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Age estimation using CT images of the pubic symphysis of Lebanese living individuals

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ABSTRACT

While the Suchey-Brooks method for age estimation is generally accepted in forensic anthropology, its accuracy varies among different populations. This retrospective cross-sectional study aims to test the reliability of the Suchey-Brooks method using Computed Tomography (CT) scans of pubic symphyses of 155 Lebanese living individuals (76 males and 79 females) aged 17 to 98 years. This study reveals that 94.9 % of the sampled individuals fell within the range of 2 standard deviations from the reference mean for predicted age. Additionally, the study assesses phase assignation, overall bias of 1.29, and overall inaccuracy of 8.09, along with strong intra and inter-observer reliability with weighted Cohen's Kappa (k) 0.901 and 0.82, respectively. Transition analysis was also used to generate new Lebanese age references. The new reference proposed in this study improves the accuracy of age estimation compared to the Suchey-Brooks method when applied to the Lebanese population.

1. Introduction

One of the main tasks of forensic anthropologists is to assist in the identification of the deceased, particularly by analyzing their skeletal remains. The process of identifying a person involves reconstructing their biological profile, which includes estimating their biological sex, age, stature, population affinity, and examining any unique identifying features [1–4]. For the living, age estimation plays a vital role in addressing legal and civil matters, especially when valid identification is unavailable. It helps establish criminal responsibility in legal proceedings, determines the legal majority for undocumented individuals, and can be performed using non-invasive imaging techniques such as Computed Tomography (CT) to minimize the need for more intrusive procedures [5]. However, forensic anthropologists and odontologists can only estimate a person's biological age, which may not perfectly align with their chronological age due to potential variances such as lifestyle, genetics, health, environmental factors, and diet. In recent years, the use of imaging has increased in forensic anthropology, such as 3D reconstructions from computed tomography images [6]. This technique enables the acquisition of bone images regardless of the condition of the remains (semi-fleshed, mummified, or burnt), making it an ideal tool for saving time and preserving skeletal samples from physical alteration by providing detail and rapid collection of structural information without removing soft tissue [6–10].

Several osteological features that are used in age estimation can be assessed through analytical techniques [11], with the pubic symphysis being one of the most well-known site [8,12–14]. It is one of the most common and dependable indicators due to distinct changes with age [1–17]. The Suchey-Brooks method [12] is the most used methodology for pubic symphyseal aging in forensic cases. Due to the accessibility of pubic cast models and the accompanying textual descriptions of age-specific phases for visual comparison, the Suchey-Brooks approach is employed by forensic practitioners globally [16]. Numerous studies have proven the accuracy of age estimation from the pubic symphyseal face using the Suchey-Brooks method on computed tomography (CT) scans on living individuals. This has been demonstrated across various populations, including but not limited to the United States [6,8], Australian [18–20], Malaysian [21], Chinese [22], South Korean [23], Indian [24], French [25–28] and Danish [29] sample groups. Savall et al. suggested that virtual reference samples could enhance age

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estimation accuracy in French individuals over 40 years old [25]. Xiong et al. found near-total agreement between phase assignments on real pubic bones and their 3D visualizations [22].

These findings emphasize the need for standardized, population-specific data in age estimation and expanding research to underrepresented regions such as Lebanon. Consequently, three main objectives were set for this study**:** (1) Test the Suchey–Brooks method for age estimation on living Lebanese individuals, ensuring its validity and accuracy for this population; (2) Calculate probability density distributions for each Suchey-Brooks (S-B) phase and provide refined age parameters for the Lebanese population using transition analysis, (3) Determine whether the 3D reconstructions of clinical CT scans overestimated or underestimated the true age and, (4) Evaluate the feasibility and simplicity of acquiring and utilizing this type of modern data, from the initial collection to practitioner observation.

2. Material and methods

2.1. Sample

The study is based on the evaluation of clinical CT scans of the pubic symphysis of 155 Lebanese patients of Middle Eastern ancestry with an almost equal representation between males (76) and females (79). The sample size in this study is larger in comparison to similar research, such as Wink's study [6] with 44 samples, but smaller than Villa et al.'s study of 319 samples [29] and Hisham et al.'s work with 355 individuals [21]. The scans from this study were obtained between 2020 and 2024 and analyzed by the first author (CM). They were obtained from the "Hôpital Notre Dame des Secours" in Byblos, Lebanon, and "St. George's University Medical Hospital" in Beirut, Lebanon, with data collection from 2023 to 2024. The scans were conducted as part of clinical care, ensuring no individual was exposed to unnecessary or repeated radiation. Given that these scans were compiled from a medical database, they were evaluated retrospectively. The minimum age of the anonymized randomly selected patient records was 17 years (female), and the maximum was 98 years (male). The study participants were categorized into age groups at 9-year intervals, except for individuals between 17 and 20. See Table 1. for the distribution of individuals by sex and known age. The mean age for females was 52 years (standard deviation = 18 years), and the mean age for males was 54 years (standard deviation = 19 years). Scans of patients with trauma, fracture, surgery, or well-known medical conditions in the pelvic area were excluded to avoid confounding variables that may distort age estimation.

2.2. Ethical Consideration

The Institutional Review Boards of both hospitals in Lebanon approved the study, ensuring it adhered to and complied with their ethical standards. In addition, the study adhered to the Universidad Complutense De Madrid Research Ethics Committee (Ref: CE_20240208_04_SAL).

Table 1
Age and sex distribution of the sample.

Known age (in age categories)	Males(n)	Females(n)	Total (n)
15–20	3	2	5
21–30	3	14	17
31–40	17	8	25
41–50	11	13	24
51–60	16	13	29
61–70	8	14	22
71–80	11	12	23
81–90	6	3	9
91–100	1	0	1
Total	**76**	**79**	**155**

2.3. CT Scanner Parameters Setting & Creation of 3D CT images

GE BrightSpeed HD 64-row CT scanner was used to acquire the reference sample with the following settings: slice thickness between 0.6 mm (N = 4) and 1.25 mm (N = 151) slice thickness, spiral pitch factor of 1, radiation dose of 6 mA, and tube voltage of 120 kV, matrix 512x512 and FOV (cm) of 25,50. Scans of the pubic symphysis of the Lebanese reference sample were saved in Digital Imaging and Communications in Medicine (DICOM) format. RadiAnt DICOM (Digital Imaging and Communications in Medicine) viewing application 4.6.5 software (Medixant, Poznan, Poland) [30] was used for 3D virtual bone reconstruction, which can be downloaded for a fee on a Windows computer. This viewer is an application for processing and displaying medical images and is used only for research and analysis. It is not intended for diagnostic purposes.

2.4. Region of Interest

Using the RadiAnt DICOM Viewer 2024.1 volume rendering technique, virtual objects of the left (side) pubic symphysis were obtained. Fig. 1 displays the reconstruction of the 3D-CT images of six Suchey-Brooks phases in RadiAnt Viewer. The virtual bone could be rotated and zoomed in the software in three dimensions, as could the dry bones in the real world. The DICOM images covered all patient identifiers except patient sex and age in years at the time of examination to protect their confidentiality. The patient's name was replaced with an ID number.

2.5. Visualization and phase assignment method

Using the Suchey-Brooks method [12], each digital model of the pubic symphysis from individuals of known sex was categorized into one of the six S-B phases without knowing the person's actual age. The Suchey-Brooks system relies on macroscopic morphological analysis of the maturation and degenerative changes in the dry pubic symphysis, categorizing individuals into six phases for both males and females, each linked to a specific age range and mean value [12,31,32]. The scores awarded were also compared to the cast models of the pubic symphysis (France Casting Trademark, Bellevue, CO) as well as with figures from the relevant literature to make the age estimate more accurate [12]. However, the volume rendering function of the RadiAnt DICOM viewer used in this study assisted in visualizing some of the key features associated with the S-B method. These included rim formation or deterioration, dorsal lipping, face depression, apex shape, possible hiatus in the upper ventral rim, and billowing and ridges (in some cases). To minimize bias in data collection, the author collecting data (CM) was blinded to the known age of the individuals in this sample. However, the sex of the individuals was known to apply sex-specific phase descriptions. All images were examined randomly and without knowledge of the patient's age during scanning.

2.6. Statistical analysis

OBSERVER AGREEMENT – Both intra- and inter-observer reliabilities were tested. Six months after the first examination, the principal observer (CM) carried out the observation of 40 random pubic symphysis cuts from the 3D CT sample of scans (19 females with a mean age of 51.6 years and 21 males with a mean age of 54.7 years), to ascertain if the phase assignment was consistent in trial 1 and trial 2. Two forensic anthropology practitioners with 10+ years of experience in the field conducted phase assignment to 10 random pubic symphysis cuts from the 3D CT sample (6 females with a mean age of 41.6 and 4 males with a mean age of 59). The squared weighted Cohen's Kappa was calculated for both [33].

DESCRIPTIVE STATISTICS & RELIABILITY OF THE REFERENCE SAMPLE – The Suchey- Brooks descriptions and illustrations for each

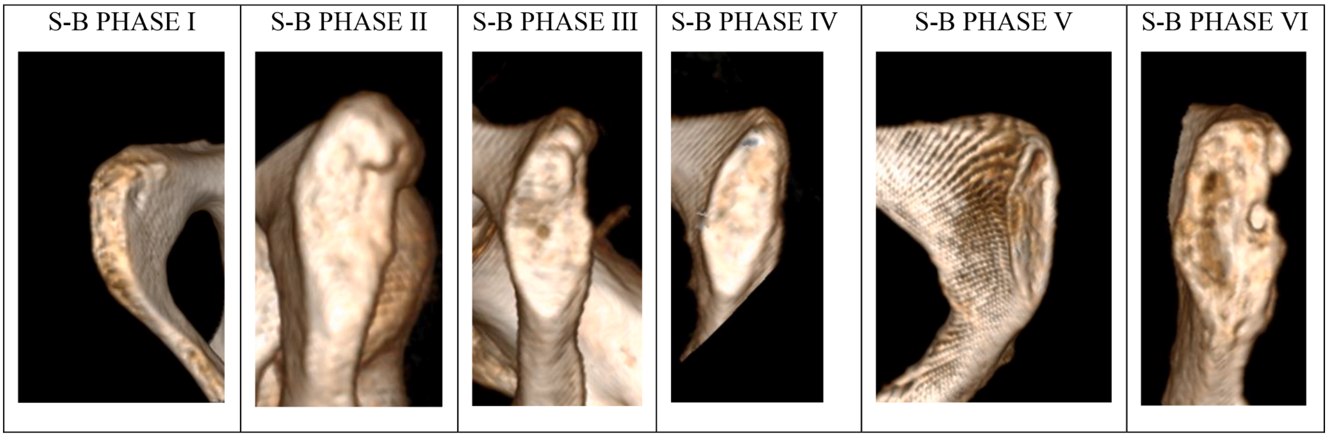

Fig. 1. Three-Dimensional reconstruction of Suchey-Brooks phases from CT scans using RadiAnt DICOM Viewer 2024.1.

phase were applied to the reconstructed CT images of the pubic symphysis. Each pubic symphysis was then assigned to one of the six Suchey-Brooks phases. The studied sample for each sex and phase was characterized by the mean, standard deviation, and 95% age range and compared with those of Suchey-Brooks. Spearman's correlation (including Spearman's rho, determination coefficient, and p-value) was used to test the correlation between age and phase [34]. The mean error, incorporating both inaccuracy and bias, between the actual and estimated ages was calculated for 10-year age intervals to compare the method's accuracy.

The inaccuracy and bias were calculated as follows:

$$Inaccuracy = \frac{\sum (|estimated\ age - known\ age|)}{n}$$

$$Bias = \frac{\sum (estimated\ age - known\ age)}{n}$$

BILATERAL DIFFERENCE – This study recognizes the possible impact of bilateral asymmetry on phase assignment for the left and right symphyseal surfaces of the same individual [18,35]. Consequently, both sides of 40 randomized CT scans (19 females, 21 males) were examined to evaluate the effects of this asymmetry on age estimation in the Lebanese sample using Wilcoxon signed-rank test analyses [35].

TRANSITION ANALYSIS – Transition Analysis (TA) was applied separately for male and female individuals within a Bayesian statistical framework to generate new age estimates. First, a restricted cumulative probit regression was fitted, obtaining the TA parameters μ and σ (mean and standard deviation). Then, assuming a Gompertz mortality model [37], hazard parameters α3 and β3 (mortality component and senescence parameter, respectively) were calculated for our sample, starting at 17 years. Using the TA and Gompertz model parameters, we obtained the Highest Posterior Density (HPD) and the Highest Posterior Density Regions (HPDR) by applying Bayes' formula as follows (see [38] for a detailed explanation of the formula):$\Pr(a|c_j) = \frac{\Pr(c_j|a)f(a)}{\int_0^\infty \Pr(c_j|x)f(x)dx}$

The HPD represents the most likely age for individuals within a particular developmental phase (based on the coverage), essentially pinpointing the age that appears most frequently within that phase. HPDRs, on the other hand, provide probabilistic age ranges. Specifically, they represent the likelihood that an individual falls within a specific age interval, given that their pubic symphysis morphology corresponds to a specific phase. These intervals function similarly to age ranges, indicating the probability of an individual's age falling within the specified range [38,39]. The width of the HPDR, or its level of coverage, is set by the observer and represents the percentage of individuals expected to fall within that range. This analysis calculated HPDRs at four confidence levels: 50 %, 75 %, 90 %, and 95 %, allowing for varied certainty levels depending on the coverage area specified, presented in Tables 7 and 8 for females and males, respectively. All statistical computations for TA and Bayesian analysis were performed in R (R Core Team, 2023).

BIAS AND INACCURACY OF THE REFERENCE SAMPLE – New bias and inaccuracy measures were used to evaluate the performance of the updated reference from the transition analysis, comparing it to the S-B method on the Lebanese sample. The goal was to determine if the new reference performed more accurately, using bias and inaccuracy as comparison benchmarks.

Statistical analyses for observer agreement, Bias and inaccuracy, bilateral variation, descriptive statistics, and transition analysis were carried out with R 3.6.2 software (R Development Core Team, http://www.R- project. org) [40].

3. Results

OBSERVER AGREEMENT- Kappa values for intra- and inter-observer agreement were excellent, with weighted Cohen's k = 0.9013 and k = 0.82, respectively, suggesting that the method is reliable and reproducible. The number of individuals whose age falls within the expected age of ± 2 Standard Deviations (SD) in trial 1 was 36/40 (90 %), and in trial 2 was 37/40 (92 %). This number of individuals within ± 2SD was expected to be equivalent for Trial 1 and Trial 2 as it was proven that there is a strong relationship between the first and second observations where overestimating or underestimating a single phase accounted for most of the errors, as seen in Table 2.

DESCRIPTVE STATISTICS & RELIABILITY OF THE REFERENCE SAMPLE –The descriptive statistics based on mean age and standard deviation for each sample phase, compared to the Suchey-Brooks, are outlined in Table 3 and Table 4. Participants were assessed to determine if their placement fell within two SD of the phase's mean age reference provided by Suchey-Brooks [12]. The results showed that 94.9 % of the individuals in this sample fell within the range of ± 2SD from the reference mean for the predicted phase. The results show that a larger number of individuals (n = 132, 85 % of the sample) were classified into

Table 2
Phase assignment in trial 1 and trial 2.

		Phase Estimation; Trial 1						
		I	II	III	IV	V	VI	Total
Phase Estimation; Trial 2	I	1						1
	II		4					4
	III			2				2
	IV			1	5		1	7
	V					6		6
	VI					3	17	20
Total		1	4	3	5	9	18	40

Table 3
Descriptive statistics of the Lebanese male sample compared to the original sample of the Suchey- Brooks.

Suchey -Brooks (N = 739)				Present study (N = 76)				
Phase	Mean	SD	95 % Range	N	Observer Mean	SD	100 % Range	Dif.* (in years)
I	18.5	2.1	14–24	**2**	18	–	–	0.5
II	23.4	3.6	17–36	**2**	21.5	2.1	[20–23]	1.9
III	28.7	6.5	20–48	**4**	34	3.6	[33–41]	−5.3
IV	35.2	9.4	22–71	**25**	40	8.6	**[23–55]**	−4.8
V	46.6	10.4	22–80	**16**	57	9.9	**[32–71]**	−10.4
VI	61.2	12.2	34–86	**27**	76	11.4	**[56–98]**	−14.8

Dif.* means the difference between mean ages of the Suchey- Brooks (1990) and the present study.

Table 4
Descriptive statistics of the Lebanese female sample compared to the original sample of the Suchey-Brooks.

Suchey- Brooks (n = 273)				Present study (N = 79)				
Phase	Mean	SD	95 % Range	N	Observer Mean	SD	100 % Range	Dif.*(in years)
I	19.4	2.6	15–24	**2**	20.5	4.9	[17–24]	−1.1
II	25	4.9	19–40	**7**	25	3.6	[20–30]	–
III	30.7	8.1	21–53	**6**	27.5	7.08	[25–43]	3.2
IV	38.2	10.9	26–70	**12**	39.5	7.32	[25–51]	−1.3
V	48.1	14.6	25–83	**13**	50	9.9	[29–63]	−1.9
VI	60.0	12.4	42–87	**39**	66	10.3	[44–82]	−6

Dif.* means the difference between mean ages of the Suchey -Brooks (1990) and the present study.

the higher phases (IV, V, and VI) compared to those classified into the lower phases (I, II, and III) (n = 23, 15 % of the sample). Nonetheless, the influence of the sample size in this study (n = 155) and the broad age range established by Suchey-Brooks [12] must be considered. The Spearman rank correlation coefficients showed that the estimated age was positively correlated with chronological age, with total rho: 0.855 and p-value $\ll 0.05$ (2.2e-16). The mean phase was observed to increase among males and females with increasing chronological age. Bias and inaccuracy statistics at 10-year intervals, when the mean sex-specific ages of the Suchey-Brooks system [12] were applied to the present study, are presented in Table 5. The highest and lowest bias values in males were 7.93 between the ages of 20 and 30 years and −36.80 between the ages of 90 and 100 years, respectively. The highest and lowest bias values in females were 3.70 between the ages of 10 and 20 years and −21.67 between the ages of 80 and 90 years, respectively. The highest and lowest inaccuracy values in males were 36.80 between the ages of 90 and 100 years and 1.95 between the ages of 10 and 20 years, respectively. The highest and lowest inaccuracy values in females were 21.67 between the ages of 80 and 90 years and 1.95 between the ages of 10 and 20 years, respectively. Although inaccuracy is a much more easily interpretable metric because it expresses the error in absolute terms, the bias allows us to determine that there is a tendency to underestimate or overestimate the age of individuals.

BILATERAL DIFFERENCE −Bilateral variation analyses showed no significant differences, as seen in the Wilcoxon signed-rank test (p-value of 0.824), which means that both left and right faces are not significantly different.

TRANSITION ANALYSIS- The transition ages for males and females across the six successive morphological phases produce five distinct distributions, each accompanied by an average age estimate and standard deviation in Table 6 and Fig. 2 for males and Fig. 3 for females. The HPDs and HPDRs for the female and male samples are shown in Table 7 and 8, respectively.

3.1. Inaccuracy and bias of the new reference ranges

Bias and inaccuracy statistics at 10-year intervals applied to the new reference sample, are presented in Table 9.

Table 6
Transition analysis parameters in years in the Lebanese sample.

Phase	Mean Age Estimate	SD	Mean Age Estimate	SD
FEMALES			**MALES**	
I-II	19.08	1.19	17.6	1.43
II-III	26.25	1.18	25.75	1.39
III-IV	31.84	1.2	30.17	1.49
IV-V	41.85	1.22	47.18	1.24
V-VI	51.96	1.19	61.88	1.22

Table 5
Inaccuracy and Bias based on sex and age.

		Inaccuracy			Bias		
	Age Range (in years)	**Overall**	**Females**	**Males**	**Overall**	**Females**	**Males**
1	(10–20]	2.82	3.70	1.95	2.82	3.70	1.95
2	(20–30]	5.84	5.36	7.93	4.02	3.12	7.93
3	(30–40]	3.86	3.23	4.16	−0.13	1.75	−1.01
4	(40–50]	8.27	6.98	9.67	−4.30	0.01	−8.97
5	(50–60]	7.23	5.19	9.03	−3.02	1.67	−7.12
6	(60–70]	8.52	7.41	10.47	−8.52	−7.41	−10.47
7	(70–80]	15.76	15.00	16.58	−15.76	−15.00	−16.58
8	(80–90]	23.98	21.67	25.13	−23.98	−21.67	−25.13
9	(90–100]	36.80	–	36.80	−36.80	–	−36.80
Overall	**9.21**				**−5.99**		

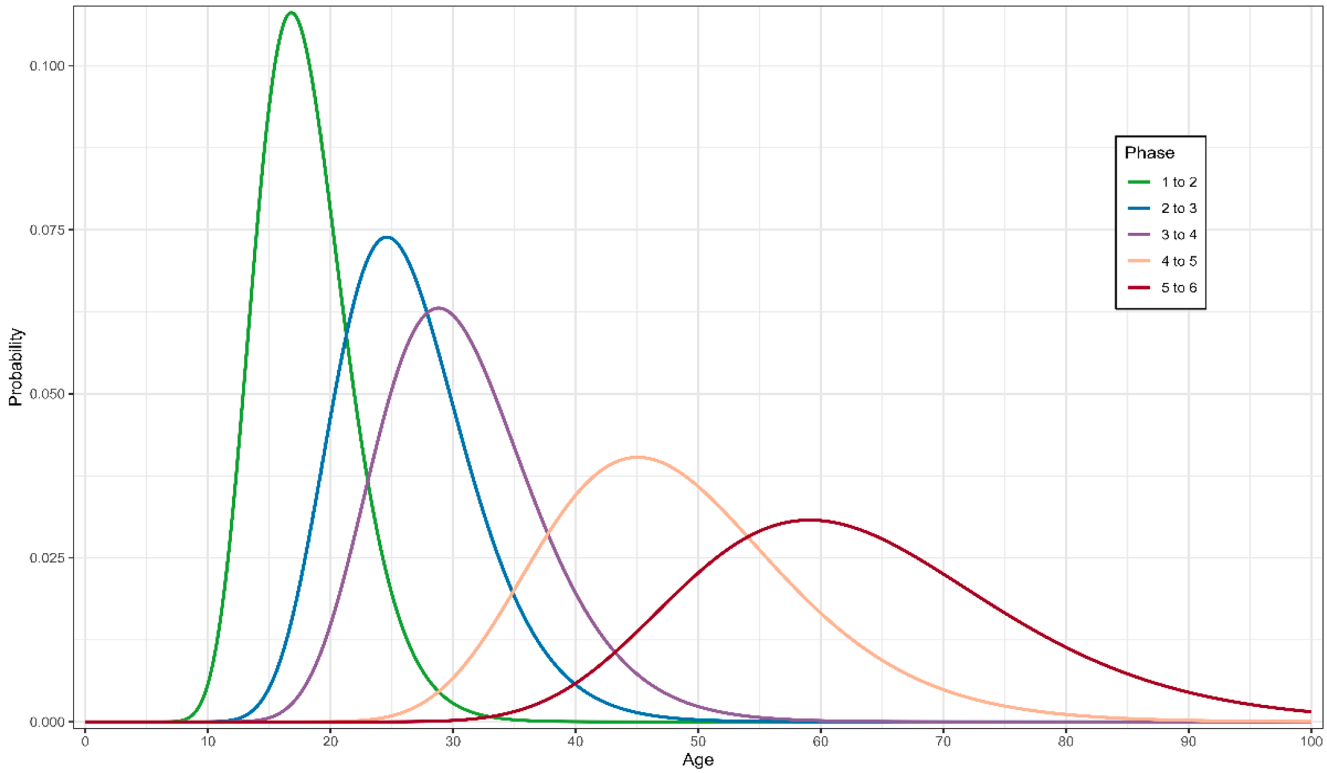

Fig. 2. Plot of probability density curves for the pubic symphysis phases TA and ages-at-transition for the Lebanese male sample.

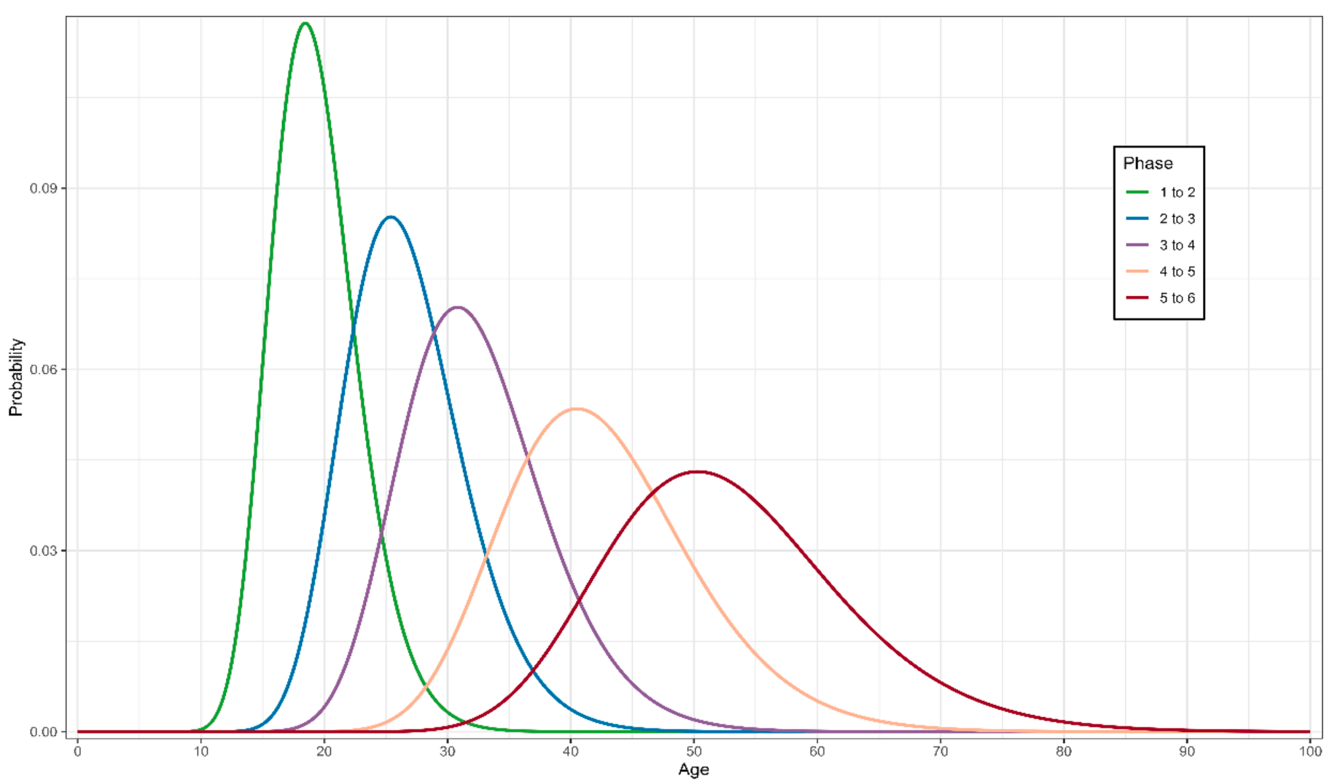

Fig. 3. Plot of probability density curves for the pubic symphysis phases TA and ages-at-transition for the Lebanese female sample.

4. Discussion

One of the main objectives of this study was to assess whether the Suchey-Brooks method produces accurate age estimates on 3D CT scans of the pubic symphysis in Lebanese individuals. This study shows that the Suchey-Brooks method, originally developed using North American human remains, yields accurate 3D pubic symphysis scores in Lebanese CT images. This aligns with Wink's findings, which showed that age

Table 7
Higher posterior density (HPD) and highest posterior density (HPDR) for females.

Phase	HPD	50 % HPDR	75 % HPDR	90 % HPDR	95 % HPDR
1	17	17–19.63	17–21.73	17–24.12	17–25.75
2	23.37	20.39–26.77	18.59–29.33	17.07–31.91	17–34.24
3	30.20	26.48–34.43	24.13–37.75	21.92–41.50	20.63–44.05
4	38.44	33.58–43.94	30.51–48.20	27.63–52.94	25.95–56.11
5	48.49	42.82–54.73	39.18–59.43	35.71–64.52	33.65–67.84
6	64.91	57.15–73.01	52.09–78.64	47.26–84.20	44.41–87.56

Table 8
Higher posterior density (HPD) and highest posterior density (HPDR) for males.

Phase	HPD	50 % HPDR	75 % HPDR	90 % HPDR	95 % HPDR
1	17	17–19.55	17–21.73	17–24.32	17–26.14
2	22.30	19.12–25.99	17.31–28.69	17–32.37	17–35.61
3	29.14	25.02–33.93	22.48–37.74	20.14–42.07	18.82–44.98
4	40.35	33.97–47.69	30.07–53.40	26.53–59.73	24.52–63.94
5	55.43	48.17–63.38	43.50–69.30	39.08–75.59	36.48–79.63
6	72.04	63.39–80.89	57.60–87.03	51.98–93.14	48.64–96.86

estimation using the Suchey-Brooks system on CT scans accurately reflected the patient's actual age in 79.5% of cases across both trials [6]. Warrier et al. concluded that the S-B method is an accurate age estimation method when applied to computed tomography (CT) scans [24]. Likewise, Hisham et al.'s results for intra- and inter-observer agreement indicate that assignation of the Suchey–Brooks phases is reproducible between observers, and this reaffirms that computed tomography may be used to visualize the pubic symphyseal face [21] effectively. Previous studies, such as Telmon et al. and Barrier et al., have used the Suchey-Brooks method to estimate the age of virtual skeletons and compared the results to physical bone samples [26,30]. Telmon et al. reported a strong agreement between the two methods (Cohen's kappa coefficient = 0.86), indicating that the Suchey-Brooks method shows similar accuracy in age estimation for both bones and CT images [26]. Conversely, Villa identified significant differences in age estimation between skeletons and 3D bone models (Cohen's kappa coefficient = 0.26) [29].

In this current study, the virtual sample demonstrates high reproducibility, achieving a weighted Cohen's kappa of 0.9013 for intra-observer reliability, which is higher than the kappa value reported by Meritt (k = 0.849) [20] and consistent with findings by Hisham et al. (k = 0.832) [21], Telmon et al. (k = 0.94) [40], Savall et al. (k = 0.90 for males and k = 0.86 for females) [42], and Lottering et al. (k = 0.92) [18]. The inter-observer reliabilities indicate that the Suchey-Brooks phase assignments are consistent between different observers, with weighted Cohen's k = 0.82 respectively, consistent with Lottering et al. (k = 0.878) [18], higher than Hisham et al. (k = 0.763) [21], and Savall et al. (k = 0.73) [42].

In this study, 94 % of the sample fell within the range of 2 standard deviations. The new reference proposed improves the accuracy of age-at-death estimation compared to the Suchey-Brooks method when applied to the Lebanese population. For instance, females Phases I and II are underestimated in the present study, by 2.4 years (Phase I) and by 1.63 years (Phase II). This may be due to the small sample size (n Phase I = 2; n Phase II = 7). Phases III, IV, and V, the attained mean ages were similar to those published by Suchey- Brooks [12]. However, for Phase VI (n = 39), the mean age in the present study is 4.91 years higher than the published data. Among Lebanese males, the mean ages of Phases I–II are consistently lower than those in the original Suchey-Brooks study, with differences ranging from 1.5 years (Phase I) to 1.1 (Phase II). However, Phases III, IV, V, and VI show progressively higher mean ages than the original sample, by 0.44, 5.15, 8.83, and 10.8 years, respectively. Overall, this study presents an enhanced age range with a narrower spread than the original Suchey- Brooks data [12].

Notably, there was a reduction in age underestimation in the later decades of life. In general, S-B seems to underage female individuals [43]. However, when comparing the new inaccuracy and bias scores, the new reference data obtained from transition analysis works best for the Lebanese population compared to the published S-B. For example, overall inaccuracy using the Lebanese sample was lower, 8.09 years (Table 9) compared to the Suchey-Brooks sample (Table 5) 9.21 years, with an overall bias score indicating slight overestimation by 1.29 years in the new study vs. the Suchey-Brooks method indicating underestimation by nearly -6 years (Table 9 vs. Table 5). Furthermore, females had lower inaccuracy than males (Table 9), especially in the age ranges of 60–70 (6.58), 70–80 (3.32), and 80–90 (9.63) versus male scores of 6.93, 6.02, and 14.29, respectively. Additionally, females aged 70–80 and 80–90 years showed bias scores of −2.96 and −9.63, which were lower than the male scores of −5.83 and −14.29 (Table 9), a trend contrary to previous studies [21 29]. Changes in hormone levels (such as estrogen levels) and childbirth, the morphological characteristics of the pubic symphysis associated with aging may differ between the sexes [44,45]. However, in our sample, the opposite trend is observed. This may be attributed to the genetic, cultural, and environmental differences in the Middle Eastern population [46]. In addition, the specific characteristics of the study sample, including size, age distribution, and sex ratio, may limit the observations. The difference may also be attributed to the female sample being particularly concentrated in the older age phases (Table 4).

This study also showed no significant differences between left and right sides, as seen in the Wilcoxon signed-rank test [36] (p-value of 0.824). Stoyanova et al. also demonstrated this [46]. Any differences in asymmetry may relate to advanced aging, weight, pathology, and/or trauma.

The Suchey-Brooks method as applied to this Lebanese sample, showed greater accuracy in younger individuals compared to the older age groups. This is consistent with studies done on Australian population [20], Thai [48], Malaysian [21], and other researchers [20,24,49], which prove that as age increases, inaccuracy and bias increase. Phase 6 of the Suchey- Brooks method is limited by its broad age ranges (42–87 for females and 34–86 for males), suggesting that individuals aged 60 to

Table 9
Bias and inaccuracy based on sex and age of the new reference sample.

		Bias			Inaccuracy		
	Age Range	Overall	Females	Males	Overall	Females	Males
1	(10–20]	0.9	1.15	0.65	1.4	1.15	1.65
2	(20–30]	3.63	1.93	11	7.28	6.32	11.47
3	(30–40]	3.55	4.08	3.31	5.74	5.3	5.95
4	(40–50]	1.3	5.78	−3.57	10.14	11.09	9.12
5	(50–60]	6.93	12.33	2.21	11.33	14.08	8.93
6	(60–70]	2.26	3.62	−0.14	6.71	6.58	6.93
7	(70–80]	−4.33	−2.96	−5.83	4.61	3.32	6.02
8	(80–90]	−12.74	−9.63	−14.29	12.74	9.63	14.29
9	(90–100]	−25.96	–	−25.96	25.96	–	25.96
Overall 1.29					**8.09**		

87 years share similar pubic symphysis characteristics. Although Hartnett [16] and Berg [44] introduced a seventh phase, their scoring relied on observations from the actual bone. It included weight as a factor, which may not be applicable unless bone density is also considered in the future. This sample included individuals up to 98 years old, but the description of phase 6 in the Suchey-Brooks method did not accurately reflect the features observed in many of the older participants. No specific phase, age range, or description could be reliably assigned to different stages of older adulthood. It is advised to investigate the incorporation of additional phases and categories for elderly individuals in the future to ensure that the method produces precise and narrower ranges.

This study employed transition analysis to establish novel, specifically tailored mean ages at transition and applied probability density distributions to evaluate the effectiveness of S–B morphological indicators in age estimation within a Lebanese population sample. The analysis revealed an overlap across five slope categories, particularly among individuals shown in Figs. 2 and 3. This overlap likely reflects age variation between individuals, which can be attributed to biological differences and genetic, lifestyle, and environmental factors that impact the timing of transitions between developmental phases. Not every individual transitions uniformly due to these unique individual factors, leading to variations in age markers.

Moreover, this study made a notable contribution by generating the first highest posterior density (HPD) ages for each S-B phase, specifically for a Lebanese sample. These HPD values are presented with corresponding probability intervals, providing valuable data that can enhance the accuracy of age estimation in forensic cases within Lebanon. These newly developed tables Table 7 and 8 are expected to aid local forensic anthropology, refining age estimation methods tailored to the Lebanese context and building on similar frameworks produced by other researchers such as Lottering et al. and Iscan et al. [18,50].

This research topic is viable since studies focusing on aging using 3D CT scans of the pelvis in the Lebanese population, have not been documented in the available literature and only scarcely in the southern Levant area [51]. Therefore, it is crucial to support the development of the discipline that can benefit the country and possibly the region, given the high workload.

4.1. Limitations

When assessing the pubic symphysis, it was observed that bone quality, surface morphology (porous or billowed), ventral ligamentous outgrowths, pubic tubercle, and the dorsal plateau, are more clearly visible in hard bone samples. The latter is also supported by Wink [5], Xiong et al. [22]., Villa et al. [29] and Savall et al. [25] who observed that only a few features were clearly visible in the CT scans. In addition, the significant variation in pubic symphysis morphology due to bone degeneration poses a notable constraint to the method. When used alone, the S-B method carries an inherent margin of error and should be complemented by other methodologies.

5. Conclusion

In conclusion, this study demonstrates the applicability and reliability of the Suchey-Brooks method on 3D CT scans of the pubic symphysis among a Lebanese population. Findings indicate that the virtual samples have high intra- and inter-observer reliability. The study reveals that the Lebanese sample achieves improved accuracy in age estimation, particularly in older age phases, by reducing the degree of underestimation observed in the original Suchey-Brooks sample. However, age estimation remains challenging in elderly phases, with a significant degree of morphological variability not adequately captured by current phase descriptions, highlighting a need for further refinement to accommodate older age groups. This research underscores the potential of virtual CT-based analysis in cases where physical bone recovery is limited, offering a reproducible and nondestructive tool that may enhance age estimation in forensic contexts. The study also addresses a notable gap in anthropological and bio-archaeological research within Lebanon and the Levant overall, positioning this reference sample as a foundational contribution to the forensic study of Lebanese and regional populations. Future research should aim to apply the new reference sample on Lebanese dry skeletal assemblages, expand virtual sample sizes, integrate additional socio-environmental variables, and explore complementary methods to refine age estimation further and broaden its forensic applicability.

A summary of this study has been presented at the Forensic Anthropology Society of Europe Symposium, August 31, 2024, at the Department of Medical Biology, Amsterdam University Medical Center (UMC), Location AMC, the Netherlands.

Ethical Approval

The Institutional Review Boards of both hospitals approved the study, ensuring it adhered to and complied with their ethical standards. In addition, the study adhered to the Universidad Complutense De Madrid Research Ethics Committee (Ref: CE_20240208_04_SAL). All CT scans were obtained retrospectively and anonymized and no identifying information was retained.

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CRediT authorship contribution statement

Cindy Mansour: Writing – original draft, Writing – review & editing, Project administration, Methodology, Resources, Conceptualization, Visualization, Investigation, Supervision, Statistical Analysis. **Nicholas Márquez-Grant:** Writing – review & editing, Conceptualization, Supervision, Methodology. **Javier Lescure:** Writing – review & editing, Statistical Analysis. **Sarah Eid:** Resources, Methodology. **María García Velasco:** Writing – review & editing. **María Benito Sánchez:** Writing – review & editing, Conceptualization, Supervision, Methodology.

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