals who have reproduced. The sample contains only adults, where the females were mothers of children whose paternity was in dispute, and the males were the potential fathers of those children.

Digit ratios were obtained by measuring the length of digits 2 and 4 from the proximal flexion crease to center of the pattern on the distal phalanx. Measuring in this way locates the distal point approximately at the center of the distal phalanx (Garn, Poznanski, & Gall, 1970). This omitted the tip of the phalanx distal to the pattern center that would be included in direct measurements. This procedure has the advantage of providing a consistent distal point that does not depend on how much of the tip was included in the print. Prints with arches on digits 2 or 4, or prints where the proximal flexion crease was not clear, were omitted. Omitting arches will have the effect of eliminating most zero values and elevating the average ridge-counts. Tented arches were included, because these patterns contain a core.

Ridge-counts were recorded from the triradius of the pattern to its core. There are 20 ridge-counts for an individual's 10 digits, one count from the radial side to the core and one count from the ulnar side to the core, for each digit. For whorl patterns both radial and ulnar counts are non-zero; for loop patterns one of the counts is zero; and for arch patterns both counts are zero. Because loops are the most common pattern in this population, a large number of zeroes results if all 20 counts are used. This has historically been accommodated in two ways a) choose the larger count of each digit, resulting in 10 non-zero variables, except for arches, which are the least common pattern, providing the only zero values; b) add the radial and ulnar count together for each digit, resulting in 10 values, arches again providing zeros. The two methods provide somewhat different information. Choosing the larger count (option a) provides a measure of pattern size but ignores pattern type. Adding radial and ulnar counts together (option b) incorporates pattern type because both radial and ulnar non-zero counts in whorls will be included.

For purposes of this paper, only the sum of radial and ulnar counts will be used (option b), because it is advisable to incorporate the pattern type contribution to the ridge-count. Hauser (1989) has argued that whorl patterns are good indicators of fetal growth variation. Her data show considerable sex dimorphism in whorl pattern frequencies. Using only the larger count would therefore miss this aspect of dimorphism.

Sex dimorphism was evaluated on individual digits using a *t*-test for each digit, along with Cohen's *d* as a measure of effect size. Because ridge-counts on different digits are highly correlated, further analysis was carried out by converting ridge-counts to orthogonal principal components. The eigenvalues and eigenvectors of the covariance matrix of the total sample were used for this purpose. Robust estimation of eigenvalues and eigenvectors from the covariance matrix using the EM algorithm(NCSS 2019) provided reliable estimates. The eigenvectors provide the structure of the covariance matrix, and the principal component scores are orthogonal variables that can be interpreted using the eigenvector weights. Using principal components in this way reveals inter-digit relationships to further evaluate their correlation with 2d:4d. Sex dimorphism of principal component scores of the large sample was also evaluated.

Relationships of principal component scores to digit ratios were evaluated using analysis of covariance (ANCOVA). Principal component scores were regressed onto sex as a categorical variable and 2d:4d as a covariate. The interaction of sex and 2d:4d provides a test of equality of slopes. If slopes are equal, sex dimorphism can be evaluated using least square means.

Statistics described above were computed with NCSS (2019). Cohen's *d* was computed using a utility program in True Basic written by the author.

3 RESULTS

The first set of results concerns the patterning of sex dimorphism over the digits. The second set explores the relationship between 2d:4d and ridge-counts.

3.1 Ridge-Count Sex Dimorphism

Summary statistics, sex differences for ridge-counts by digit, and effect sizes are shown in Table 1. Sex differences are relatively small, but all are statistically significant, except right and left digit 2. The greatest dimorphism occurs on digits 1 and 5, and right hand dimorphism is greater for all digits, except digit 3. Digits 1, 4, and 5 are marked by substantially greater right-hand dimorphism. The effect sizes are all small.

Table 1 here

Table 2 presents the eigenvectors and eigenvalues of the covariance matrix obtained from pooled sexes. The first eigenvector has positive loadings for all variables, although there is some variation. The first eigenvector accounts for almost 66 % of variation contained in the covariance matrix, and is more or less comparable to ARC, the simple sum of all radial and ulnar counts of digits. The second eigenvector indicates the independence of the thumb in relation to the other digits. Eigenvector 3 is interesting because digit 2 has positive loadings and digit 4 negative loadings, which is more or less comparable to a ratio. Eigenvector 4 opposed digit 3 to 5, again suggesting a ratio. Eigenvector 5 has positive loadings on right and left digit 5, against a negative weight on right digit 4. Eigenvectors 6 through 10 express asymmetry of individual digits, with a positive weight on one hand and a negative weight for the corresponding digit on other hand.

Table 2 here

The last row in Table 2 lists the *t*-test for sex differences of the principal component scores. Principal component scores 1, 2, 3, 5, and 6 are significantly dimorphic. PC 6 is the most dimorphic, followed by PC 3. Neither is especially dimorphic; Cohen's *d* values are 0.28 and 0.2 for PC 6 and 4, respectively. These values are higher than for most individual digits in Table 2, exceeded only by right and left digit 5 and right digit 1. The principal components reveal aspects of sex dimorphism not seen in the individual digits, particularly the digit 2 and 4 contrast on PC 3 and digit 1 asymmetry seen on PC 6.

3.2 Ridge-count relationship to 2d:4d

Table 3 gives the summary statistics for 2d:4d and the finger lengths. The 2d:4d is similar to values for European populations (Manning 2002). Manning (2002) presents values for Germans specifically. Our values are slightly lower, which could result from measurement technique or just population variation. In accordance with values for numerous populations (Manning, 2002, pp. 21-22) the right hand is more dimorphic than the left hand. The effect size for the right 2d:4d is the same as that reported by Manning (2002) for Germans. Sex dimorphism is obviously greater for finger length measurements than 2d:4d because measurements directly reflect size difference. Digit 4 has a greater effect size than digit 2 on both hands but digit 4 has a greater effect size on the right hand, while the reverse is seen in digit 2. The difference between the finger length measurements in Table 3 and means of direct total digit length given in Greiner (1991) is about 20 and 17 mm for males and females, respectively. The difference reflects the distance from the pattern center to the end of the digit.

Table 3 here

Table 4 presents the significance tests of regressing each principal component onto right 2d:4d, sex, and the interaction of 2d:4d and sex. The full model is significant for four principal components, revealing two distinct patterns. PC 3 and PC 7 show the significance of the full model is mainly due to the regression onto right 2d:4d. The non-significant interaction and sex terms means the sexes have a common regression line and there is no sex difference in the means. Figure 1a and b show the relationship of PC 3 and PC 7 to right 2d:4d. For PC 3, we can see from the eigenvector weights that higher right 2d:4d values are associated with higher ridge-counts on digit 2 and lower counts on digit 4. The eigenvector weights on the right and left hand are similar, so it is a bilateral effect. PC 3 also has a significant relationship to left 2d:4d but weaker than that with right 2d:4d (results not shown). PC 7 reflects asymmetry of digit 2, and does not have a significant relationship to left 2d:4d. The eigenvector weights show that higher female-like 2d:4d values increase the right bias on digit 2 and lower male-like 2d:4d values increase the left bias.

Table 4 and Figure 1 here

PC 3, primarily involving digits 2 and 4, has the strongest relationship to 2d:4d, and the relationship is the same in both sexes. It is therefore worth asking whether the raw ridge-counts for these two digits are also correlated with 2d:4d. Table 5 presents the regression equations for right-hand digits 2 and 4 ridge-counts onto right 2d:4d. All of the sex-specific regressions are significant except for digit 4 in males. Digit 2 has a positive relationship with 2d:4d and digit 4 a negative relationship. That means a higher more female 2d:4d yields higher ridge-counts on digit 2 and lower counts on digit 4 and this reverses for the lower more male 2d:4d. Digit 2 has a more consistent and overall slightly higher correlation. It should be noted that the relationship of 2d:4d to digit 4 ridge-count is similar to that reported by Manning (2002) on a sample of very low birth weight individuals, indicating that low birth weight is not a factor in the correlation.

Table 5 here

A different pattern appears in PC 4 and PC 6 where the significant model resulted to a considerable extent from the sex-2d:4d interaction term, meaning that we can reject the hypothesis that the regression of the principal component onto right 2d:4d is the same in both sexes. Figure 2a and b shows the regressions have opposite slopes. In both cases, the female slope is positive and the male slope negative. PC 4 mainly contrasts digit 3 (negative weights) and digit 5 (positive weights), which might be construed as a ratio of digits 3 to 5. The significant difference in slopes can further be examined by asking whether the sex-specific regressions differ from zero. Males exhibit a significant negative regression for PC 4, while females exhibit a significant positive regression. This indicates sexes respond in opposite ways to changes in 2d:4d.

Figure 2 here

PC 6 is not as straightforward as other eigenvectors. Its highest loadings reflect digit 1 asymmetry and secondarily a kind of asymmetry/finger contrast involving right digit 4 and left digit 3. Sex difference is visible for PC 6, seen in Figure 2b, but because the regression slopes are unequal the sex difference cannot be tested using least square means. However, a test on the PC 6 scores in the full sample shows highly significant sex differences ($t = 6.51$, $df = 2163$, $p < 0.001$). For PC 6 the positive regression onto 2d:4d in females is significant, but the negative regression in males is not. The difference in regression slopes is therefore due to the significant female regression and the absence of a regression in males. Digit 1asymmetry is the main contributor and it too is dimorphic (L – R $t = 5.2$, $p < 0.001$, df=2163, effect size = 0.22), but slightly less so than PC 6. A simple regression of digit 1 asymmetry onto 2d:4d is significant in females ($t = 2.2$; $p = 0.03$) but not males. The pooled sex regression is also significant (t=2.36, p=0.02). The slope is positive in both female and pooled sex regressions, indicating higher 2d:4d reduces the right bias of digit 1. This conforms to the L-R sex differences observed in the total sample, -4.65 in males and -2.76 in females.

4. DISCUSSION

The correlation of finger ridge-counts with 2d:4d strongly supports the role of sex hormones in finger ridge-count variation. There are several points we can derive from the results that deserve emphasis. First, the relationship of finger ridge-counts with 2d:4d is complex and unlikely to be detected with summary variables such as TRC or ARC. The present results did not demonstrate a relationship with ARC, in line with similar findings reported by Dressler and Voracek (2011) and Klimek, Galbarczyk, Nenko, & Jasienska, (2021) That is because ridge-counts have numerous underlying processes that contribute to the phenotype, most of which are not significantly influenced by fetal hormones. The association between ridge-counts and 2d:4d was not found in those principal components reflecting the largest proportion of variation in the covariance matrix. The four principal components with significant relationships to 2d:4d altogether account for only about 16 % of the variation. To some extent the raw ridge-counts on digits 2 and 4 were related to 2d:4d but emerge most strongly after partialing out the first two principal components.

An important feature of 2d:4d is sex dimorphism, and that dimorphism arises early in fetal life. PC 3 has the second-largest sex difference in Table 2, although it is substantially less than that seen in 2d:4d, as expressed in effect sizes. The sexes share a common regression when PC 3 is compared to 2d:4d. That means higher 2d:4d associated with lower testosterone results in higher counts on digit 2 and lower counts on digit 4. The reverse is the case for low 2d:4d ratios. This is evident in both the eigenvector weights for PC 3 and the individual regressions of of digit 2 and 4 ridge-counts on 2d:4d. The correlation between the right ridge-count ratio examined here, 2rc:4rc, and 2d:4d is 0.43, which is highly significant but not large enough to be useful in the same way as 2d:4d. The ridge-count ratio (2rc:4rc) is much more variable than 2d:4d.

The degree to which finger ridge-counts might show correlations with the many behavioral traits observed in the 2d:4d digit ratio remains only partially known. Much of the attention has focused on sexual orientation or transsexuality (Hall & Kimura, 1994; Hall, 2000; Slabbekoorn, van Goozen, Sanders, Gooren, & Cohen-Kettenis, 2000; Mustanski, Bailey, & Kaspar, 2002; Dermatoglyphic asymmetry also appears to be related to certain cognitive traits (Kimura and Carson 1995; Sanders and Kadam 2001). Asymmetry is also a common theme in the papers dealing with sexual orientation and transsexuality. The results of the present paper support the importance of asymmetry as a hormone response, particularly on digits 1 and 2.

As a methodological matter, it should be noted that several papers use asymmetry of digits 1 and 5, either because they contain fewer arches than the intervening digits (Hall & Kimura (1994) Kimura & Carson 1995; Sanders and Kadam 2001; Mustanski, Bailey, & Kaspar, 2002) or because they have the highest correlation with TRC and can be used as a surrogate (Slabbekoorn, van Goozen, Sanders, Gooren, & Cohen-Kettenis, 2000). The present results provide little support for including digit 5 in asymmetry measures. From Table 1 it is apparent that digit 5 asymmetry averages less then a ridge in both sexes and the average sex dimorphism is only about 0.6 ridges. By contrast sex dimorphism for digit 1 averages almost 1.9 ridges. One suspect that it is digit 1 driving the results in the aforementioned papers.

The proximate generator of pattern types is known to be related to the shape of the fetal pad (Penrose, 1965), and the consequence of this early relationship persists into adulthood (Katzenmaier, 1979). Babler (1991) has shown during fetal life the length of the distal phalanx is correlated with pattern type, shorter phalanges are associated with whorl patterns. This general relationship is not seen in the lengths of the distal segments in adults, which are smaller on digit 2 than on digit 4 (Greiner, 1991). Whorl pattern frequencies are lower on digit 2 than on digit 4. That distal phalanges influence fetal pads is seen in distal phalangeal hypoplasia, which results in a high frequency of arches (Robinow & Johnson, 1972). The present results suggest the factors that generate pattern types are to some extent subject to hormonal influence.

The relationship of asymmetry on digits 1 and 2 to 2d:4d adds to a number of existing asymmetry associations, including face (Fink, Manning, Neave, & Grammer, 2004), hippocampus (Kallai et al., 2005), and fingers (Manning, Fink, Neave, & Szwed, 2006). More broadly, what emerges from the relationships with 2d:4d is that the ridge-counts driving PC 3 and PC 4, specifically involve digits 2 and 4 (PC 3), or adjacent digits 3 and 5 (PC 4). The regression of PC 3, and the regressions of individual digits 2 and 4, onto 2d:4d may be seen as reflecting a hormone response similar to that responsible for the digit ratio (2d:4d), although with less pronounced sex dimorphism. PC 4, involving mainly digits 3 and 5, was not significantly dimorphic, but because of the opposite regression slopes of the sexes, dimorphism would be seen at the extremes. For example, in males the high 2d:4d values were found with high ridge-counts on digit 3 and low ridge-counts on digit 4, and the reverse is found for low 2d:4d values. The opposite relationship would be the case in females. A possible explanation is that estrogen acts to increases the ridge-count on digit 5 and to decreases it on digit 3 in females, and testosterone does the opposite in males, acting to decrease the ridge-count on digit 5 and increase it on digit 3.

Something similar to the significant interaction of sex and 2d:4d with PC 4 was observed by Brookes, Neave, Hamilton, & Fink, (2007). They also detected a significant interaction of sex and 2d:4d in relation to hand asymmetry for subitizing reaction time. Males with low 2d:4d had greater right hand advantage, while females with low 2d:4d had lower asymmetry. This situation reversed for high 2d:4d. It is not possible to infer any connection between the findings, one involving a morphological trait, the other a cognitive behavioral trait. But it does show that the present findings are not an isolated event.

Bidarkotimath, Avadhan, Viveka, and Kumar (2011) have reported that patients with Down Syndrome have reversed 2d:4d sex dimorphism, males having higher 2d:4d than females, which the authors attribute to reduced androgen levels during fetal development. As present results have shown, digit 1 asymmetry is dimorphic, with males exhibiting a stronger right bias than females. That is to some degree due to males having higher whorl frequencies on right digit 1 than females. In the present sample males and females have roughly equal frequencies of whorls on left digit 1(35.5 % and 35.7 % respectively) but males have 9 % more whorls on right digit 1 (47.9 % and 38.9 % respectively). Hauser (1989) has shown whorl frequency on digit 1 is much reduced in patients with Down Syndrome, and whorl asymmetry reduced in males and even reversed in females, left digit 1 having the higher frequency of whorls. That aligns with what lower androgen levels would predict.

The results of the present study provided strong evidence that finger ridge-counts, formed prenatally around the seventh week and not subject to change thereafter, are correlated with 2d:4d. The relationship is complex and involves several aspects of variation. The correlation of digits 2 and 4 with 2d:4d is perhaps the most intuitive, but other correlations involved different digit combinations and asymmetry. The exact mechanism by which hormones influence ridge-counts remains far from clear. Manning, Bundred, and Flanagan (2002) hypothesized that 2d:4d may reflect androgen sensitivity that is regulated by CAG repeats. Tissue sensitivity was hypothesized long ago to account for the relationship between sex chromosome aneuploidies and finger pattern variation (Jantz & Hunt, 1986). The association of finger patterns with 2d:4d may offer support for that hypothesis.

The role of sex hormones in variation in finger ridge-counts may offer new perspectives on population variation. Jantz and Hawkinson (1979) found the digits (4 + 5) - (2 + 3) were spatially patterned in Sub-Saharan Africa, lower values being found in East and Southeast Africa. Could this suggest that hormone exposure or sensitivity varies among groups? Here, it is noteworthy that Ibegbu et al. (2012) found 2d:4d sex dimorphism in Nigeria is similar to that seen in European populations, but in the Hadza sex dimorphism is absent or even reversed (Apicella, Tobolsky, Marlowe, & Miller, 2015). Although limited, this variation in digit contrasts reported by Jantz and Hawkinson (1979) could be seen as agreeing with lower values of sex difference in East Africa compared to West Africa reported by Ibegbu et al. (2012).

This paper has demonstrated relationships of finger ridge-counts with 2d:4d beyond what has been previously reported. As such, it raises heretofore-unaddressed questions about the meaning of dermatoglyphic variation. How much inter-population variation may be attributed to prenatal hormone exposure? To what extent can finger ridge-count variation be used as a marker of fetal origin of postnatal morphology or behavior? Postnatal changes in 2d:4d have been documented (McIntyre, Cohn & Ellison 2005) leading to the suggestion there may be a postnatal hormone response (Králík, Ingrova, Koziel, Hupkova, & Klima, 2017). But because ridge-counts experience no postnatal modification at all, or even prenatal modification beyond about 10 gestational weeks, the association with 2d:4d supports early prenatal hormone exposure as their principal determinant.

ACKNOWLEDGEMENTS

Parts of this work were accomplished while the author was an Alexander von Humboldt Fellow in the Institute of Human Genetics and Anthropology, Freiburg University.

References

Andreenko, E., & Baltova, S. (2017). Sexual dimorphism in dermatoglyphic traits and fluctuating asymmetry in Bulgarians from northeast Bulgaria. *Homo-Journal of Comparative Human Biology,* 68, 316-327. https://doi.org/10.1016/j.jchb.2017.05.006

Apicella, C. L., Tobolsky, V. A., Marlowe, F. W., & Miller, K. W. (2015). Hadza hunter-gatherer men do not have more masculine digit ratios (2D:4D). *American Journal of Physical Anthropology,* 159(2), 223–232. https://doi.org/10.1002/ajpa.22864

Asen, D. (2019). Fingerprints and paternity testing: a study of genetics and probability in pre-DNA forensic science. *Law, Probability and Risk*, 18, 177-199. https://doi.org/10.1093/lpr/mgz014

Babler, W. J. (1987). Prenatal development of dermatoglyphic patterns: Associations with epidermal ridge, volar pad and bone morphology. *Collegium Antropologium,* 11, 297-304.

Babler, W. J. (1991). Embryologic development of epidermal ridges and their configurations. *Birth Defects Original Article Series,* 27(2), 95-112.

Bidarkotimath, S., Avadhan, R., Viveka, S., & Kumar, A. (2011). Reverse Sexual Dimorphism in Digit Ratios Detected in Down Syndrome. *International journal of forensic practice and research* 1(1), 21-25. https://ijfpr.org/archives/180

Brookes, H., Neave, N., Hamilton, C., & Fink, B. (2007). Digit Ratio(2D:4D) and Lateralization for Basic Numerical Quantification. *Journal of Individual Differences, 28*(2), 55–63. https://doi.org/10.1027/1614-0001.28.2.55

Dressler SG, & Voracek M. 2011. No Association Between Two Candidate Markers of Prenatal Sex Hormones: Digit Ratios (2D:4D and Other) and Finger-Ridge Counts *Developmental Psychobiology* 53(1), 69-78. https://doi.org/10.1002/dev.20488

Fink, B., Manning, J. T., Neave, N., & Grammer, K. (2004). Second to fourth digit ratio and facial asymmetry. *Evolution and Human Behavior 25*(2), 125-132. https://doi.org/10.1016/S1090-5138(03)00084-9

Garn, S. M., Poznanski, A. K., & Gall, G. C. (1970). Applications of Radiodermatography to Human and Primate Studies. *American Journal of Physical Anthropology* 33, 109-114. https://doi.org/10.1002/ajpa.1330330116

Garn, S. M., Burdi, A. R., Babler, W. J., & Stinson, S. (1975). Early prenatal attainment of adult metacarpal phalangeal rankings and proportions. *American Journal of Physical Anthropology* 43, 327-332. https://doi.org/10.1002/ajpa.1330430305

Greiner, T. M. (1991). *Hand Anthropometry of U.S. Army Personnel* Natick, MA: Research Development and Engineering Center Retrieved from https://apps.dtic.mil/dtic/tr/fulltext/u2/a244533.pdf

Hall, J. A. Y., & Kimura, D. (1994). Dermatoglyphic asymmetry and sexual orientation men. *Behavioral Neuroscience,* 108, 1203-1206.

Hall, L. S. (2000). Dermatoglyphic analysis of total finger ridge count in female monozygotic twins discordant for sexual orientation. *Journal of Sex Research, 37*(4), 315-320. https://doi.org/10.1080/00224490009552053

Hampson, E., Ellis, C. L., & Tenk, C. M. (2008). On the Relation Between 2D:4D and Sex-Dimorphic Personality Traits. *Archives of Sexual Behavior,* 37, 133-144. https://doi.org/10.1007/s10508-007-9263-3

Hauser, G. (1989). Dermatoglyphic clues to developmental retardation. *Anthropologie et Préhistoire.,* 100, 83-87.

Holt, S. B. (1968). The Genetics of Dermal Ridges. Springfield, IL: Charles C. Thomas.

Ibegbu, A. O., Danjuma, Z. C., Hamman, W. O., Umana, U. E., Ikyembe, D. T., & Musa, S. A. (2012). Anthropometric Study of the Index (2nd) and Ring (4th) Digits in Ebira Ethnic Group of Nigeria. Asian Journal of Medical Sciences 4(2), 79-84.

Jamison, C. S., Meier RJ, & Campbell BC. (1993). Dermatoglyphic asymmetry and testosterone levels in normal males. *American Journal of Physical Anthropology* 90, 185-198. https://doi.org/10.1002/ajpa.1330900205

Jantz, R. L., & Hawkinson, C. H. (1979). Finger ridge-count variability in Subsaharan Africa. *Annals of Human Biology, 6*(1), 41-53. https://doi.org/10.1080/03014467900003351

Jantz, R. L., Hawkinson, C. H., Brehme, H., & Hitzeroth, H. W. (1982). Finger Ridge-Count Variation Among Various Subsaharan African Groups. *American Journal of Physical Anthropology 57*, 311-321. https://doi.org/10.1002/ajpa.1330570308

Jantz, R. L., & Hunt, D. R. (1986). The influence of sex chromosomes on finger dermatoglyphic patterns. *Annals of Human Biology,* 13, 287-295. https://doi.org/10.1080/03014468600008461

Katzenmaier, U. (1979). Zusammenhänge zwischen Fingerbeerenmustern und Form der Fingerendglieder. *Homo,* 30, 12-23.

Kallai, J., Csathóé, A., Kövér, F., Makány, Nemes, J., Horváth, Kovács, N., Manning, J. T., Nadel, L., & Nagy, F. (2005). MRI-assessed volume of left and right hippocampi in females correlates with the relative length of the second and fourth fingers(the 2D:4D ratio). *Psychiatry Research: Neuroimaging* 140, 199-210. https://doi.org/10.1016/j.pscychresns.2004.05.010

Kimura, D., & Carson, M. W. (1995). Dermatoglyphic asymmetry: relation to sex, handedness and cognitive pattern. *Personality and Individual Differences, 19*(4), 471-478. https://doi.org/10.1016/0191-8869(95)00076-

Klimek, M., Galbarczyk, A., Nenko, I., & Jasienska, G. (2021). Biomarkers of fetal conditions: Finger ridge-counts, facial fluctuating asymmetry, and digit ratio (2D:4D)—are they correlated in women? *American Journal of Physical Anthropology, 174*, 224-231.

Králík, M., Ingrova, P., Koziel, S. K., Hupkova, A., & Klima, O. (2017). Overall trends vs. individual trajectories in the second-to-fourth digit (2D:4D) and metacarpal (2M:4M) ratios during puberty and adolescence. *American Journal of Physical Anthropology* 162(4), 641-656. https://doi.org/10.1002/ajpa.23153

McFadden, D., Loehlin, J. C., Breedlove, M., Lippa, R. A., Manning, J. T., & Rahman, Q. (2005). A Reanalysis of Five Studies on Sexual Orientation and the Relative Length of the 2nd and 4th Fingers (the 2D:4D Ratio). *Archives of Sexual Behavior 34*(3), 341-356. https://doi.org/10.1007/s10508-005-3123-9

McIntyre MH, Cohn BA, & Ellison PT. 2005. Sex dimorphism in digital formulae of children. *American Journal of Physical Anthropology* 129(1), 143-150. https://doi.org/10.1002/ajpa.20240

Manning JT. 2002. Digit Ratio: A Pointer to Fertility, Behavior and Health. New Brunswick, NJ and London: Rutgars University Press. xvi+173 p.

Manning, J. T., Bundred, P. E., & Flanagan, B. F. (2002). The ratio of 2nd to 4th digit length: a proxy for transactivation activity of the androgen receptor gene? *Medical Hypotheses, 59*(3), 334-336. https://doi.org/10.1016/S0306-9877(02)00181-0

Manning, J. T., Fink, B., Neave, N., & Szwed, A. (2006). The second to fourth digit ratio and asymmetry. *Annals of Human Biology, 33*(4), 480-492. https://doi.org/10.1080/03014460600802551

Mustanski, B. S., Bailey, J. M., & Kaspar, S. (2002). Dermatoglyphics, Handedness, Sex, and Sexual Orientation. *Archives of Sexual Behavior,* 31, 113-122. https://doi.org/10.1023/A:1014039403752

NCSS 2019 Statistical Software (2019). NCSS, LLC. Kaysville, Utah, USA, ncss.com/software/ncss.

Penrose, L. S. (1965). Dermatoglyphic topology. *Nature, M.,* 205, 544-546.

Polani PE, & Polani N. 1979. Dermatoglyphics in the testicular feminization syndrome. *Annals of Human Biology* 6(5), 417-430. https://doi.org/10.1080/03014467900003811

Robinow, M., & Johnson, F. (1972). Dermatoglyphics in distal phalangeal hypoplasia. *The American Journal of Diseases of Children 124*(6), 860-863. https://doi:10.1001/archpedi.1972.02110180062008.

Sanders, G. & Kadam A. (2001). Prepubescent children show the adult relationship between dermatoglyphic asymmetry and performance on sexually dimorphic tasks. Cortex 37(1), 91-100. https://doi.org/10.1016/S0010-9452(08)70560-4

Slabbekoorn, D., van Goozen, S. H. M., Sanders, G., Gooren, L. J. G., & Cohen-Kettenis, P. T. (2000). The dermatoglyphic characteristics of transsexuals: is there evidence for an organizing effect of sex hormones. *Psychoneuroendocrinology,* 25(4), 365-375. https://doi.org/10.1016/S0306-4530(99)00063-3

Schwerdtfeger, A., Heims, R., & Heer, J. (2010). Digit ratio (2D:4D) is associated with traffic violations for male frequentcar drivers. *Accident Analysis and Prevention*, 42, 269-274. doi:10.1016/j.aap.2009.08.001

Stein, A. D., Kahn, H. S., & Lumey, L. H. (2010). The 2D:4D digit ratio is not a useful marker for prenatal famine exposure: Evidence from the Dutch Hunger Winter Families Study. *Am J Hum Biol. 2010 ; 22(6): 801–806. , 22*(6), 801-806. doi:doi:10.1002/ajhb.21085

Wacker, J., Mueller, E. M., & Stemmler, G. (2013). Prenatal testosterone and personality: Increasing the specificity of trait assessment to detect consistent associations with digit ratio (2D:4D). *Journal of Research in Personality, 47*, 171-177. htpp:/dx.doi.org/10.1016/j.jrp.2012.10.007.

CAPTIONS FOR FIGURES

Figure 1a and b. Plots of PC 3 and PC 7 on right 2d:4d, showing equal or parallel regression slopes for the sexes. Females are solid line, males dashed.

Figure 2a and b. Plots of PC 4 and PC 6 on right 2d:4d showing different regression slopes for the sexes. Females are solid line, males dashed.

Table 1. Means, standard deviations, sex differences, and effect sizes for large German sample. ES, effect size

	Males (n = 1,134)		Females (n = 1,031)				
Digit	Mean	SD	Mean	SD	M-F	*t*-value	ES
L1	22.19	12.11	20.5	11.71	1.69	3.23	0.14
L2	15.48	12.16	14.98	12.27	0.5	0.94	0.04
L3	15.85	11.09	14.23	11.03	1.62	3.34	0.15
L4	22.14	12.16	20.81	12.19	1.33	2.5	0.11
L5	15.4	7.31	13.64	7.37	1.76	5.54	0.24
R1	26.84	12.64	23.27	11.81	3.58	6.74	0.29
R2	16.05	12.42	15.4	12.21	0.64	1.18	0.05
R3	15.3	10.84	13.79	9.7	1.5	3.39	0.15
R4	24.35	12.75	22.06	11.97	2.3	4.31	0.19
R5	16.2	8.15	13.85	7.37	2.36	7.05	0.3
ARC	189.75	88.7	172.53	85.04	17.22	4.58	0.2

Table 2. Eigenvectors and eigenvalue of total covariance matrix for finger ridge-counts; EV, eigenvector

Variables	EV1	EV2	EV3	EV4	EV5	EV6	EV7	EV8	EV9	EV10
L1	-0.31	0.61	-0.03	-0.2	0.23	0.57	0.24	0.23	-0.04	0.04
L2	-0.36	-0.12	0.55	0.14	0.09	0.2	-0.68	0.13	-0.08	-0.02
L3	-0.31	-0.18	0.03	-0.58	0.23	-0.12	-0.02	-0.23	0.64	0.05
L4	-0.36	-0.24	-0.38	0.01	-0.12	0.34	-0.07	-0.64	-0.35	0.06
L5	-0.19	-0.04	-0.18	0.33	0.53	-0.13	0.08	-0.03	0.03	-0.72
R1	-0.34	0.63	-0.09	0.09	-0.31	-0.52	-0.23	-0.21	0.03	-0.03
R2	-0.37	-0.13	0.53	0.29	-0.25	-0.03	0.63	-0.14	0.08	0
R3	-0.28	-0.17	0.05	-0.5	0.07	-0.38	0.14	0.29	-0.62	-0.06
R4	-0.38	-0.26	-0.44	0.14	-0.42	0.09	-0.03	0.56	0.26	-0.06
R5	-0.21	-0.05	-0.17	0.37	0.5	-0.23	0.05	0.1	-0.01	0.69
Eigenvalue	639.58	109.1	65.19	37.17	27.81	26.98	23.38	18.49	15.55	7.45
Percent	66.89	11.24	6.72	3.83	2.86	2.78	2.41	1.9	1.6	0.77
t-test M-F	-4.31	2.81	-4.72	1.04	2.42	-6.57	-0.47	1.4	1.46	1.74

Table 3. Summary statistics for 2d:4d and digits 2 and 4 measurements. ES, effect size

	Males (n = 80)		Females (n = 86)			
Variable	Mean	SD	Mean	SD	*t*-value	ES
L 2d:4d	0.94	0.04	0.96	0.05	2.15*	0.33
R 2d:4d	0.94	0.04	0.96	0.05	3.53**	0.56
Left digit 2	55.43	3.81	51.97	4.33	5.45	0.85
Left digit 4	58.95	4.27	54.37	4.42	6.78	1.05
Right digit 2	55.55	4.1	52.54	4.33	4.59	0.71
Right digit 4	**59.2**	**3.89**	**54.58**	**4.29**	**7.25**	**1.12**

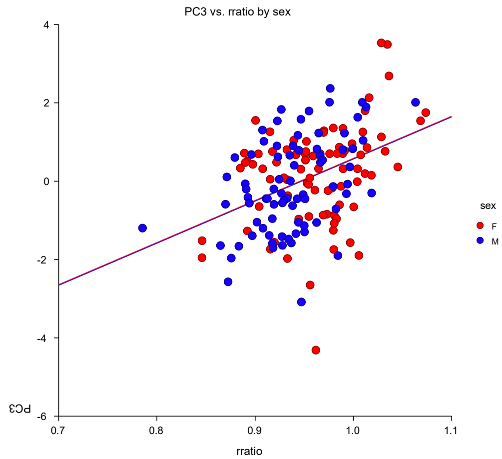
* $p < .05$
** $p < .001$

Table 4. Analysis of covariance (ANCOVA) for principal component scores on *right 2d:4d* (covariate), sex (categorical), and interaction of 2d:4d and sex.

Variable	Model *F* (*p*)	*R*-ratio *F* (*p*)	Sex *F* (*p*)	Interaction *F* (*p*)
PC1	0.23 (.88)	0.65 (.42)	0.00 (.97)	0.00 (.96)
PC2	0.88 (.45)	0.48 (.49)	0.27 (.61)	0.35 (.56)
PC3	11.14 (< .001)	30.78 (< .001)	0.68 (.41)	0.68 (.41)
PC4	3.88 (.01)	0.15 (.70)	9.78 (.002)	9.35 (.003)
PC5	2.40 (.07)	1.73 (.19)	4.97 (.03)	4.83 (.03)
PC6	7.33 (< .001)	1.18 (.28)	4.85 (.03)	5.61 (.02)
PC7	3.23 (.02)	9.39 (.003)	0.50 (.48)	0.57 (.45)
PC8	1.74 (.16)	0.51 (.48)	3.13 (.08)	3.28 (.07)
PC9	2.66 (.05)	3.49 (.06)	1.83 (.18)	1.95 (.16)
PC10	1.19 (.31)	2.42 (.12)	0.01 (.93)	0.02 (.88)

Table 5. Regression of raw right digit 2 and 4 ridge-counts onto right 2d:4d.

Digit	**slope**	**r**	**intercept**	***t*-test slope**	**p**
Males, digit 2	61.26	0.23	-37.47	2.1	0.04
Females, digit 2	51.06	0.22	-28.56	2.1	0.04
Sexes pooled, digit 2	53.5	0.23	-30.56	3	0
Males, digit 4	-37.75	-0.15	63.05	-1.4	0.18
Females, digit 4	-62.6	-0.24	86.44	-2.2	0.03
Sexes pooled, digit 4	-51.8	-0.21	76.15	-2.7	0.01



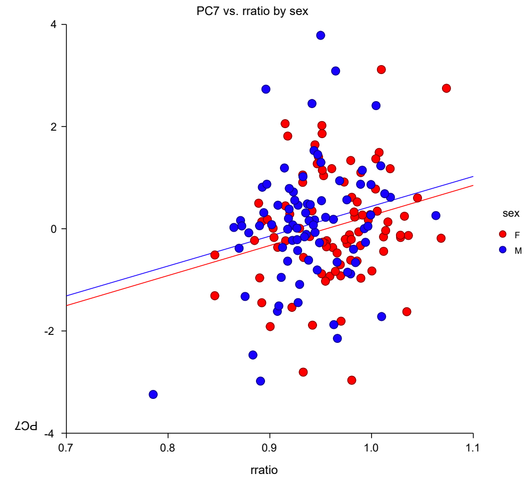


Figure 1a and b. Plots of PC 3 and PC 7 on right 2d:4d, showing equal or parallel regression slopes for the sexes. M, male; F, female.

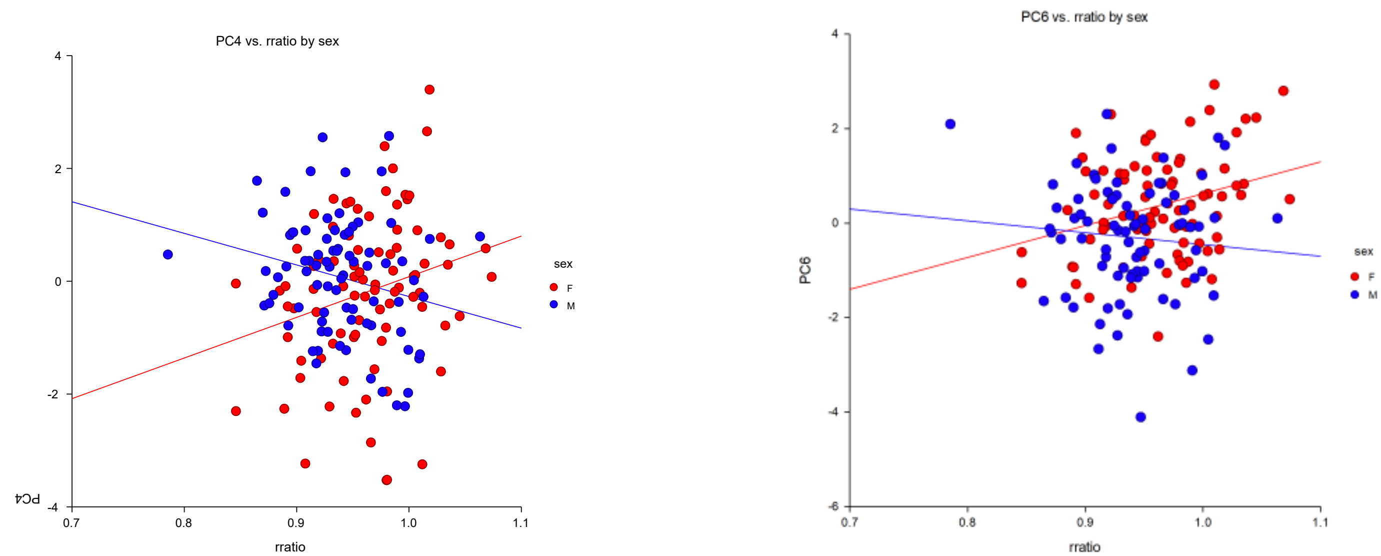


Figure 2a and b. Plots of PC 4 and PC 6 on right 2d:4d showing different regression slopes for the sexes. M, male; F, female.