FORENSIC SCIENCE JOURNAL SINCE 2002

Forensic Science Journal
2021;20(1):21-32
fsjournal.cpu.edu.tw
DOI:10.6593/FSJ.202112_20(1).0003

Profiling Fingerprint Patterns in Singapore Across Race and Gender for Forensic Applications

Kwok-Pui Choi[1*], Ph.D.; Wei-Ling, Stella Tan[2], M.Sc., LLB.; Shi-Yun Tan[2], B.Sc.; Jessica Gunawan[1], B.Sc.,; Huilin Rochelle NG[2], B.Sc.

[1] Department of Statistics and Data Science, Faculty of Science, National University of Singapore, 6 Science Drive 2, Singapore 117546, Singapore

[2] Forensic Science Research Laboratory, Department of Biological Sciences, Faculty of Science, National University of Singapore, 16 Science Drive 4, Singapore 117558, Singapore

Received: June 6, 2021; Accepted: October 26, 2021.

Abstract

Previous empirical studies conducted overseas have suggested a possible correlation between fingerprint patterns and gender, and between fingerprint patterns and race. However, no such studies have been carried out in Singapore. Therefore, this study aims to profile the fingerprint patterns in Singapore across different genders and races, so as to determine the relationship between fingerprint patterns and gender, as well as between fingerprint patterns and race. Our results have confirmed that the proportion of fingerprint patterns on all thumbs and fingers are independent of an individual's gender. On the other hand, surprisingly, our results showed that the proportion of fingerprint patterns on the left thumb, left middle and left ring fingers depend on one's race. It was also observed that the most common fingerprint pattern on our thumbs (right: 56.0%, left: 50.0%), index (right: 48.2%, left: 47.5%) and ring fingers (right: 60.0%, left: 62.4%) are whorls, while the most common fingerprint pattern on our middle (right: 63.1%, left: 58.9%) and little fingers (right: 71.6%, left: 76.2%) are ulnar loops. Looking only at gender, the majority of female and male subjects have whorls on all thumbs and fingers. However, taking only race into account, the majority of Chinese subjects have whorls on all thumbs and fingers. In the case of Indian and Malay subjects, most have ulnar loops on all thumbs and fingers.

Keywords: forensic science; fingerprint; fingerprint pattern profiles; race; gender; identification; human hand bilateral symmetry

Introduction

Fingerprints are the ridge patterns found on fingertips. Fingerprints are permanent [1], durable [2] and unique [3] to each individual. Even identical twins, who have almost identical DNA, have slightly different fingerprints [4]. These properties allow fingerprints to be a reliable forensic human identifier for many purposes, including but not limited to, biometric security, mass disaster identification, and criminal investigations. In addition, fingerprints are also easily obtainable from subjects for the purpose of forensic human identification, as compared to the collection of DNA from blood samples and other biological materials.

[*] Corresponding author: Kwok Pui Choi, Ph.D, Department of Statistics and Data Science, Faculty of Science, National University of Singapore, 6 Science Drive 2, Singapore 117546, Singapore
Tel: (+65) 6516 4387
Email: stackp@nus.edu.sg

In general, there are three levels of fingerprint details. The first level of detail involves the macroscopic ridge flow and pattern of fingerprints. The second level of detail involves features relating to minutiae and ridge characteristics. The third level of detail involves microscopic edgeoscopy (examination of ridge structures) and poroscopy (comparison of impressions made by sweat pores) [5]. For the purpose of this study, the first level of detail was chosen for analysis across the ten fingers of a subject, because it is the most practical technique used for fingerprint classification worldwide. The first level of detail is discriminative even for identical twins, with identical twins showing differences in the first level of fingerprint detail across their ten fingers [4]. Furthermore, latent fingerprints found and collected at crime scenes are often of poor quality [6] and features such as minutiae might not be clear enough for analysis at the second and third levels of fingerprint detail. Thus, analysis of latent fingerprints at the first level of detail is the most practical.

The first level of detail consists of three main classification classes: whorl, arch, and loop. In whorls, two deltas are present, and some of the ridges will make a complete circuit in the middle of the pattern (Fig. 1).

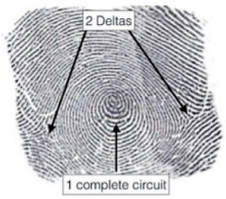

Fig. 1 Most common whorl pattern observed. Whorls have two deltas and the complete circuit in the middle of the pattern resembles a target.

In arches, the fingerprint ridges enter from one end of the fingerprint impression and flow smoothly to the opposite end (as depicted by the arrows in Fig. 2(a)). No deltas are present. Arches can be further categorized into plain arches and tented arches. The difference between plain and tented arches lies in the center of the pattern: a tented arch has an obvious and significant up thrust, while a plain arch does not.

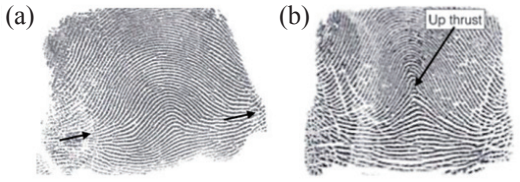

Fig. 2 (a) Plain arch. (b) Tented arch. A significant up thrust is observed in the tented arch.

In loops, the ridges enter from one side of the fingerprint impression and curve back in between a core and delta, leaving on the same side of the impression. Only one delta is present. Loops can be further categorized into ulnar loops and radial loops. The difference between ulnar and radial loops lie in the flow of the pattern: in an ulnar loop, the loop pattern flows towards the little finger while in a radial loop, the pattern flows towards the thumb.

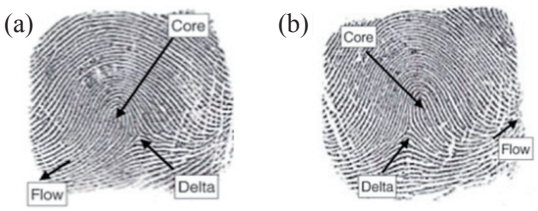

Fig. 3 (a) Left hand ulnar loop, or right hand radial loop. (b) Left hand radial loop, or right hand ulnar loop.

In this paper, five classification classes will be used: plain arch, tented arch, ulnar loop, radial loop, and whorl. For convenience, the following naming convention will be adopted for the respective ten fingers of a subject: right thumb as RT; right index as RI; right middle as RM; right ring as RR; right little as RL; left thumb as LT; left index as LI; left middle as LM; left ring as LR and left little as LL.

Previous empirical studies conducted overseas have suggested the possibility of variations in fingerprint patterns due to a possible correlation between fingerprint patterns and gender [7], [8], and between fingerprint patterns and race [9], [10]. The Singapore population is ideal for such studies, in particular, the study of the correlation between fingerprint patterns and race. This is due to Singapore's multi-racial demographics which comprises mainly the Chinese (74.3%), Malays (13.4%) and Indians (9.0%) [11]. Yet, no studies on the fingerprint

pattern characteristics of the Singapore population have been carried out. As such, this study aims to profile the fingerprint patterns in Singapore across different races and genders. Data obtained from the profiling of fingerprint patterns across the different races and genders will strengthen the capabilities of fingerprint evidence in criminal investigations and legal proceedings. Thus, this paper aims to address five main research questions:

(1) Are there significant differences between the percentage distributions of fingerprint patterns in the Singapore population compared to the international population?
(2) Is there an association between gender and the proportion of the fingerprint patterns? Further, is there an association between race and the proportion of the fingerprint patterns?
(3) What is the prevalence of each type of fingerprint pattern on each finger?
(4) To what extent are our corresponding thumbs and fingers on our left and right hands bilaterally symmetrical to each other?
(5) How unique are our fingerprint sequences across our ten fingers?

The five main research questions addressed in this paper form the basis for important forensic applications. Profiling the distribution of fingerprint patterns in Singapore's population and comparing it with that of the international population in Question (1) will provide the information as to whether the probability calculations can be imported from international figures to Singapore's figures. If the answers to Questions (2) and (3) are yes, they will provide useful leads for investigators as to who and which finger made the fingerprint impression(s) at the crime scene respectively. Similarly, data obtained from Question (4) will be able to give a better prediction of the fingerprint pattern on the corresponding digit on the other hand as well as provide useful intelligence leads as to whether there were multiple perpetrators present at the crime scene. Establishing the uniqueness of our fingerprint sequences in Question (5) will help to differentiate between persons with identical genetic makeup. This is because a concurrent project conducted on 20 pairs of identical twins showed that over 95% of the 20 pairs of twins have at most one or two corresponding digits that differ in their fingerprint patterns at the first level of fingerprint detail.

Methodology

Subjects

The main study involves a total of 282 subjects (140 males and 142 females) of different races, with ages ranging from 16 to 40 years old. A concurrent project was conducted with 20 pairs of identical twins, where the full results of the twins study will be published in a subsequent paper.

Table 1 Breakdown of subjects engaged in the main study.

	Female	Male	Total
Chinese	80	80	160
Indian	32	30	62
Malay	30	30	60
Total	142	140	282

Collection of Prints

Prints of all subjects were collected using ink pads and fingerprint cards. Ink from the ink pads used (Shiny® SM-2 Black Thumb Print Pad) is fade- and water-proof. Before the collection of prints from the subjects, consent were obtained with the collection process and aims of the study clearly explained to the subjects. For each subject, at least two sets of prints were collected on each fingerprint card to ensure the consistency of the prints collected. To maintain confidentiality, the prints collected from each subject were coded, and only gender and race were noted down for analysis purposes.

Subjects were instructed to wash and dry their hands thoroughly to remove possible dirt residuals. The first set of prints collected were rolled impressions. The investigators rolled the subjects' thumbs and fingers from nail edge to nail edge on an ink pad, before printing their prints using the same motion and with light pressure onto the fingerprint cards. The ideal result would be a set of relatively rectangular impressions.

The second set of prints collected was plain impressions. Investigators pressed the subjects' fingers flat onto the ink pad, before printing their prints onto the same fingerprint card, without any rolling of their thumbs and fingers.

ACE-V Analysis of Fingerprint Cards

All fingerprint cards underwent the four fundamental phases of friction ridge classification: Analysis, Comparison, Evaluation and Verification (ACE-V) [12]. An independent and thorough analysis was carried out on each fingerprint card by five trained fingerprint examiners. Consistency in the classifications from independent examiners ensured that the data set used in analysis had a high degree of accuracy.

Intensive trainings were provided to the second, third, and fourth authors by two forensic fingerprint experts from the Forensics Division of the Singapore Police Force, namely Ms. Lee Mei Fun and Assistant Superintendent of Police Mohd Yazid Bin Abdullah. Ms. Lee has been the Officer-in-Charge of the Fingerprint Examination Team since 2006, and has given expert testimonies in many court cases since 2001. She has also conducted fingerprint courses since 2000 and became a member of the International Association for Identification in 2018 (IAI member identification number 32621). Assistant Superintendent of Police Mohd Yazid has been a Senior Fingerprint Specialist since 2013. He has given expert testimonies in numerous court cases since 2005 and conducted fingerprint courses since 2000. He became a member of IAI in 2018 (IAI member identification number 32619).

The first round of ACE analysis was carried out independently by the fourth author.

The second round of ACE analysis was done independently by the second and third authors.

The third round of ACE analysis was carried out independently by the team from the Singapore Police Force comprising of Ms. Lee Mei Fun and Assistant Superintendent of Police Mohd Yazid.

Analysis. Completed fingerprint cards were first examined carefully to determine if the class characteristics of the fingerprints were visible enough for further study. When required, subjects were instructed to re-print the necessary fingerprints.

Comparison. Each fingerprint was manually compared against a set of exemplars consisting of five different classification classes: ulnar loop, radial loop, whorl, plain arch and tented arch.

Evaluation. The characteristics of each finger-print were carefully examined against the standard characteristics of each classification class, before arriving at a conclusion of the classification class the print belongs to.

Verification. The second and third authors as well as the team from the Singapore Police Force applied the ACE process independently to verify the results obtained by the fourth author. The second, third and fourth author held meetings to compare their independent results. In the event of any disagreement between the aforementioned authors, a note was made on the data set to highlight to the examiners from Singapore Police Force. The cross-checked data sets from the second, third and fourth authors were then compared against the classifications of the Singapore Police Force's examiners. Any discrepancies in the classifications were then highlighted and discussions were held to resolve the differences.

Bootstrapped Confidence Interval (CI)

To determine if there are any significant differences in the percentage distribution of fingerprint patterns between the international and Singapore populations, 95% bootstrapped CIs were generated.

Bootstrapping is the resampling of data, with replacement from a single original sample, to estimate parameters. This technique does not need to make any distributional assumptions of the data. In this study, sampling with replacement was carried out 100,000 times in total, and each bootstrapped sample size was the same as the original sample size. Based on these 100,000 bootstrapped samples, a 95% CI of the parameter of interest was constructed.

The international percentages of distribution of fingerprint patterns are: ulnar loops (60%), radial loops (5%), whorls (30%), plain arches (4%) and tented arches (1%) [13]. However, the publication did not reveal whether the left and/or right thumb or all ten fingers were used to calculate the international percentages. For the purpose of this study, assuming that the international percentages of distribution were based on both the right and left thumbs, the right and left thumbs were used for comparison. The right thumb percentages of distribution of fingerprint patterns in Singapore are: ulnar loops (42.9%), radial loops (0%), whorls (56.0%), plain arches (1.1%) and tented arches (0%). Additionally, the left thumb percentages of distribution of fingerprint patterns in Singapore are: ulnar loops (46.8%), radial loops (0.4%), whorls (50.0%), plain arches (2.8%) and tented arches (0%).

Monte Carlo Simulation Chi-Square Test

To determine if the proportion of fingerprint patterns are gender/race independent, a Monte Carlo simulation chi-square test was used [14]. Unlike a chi-

square test, this test does not require entries in the chi-square contingency table to be at least five, and works even when the underlying distribution of the sample is unknown [15], [16]. The null and alternative hypotheses were as follows:

$\mathbf{H_0}$ **:** *Proportion is gender/race independent.*

$\mathbf{H_A}$ **:** *Proportion is gender/race dependent.*

Hierarchical Clustering

Total variation distance [26], which is half of the Manhattan distance, was used to measure the dissimilarity of the proportions of arch, loop and whorl of any two ethnicities in Table 3. Ward error sum of squares hierarchical clustering method [27] was chosen as the agglomerative approach in the hierarchical clustering.

Results and Discussion

ACE-V was conducted, where only 5 out of the 2820 fingerprint patterns were not classified as the same pattern by the second, third, fourth authors and the SPF examiners. These were later resolved upon unanimous agreement.

Distribution of Fingerprint Patterns in the International and Singapore Populations

When the international percentage of fingerprint patterns fell within the 95% bootstrapped CI, it can be concluded that the international percentage is similar to the percentage in Singapore. From the 95% bootstrapped CIs (Table 2), three main groups of conclusions were arrived at:

(1) ***Percentage of right/left thumb whorl in Singapore is considerably higher than the international figure.*** The 95% CI (50.12, 61.94) for the RT whorl and the 95% CI (44.05, 55.95) for the LT whorl are considerably higher than the international figure for whorl (30%).

(2) ***Percentage of right/left thumb loop and percentage of right/left thumb arch in Singapore are lower than the international figure.*** Both the RT ulnar loop with 95% CI (37.01, 48.80) and LT ulnar loop with 95% CI (40.87, 52.75) are lower than the international figure for ulnar loop (60%). Both the RT radial loop with 95% CI (0, 0) and LT radial loop with 95% CI (0, 1.06) are also lower than the international figure for radial loop (5%). The RT plain arch with 95% CI (0, 2.28) is lower than the international figure for plain arch (4%). Lastly, both the RT and LT tented arch with 95% CI (0, 0) are lower than and do not include the international figure for tented arch (1%).

(3) ***Percentage of left thumb plain arch in Singapore is similar to the international figure.*** Only the LT plain arch falls within this category. The 95% CI (0.86, 4.81) includes the international figure for plain arch (4%).

Table 2 95% bootstrapped CIs of the five fingerprint patterns for both the right (RT) and left thumbs (LT) used to determine if the percentage of the patterns in Singapore are lower (L) than, higher (H) than, or similar (S) to that of the international percentage. 100,000 iterations were carried out.

	Lower (%)	Upper (%)	Intl Fig. (%)	Concl.
T.Arch (RT)	0.00	0.00	1.00	L
P.Arch (RT)	0.00	2.28	4.00	L
Radial (RT)	0.00	0.00	5.00	L
Ulnar (RT)	37.01	48.80	60.00	L
Whorl (RT)	50.12	61.94	30.00	H
T.Arch (LT)	0.00	0.00	1.00	L
P.Arch (LT)	0.86	4.81	4.00	S
Radial (LT)	0.00	1.06	5.00	L
Ulnar (LT)	40.87	52.75	60.00	L
Whorl (LT)	44.05	55.95	30.00	H

Besides comparing the distribution of fingerprint patterns in the general Singapore population with that of the general international population, comparison was also made based on ethnicities (Table 3). The percentage distribution of fingerprint patterns in Singapore was further divided into that of the Chinese, Malays and Indians, which were then compared with the percentage distribution of fingerprint patterns among the various ethnicities around the world.

There are several notable observations to be made from Table 3. An interesting observation will be that the distribution of fingerprint patterns in the Singapore Chinese appears close to that of the Taiwanese. This observation can be seen from Table 3; with the Singapore Chinese having the lowest percentage of loops (37.5%) and the Taiwanese having the second lowest percentage

of loops (41.1%). Additionally, it is also observed that the Singapore Chinese has the highest percentage of whorl (60.3%) while the Taiwanese has the second highest percentage of whorl (57.7%). Hence, hierarchical clustering technique was applied to examine the relationship between the distributions of fingerprint patterns of the ethnicities reported in Table 3. The dendrogram in Fig. 4. was produced by hclust function in R 3.4.3 [28].

Many interesting features can be observed from Fig. 4. Due to space consideration, features pertinent to our study will be highlighted. Expectedly, the distributions of fingerprint patterns of the Singapore Chinese, Taiwanese and Mainland Chinese forms a cluster. However, the distribution of fingerprint patterns of the Singapore Chinese is more similar to that of the Taiwanese than the Mainland Chinese. Another notable feature in Fig. 4 is that Malays from Singapore and Malaysia, Indians from Singapore and India, Thais and Nepalese all share very similar distributions of fingerprint patterns.

The similarities between the percentage distributions of fingerprint patterns of two different ethnic groups, such as the Singapore Chinese and Taiwanese as mentioned above suggest a possible common ancestral origin. Similarities in the fingerprint distributions of the Singapore Chinese and Taiwanese could be attributed to a common Fujian root. Hokkien is the largest dialect group among the Singapore Chinese [29], with ancestors originating mainly from China's Fujian province [30]. Likewise, around 70% of the Taiwanese have their roots traced back to the Hoklo immigrants from China's Fujian province [31].

Table 3 Percentage (rounded to the nearest one decimal place) distribution of fingerprint patterns of the 3 ethnicities in Singapore (SG), namely the Chinese, Malays and Indians, together with those of the various ethnicities around the world. *NR=Not Reported.

Ethnicities	Abbr.	Arch (%)	Loop (%)	Whorl (%)	Sample Size
Chinese (SG)	SC	2.2	37.5	60.3	160
Malay (SG)	SM	1.0	54.0	45.0	60
Indian (SG)	SI	2.0	57.0	41.0	62
Chinese (China)[23]	CC	3.5	46.2	50.4	1301
Malay (Malaysia)[8]	MM	0.8	55.3	43.9	NR*
Indian (India)[17]	II	2.9	54.2	43.0	536
Thais[7]	Th	3.8	50.9	45.3	2134
Taiwanese[24]	Ta	1.2	41.1	57.7	100
American[18]	Am	6.1	65.0	28.6	NR*
African American[19]	AA	4.3	59.7	36.0	30
European American[22]	EA	23.1	57.0	19.8	121
Swedish[20]	Sw	7.0	63.9	28.2	120,000
Dutch[25]	Du	4.9	65.0	30.1	24,104
Nepalese[21]	Ne	5.5	51.8	42.8	300

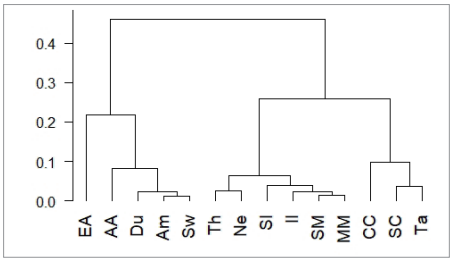

Fig. 4 Dendrogram depicting the similarity of fingerprint pattern distributions of various ethnicities. Refer to Table 3 for the abbreviations of the samples.

Relationship between Gender/Race and the Proportion of Fingerprint Patterns

If the *P* value is less than 0.05 for the Monte Carlo simulation chi-square test, the null hypothesis will be rejected and it will be concluded that, at the 5% significance level, there is evidence of an association between gender/race and the proportion of fingerprint patterns such that the proportion of the fingerprint patterns is dependent on gender/race.

When using the Monte Carlo simulation chi-square test to determine if the proportion of fingerprint patterns is gender independent, none of the *P* values fell below 0.05, with *P* values from all ten fingers being no smaller than 0.19. It was thus concluded that the proportion of fingerprint patterns is independent of gender.

However, when using the same test to determine the relationship between the proportion of fingerprint patterns and race, it was observed that only the *P* values for the LT, LM and LR fingers fell below 0.05 (Table 4). These suggest that the proportion of fingerprint patterns on the LT, LM and LR fingers are dependent on race.

Table 4 P values for left thumb, left middle and left ring fingers obtained using the Monte Carlo simulation chi-square test, which show that the proportions of arches (A), loops (L) and whorls (W) on the aforementioned three fingers are dependent (Dep.) on race. For Chinese (C), n = 160. For Indian (I), n = 62. For Malay (M), n = 60.

	Race	A (#)	L (#)	W (#)	*P*	Concl.
LT	C	5	61	94	0.01	**Dep.**
	I	2	34	26		
	M	1	38	21		
LM	C	9	84	67	0.04	**Dep.**
	I	4	42	16		
	M	1	43	16		
LR	C	5	47	108	0.03	**Dep.**
	I	0	30	32		
	M	0	24	36		

Prevalence of Patterns and Extent to which our Corresponding Fingers are Bilaterally Symmetrical to Each Other

The type of pattern on each finger (n = 282 for each finger) was computed one at a time to understand the prevalence of each type of pattern on different fingers. It was observed that fingerprint patterns on RT and LT, RI and LI, RR and LR fingers are mostly whorls, while the most common patterns on RM and LM, RL and LL fingers are ulnar loops (Table 5).

The prevalence of each type of pattern on the different fingers can be of evidential value in criminal investigations and subsequent legal proceedings. This is particularly so when a rare fingerprint pattern on a finger of the suspect was found to be a match to the latent fingerprint recovered from the crime scene. An example would be the lower prevalence of whorl on the RM (33.69%), LM (35.11%), RL (27.66%) and LL (23.40%) fingers as compared to the other fingers on both hands (Table 5). Another notable observation will be the higher prevalence of radial loop on both the RI and LI fingers, at 7.80% and 8.16% respectively (Table 5) as compared to the other 4 corresponding fingers on both hands.

Table 5 Percentage of each type of fingerprint pattern on all fingers (n = 282 for each finger) on both right (R) and left (L) hands. The percentages highlighted in red are the highest percentages for a particular finger.

%		Thumb	Index	Mid.	Ring	Little
P.Arch	R	1.06	4.61	2.84	1.06	0.36
	L	2.84	5.67	4.26	1.77	0.35
T.Arch	R	0.00	1.77	0.00	0.35	0.00
	L	0.00	3.19	0.71	0.00	0.00
Ulnar	R	42.91	37.59	**63.12**	37.59	**71.63**
	L	46.80	35.46	**58.86**	35.10	**76.24**
Radial	R	0.00	7.80	0.35	1.06	0.35
	L	0.35	8.16	1.06	0.71	0.00
Whorl	R	**56.03**	**48.23**	33.69	**59.93**	27.66
	L	**50.00**	**47.51**	35.11	**62.41**	23.40

A high percentage of subjects was observed to have the same fingerprint pattern on the corresponding left and right fingers. Referring to row 1 of Table 6, 78% of the subjects was observed having the same fingerprint pattern on the LT and the RT. This is the highest percentage seen when comparing between the RT-RI (58%), RT-RM (62%), RT-RR (61%), RT-RL (53%), RT-LI (55%), RT-LM (58%), RT-LR (63%) and RT-LL (52%). Interestingly, the same trend was seen for the rest of the fingers.

This trend is illustrated in Table 6, where the percentage of the same fingerprint pattern appearing on the corresponding left and right fingers is the highest (as reflected by the red numbers in Table 6). This provides empirical evidence that even the fingerprints on our corresponding fingers exhibit biological bilateral symmetry.

To take the analysis a step further, the corresponding fingers of the right and left hands of each subject were

paired up to form five pairs. The number of pairs which share the same fingerprint pattern (match pairs) was then recorded for each subject; the total number of match pairs for a single individual can range from zero to five. It was observed that all 282 subjects had at least one match pair, regardless of race or gender; with the highest percentage of subjects having four match pairs (Table 7). To determine if the number of match pairs is independent of race or gender, Monte Carlo simulation chi-square tests at 5% significance level (100,000 iterations) were carried out.

Table 6 Whole number percentage of match pair (having the same fingerprint pattern) for the 45 possible pairs (n = 282 for each pair).

%	RI	RM	RR	RL	LT	LI	LM	LR	LL
RT	58	62	61	53	**78**	55	58	63	52
RI		53	61	53	56	**66**	59	61	52
RM			65	71	60	59	**78**	63	73
RR				64	58	57	65	**81**	59
RL					53	49	68	60	**86**
LT						55	60	62	56
LI							61	60	50
LM								64	70
LR									58

To determine if the number of match pairs is race independent, a *P* value of 0.25 (> 0.05) was obtained. It was thus concluded that the number of match pairs is independent of an individual's race. Similarly, when using the test to determine if the number of match pairs is gender independent, the *P* value obtained was 0.90 (> 0.05), suggesting that the number of match pairs is also independent of one's gender.

Observations made from Table 7 further support the point that fingerprints on our corresponding fingers exhibit bilateral symmetry. It was observed that approximately two-thirds of the subjects have at least four match pairs; with the highest percentage of subjects (36.52%) having four match pairs and the second highest percentage of subjects (31.21%) having five match pairs (Table 7).

Table 7 Percentage of individuals with 1, 2, 3, 4 and 5 match pairs. The percentages highlighted in red are the highest percentages for each distribution. For overall distribution, n = 282. For Chinese, n = 160. For Indian, n = 62. For Malay, n = 60. For female, n = 142. For male, n = 140.

	No. of match pairs per person				
%	1	2	3	4	5
Overall	1.77	7.80	22.70	**36.52**	31.21
Chinese	2.50	6.25	21.25	**38.12**	31.87
Indian	0.00	8.06	33.87	**33.87**	24.19
Malay	1.67	11.67	15.00	**35.00**	36.67
Female	1.41	9.16	23.24	**35.21**	30.99
Male	2.14	6.43	22.14	**37.86**	31.43

Uniqueness of our Fingerprint Sequences

A fingerprint pattern sequence is a specific order of patterns starting from the right thumb to the left little finger. Fig. 5 shows three subjects with two different fingerprint pattern sequences: Subject 1 has a unique sequence which is not shared by either Subject 2 or 3, while Subjects 2 and 3 share the same sequence.

Subj.	RT	RI	RM	RR	RL	LT	LI	LM	LR	LL
#1	W	**L**	L	W	L	W	W	W	W	W
#2	W	**W**	L	W	L	W	W	W	W	W
#3	W	**W**	L	W	L	W	W	W	W	W

Fig. 5 Example of the fingerprint pattern sequences of three subjects (Subj.). The fingerprint pattern sequences start from the right thumb (RT) and end on the left little finger (LL). Subjects 2 and 3 share the same fingerprint pattern sequence, which differs from the fingerprint pattern sequence of Subject 1. The differences in the 2 fingerprint pattern sequences are highlighted in red.

Based on our data, there were a total of 171 fingerprint sequences out of the 282 subjects. It was observed that there were 128 unique fingerprint pattern sequences, with each of the 128 sequences having only one subject amongst the 282 subjects with that particular sequence. However, other fingerprint pattern sequences had more than one subject sharing the same sequence. Based on the overall distribution, the most common

sequence, shared by 24 subjects, was the sequence with whorls on all thumbs and fingers. The second most common sequence, shared by 17 subjects, was the sequence with ulnar loops on all thumbs and fingers. The results are summarized in Table 8.

Table 8 Overall distribution of 171 (60.64%) fingerprint pattern sequences (seq.) among 282 subjects.

	No. of people with the specific seq.							
	1	2	3	4	5	10	17	24
No. of seq.	128	27	6	4	3	1	1	1

Further analysis of our data by race and gender led to three main conclusions:

(1) ***The most common and second most common sequences remain the same as in the overall distribution, regardless of gender.*** For females, 11 subjects shared the most common sequence (whorls on all thumbs and fingers), and 10 subjects shared the second most common sequence (ulnar loops on all thumbs and fingers). In total, there were 104 (73.24%) fingerprint sequences out of the 142 female subjects. For males, 13 subjects shared the most common sequence, and 7 subjects shared the second most common sequence. In total, there were 98 (70%) fingerprint sequences out of the 140 male subjects.

(2) ***The most common and second most common sequences for the Chinese is the same as in the overall distribution.*** For the Chinese, 17 subjects shared the most common sequence (whorls on all thumbs and fingers), and 8 subjects shared the second most common sequence (ulnar loops on all thumbs and fingers). In total, there were 109 (68.13%) fingerprint sequences out of the 160 Chinese subjects.

(3) ***For the Indians and Malays, the most common and second most common sequences are different from the overall distribution.*** For the Indians, the most common sequence was one with ulnar loops on all thumbs and fingers; shared by 4 subjects. The second most common sequence for Indians was one with whorls on all thumbs and fingers, shared by 3 subjects. In total, there were 53 (85.48%) fingerprint sequences out of the 62 Indian subjects. Similar to the Indians, the most common sequence for the Malays was the sequence with ulnar loops on all thumbs and fingers, shared by 5 subjects. There were 2 second most common sequences for Malays, shared by 4 subjects each. Both sequences consist of whorls and ulnar loops, and are shown in Fig.6 below. In total, there were 46 (76.67%) fingerprint sequences out of the 60 Malay subjects.

RT									LL
W	W	W	W	W	W	W	W	W	W
UL	UL	UL	W	UL	UL	W	UL	W	UL

Fig. 6 The 2 fingerprint sequences that are tied for the second most common fingerprint sequence for the Malays.

Conclusion

Our study has found that, among the subjects, only the percentage of plain arch on their left thumbs is similar to the international figure of 4%. Our results have also confirmed that the proportion of fingerprint patterns on all thumbs and fingers are independent of an individual's gender. Surprisingly, it was found that the proportion of fingerprint patterns on the left thumb, left middle and left ring fingers are dependent on one's race.

Based on our study's results, it was also found that the most common fingerprint pattern on our thumbs, index and ring fingers are whorls, while the most common fingerprint pattern on our middle and little fingers are ulnar loops. Additionally, out of the 45 possible pairs of fingers for each of the 282 subjects, it was observed that the highest percentages of match pair (having the same fingerprint pattern) are the corresponding fingers of our two hands. Looking at the right hand only, the highest percentage of match pair is RM-RL (70.57%) while the lowest percentage of match pair is RI-RL (52.48%). Likewise, taking a closer look at the left hand only, the highest percentage of match pair is LM-LL (69.15%) while the lowest percentage of match pair is LI-LL (49.65%). When the corresponding thumbs and fingers of both hands were paired up to obtain 5 pairs, it was found that majority of subjects have 4 match pairs.

Lastly, the most common fingerprint pattern sequence observed was the sequence with whorls on all thumbs and fingers. This sequence remains the

most common for females, males and the Chinese. For the Indians and Malays, however, the most common fingerprint pattern sequence was the sequence with ulnar loops on all thumbs and fingers.

Acknowledgements

We are grateful for the expertise and help rendered by the two fingerprint experts, namely Ms. Lee Mei Fun (Officer-in-Charge of the Fingerprint Examination Team in the Forensics Management Division of the Singapore Police Force) and Assistant Superintendent of Police Mohd Yazid Bin Abdullah (Senior Fingerprint Specialist).

We are also thankful to Mandi See Suet Ning and Ng Wei Bo, Research Assistants of the National University of Singapore Forensic Science Laboratory for their help in the editorial work of the paper. In addition, we would like to express our gratitude to Jariah Bte Abdul Nassar from NUS Department of Statistics & Applied Probability for her help in the statistical analysis of the data in this study.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

1. Yoon S, Jain A-K. Longitudinal study of fingerprint recognition. Proceedings of the National Academy of Sciences of the United States of America 2015; 112(28): 8555-8560.
2. Holder E-H, Robinson L-O, Laub J-H. The Fingerprint Sourcebook. Washington: U.S. Department of Justice, Office of Justice Programs, National Institute of Justice 2011: 72.
3. Han Y, Ryu C, Moon J, Kim H, Choi H. A Study on Evaluating the Uniqueness of Fingerprints Using Statistical Analysis. In: Park C., Chee S. (eds) Information Security and Cryptology – ICISC 2004. Lecture Notes in Computer Science 2005; 3506: 467-477.
4. Patwari P, Lee R-T. Mechanical Control of Tissue Morphogenesis. Circulation Research 2008; 103(3): 234-243.
5. Anthonioz A, Egli N, Champod C, Neumann C, Puch-Solis R, Bromage-Griffiths A. Level 3 details and their role in fingerprint identification: A survey among practitioners. Journal of Forensic Identification 2008; 58: 562-589.
6. Kellman P-J, Mnookin J-L, Erlikhman G, Garrigan P, Ghose T, Mettler E, et al. Forensic Comparison and Matching of Fingerprints: Using Quantitative Image Measures for Estimating Error Rates through Understanding and Predicting Difficulty. PLoS ONE 2014; 9(5): e94617.
7. Nanakorn S, Kutanan W, Chusilp K. An Exploration of Fingerprint Patterns and Their Concordance Among Thai Adolescents. Chiang Mai Journal of Science 2013; 40: 332-343.
8. Gan S-H, Ismail N-A, Rahman Z-A-A, Anan A. Distribution of fingerprint patterns among young adults and siblings in Malaysia. The International Journal of Medicine and Sciences 2018; 3: 11-17.
9. Cummins, H. Racial Differences in Finger-Prints. Journal of Criminal Law and Criminology 1935; 25(5): 829.
10. Fournier N-A, Ross A-H. Sex, Ancestral, and pattern type variation of fingerprint minutiae: A forensic perspective on anthropological dermatoglyphics. American Journal of Physical Anthropology 2015; 160(4): 625-632.
11. Department of Statistics Singapore. Population Trends 2020. Available at: https://www.singstat.gov.sg/-/media/files/publications/population/population2020.pdf [Accessed 1 November. 2020]
12. Triplett M, Cooney L. The etiology of ACE-V and its proper use: An exploration of the relationship between ACE-V and the scientific method of hypothesis testing. Journal of Forensic Identification 2006; 56(3): 345.
13. Classification of fingerprints, Henry System and probability. (n.d.); at p.54. Available at: http://mthsforensics.pbworks.com/f/Classification+of+Fingerprints%2C+Henry+System%2C+and+Probability.pdf [Accessed 22 Sep. 2020].
14. Statistics Solutions. Using Chi-Square Statistic in Research - Statistics Solutions (n.d.). Available at: http://www.statisticssolutions.com/using-chi-square-statistic-in-research/ [Accessed 22 Sep. 2020].
15. Astrostatistics.psu.edu. R: Pearson's Chi-squared Test for Count Data (n.d.). Available at: http://astrostatistics.psu.edu/su07/R/html/stats/html/chisq.

test.html [Accessed 22 Sep. 2020].
16. Hope A-C-A. A simplified Monte Carlo significance test procedure. J. Roy, Statist. Soc. B 1968; 30: 582-598.
17. Bansal H-D, Badiye A-D, Kapoor N-S. Distribution of Fingerprint Patterns in an Indian Population. Malaysian Journal of Forensic Sciences 2014; 5(2):18-21.
18. Champod C, Lennard C-J, Margot P, Stoilovic M. Fingerprints and other ridge skin impressions. Boca Raton, FL 2004: CRC Press.
19. Wang L, Alexander C-A. Fingerprint Patterns and the Analysis of Gender Differences in the Patterns Based on the U Test. International Transaction of Electrical and Computer Engineers System 2014; 2(3): 88-92.
20. Rignell A, Sjoqvist K-E. A Swedish method of fingerprint classification. Hereditas 1983; 98(1):115-25.
21. Sudikshya KC, Maharjan N, Adhikari N, Shrestha P. Qualitative Analysis of Primary Fingerprint Pattern in Different Blood Group and Gender in Nepalese. Anatomy Research International 2018; 3-4.
22. Fournier N-A, Ross A-H. Sex, Ancestral and Pattern Type Variation of Fingerprint Minutiae: A Forensic Perspective on Anthropological Dermatoglyphics. American Journal of Physical Anthropology 2016; 625-632.
23. Lin L, Li H, Zhang H-G, Xia Y-M, Jin L. Physical constitution and genetic relationship of Shanghai suburbia. Acta Anthropologica Sinica 21 2002; 293-305.
24. Chen Y-F, Zhang H, Lai C-H, Lu Z, Wang Z. A dermatoglyphic study of the Kavalan aboriginal population of Taiwan. Science in China Series C: Life Sciences 2007; 50(1): 135-139.
25. de Jongh A, Lubach A-R, Lie Kwie S-L, Alberink I. Measuring the Rarity of Fingerprint Patterns in the Dutch Population Using an Extended Classification Set. Journal of Forensic Sciences 2019; 64(1): 108-119.
26. Gibbs A-L, Su F-E. On Choosing and Bounding Probability Metrics. International Statistical Review 2002; 70(3): 419-435.
27. Murtagh F, Legendre P. Ward's hierarchical agglomerative clustering method: which algorithms implement Ward's criterion? Journal of Classification, 2014; 31: 274-295.
28. R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria 2017. Available at: http://www.R-project.org/. [Accessed 14 July 2020]
29. Department of Statistics Singapore. Singapore census of population 2010 statistical release 1: Demographic characteristics, education, language and religion. Available at: http://www.singstat.gov.sg/publications/publications-and-papers/cop2010/cop2010-sr1 [Accessed 10 July 2020]
30. Tan T-T-W. Introduction to Chinese culture, dialect groups and their trades. In T. T. W. Tan (Ed.), Chinese dialect groups: Traits and trades 1990; Singapore Opinion Books: 9.
31. Davidson J-W. The Island of Formosa, Past and Present. London and New York 1903: Macmillan.