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Evaluation of the Suchey-Brooks method of age estimation in an Australian Sub-Population using Computed Tomography of the Pubic Symphyseal Surface.

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ABSTRACT

Despite the prominent use of the Suchey-Brooks (S-B) method of age estimation in forensic anthropological practice, it is subject to intrinsic limitations, with reports of differential inter-population error rates between geographical locations. This study assessed the accuracy of the S-B method to a contemporary adult population in Queensland, Australia and provides robust age parameters calibrated for our population. Three-dimensional surface reconstructions were generated from computed tomography scans of the pubic symphysis of male and female Caucasian individuals aged 15–70 years ($n = 195$) in Amira[®] and Rapidform[®]. Error was analyzed on the basis of bias, inaccuracy and percentage correct classification for left and right symphyseal surfaces. Application of transition analysis and Chi-square statistics demonstrated 63.9% and 69.7% correct age classification associated with the left symphyseal surface of Australian males and females, respectively, using the S-B method. Using Bayesian statistics, probability density distributions for each S-B phase were calculated, providing refined age parameters for our population. Mean inaccuracies of 6.77 (± 2.76) and 8.28 (± 4.41) years were reported for the left surfaces of males and females, respectively; with positive biases for younger individuals (<55 years) and negative biases in older individuals. Significant sexual dimorphism in the application of the S-B method was observed; and asymmetry in phase classification of the pubic symphysis was a frequent phenomenon. These results recommend that the S-B method should be applied with caution in medico-legal death investigations of Queensland skeletal remains and warrant further investigation of reliable age estimation techniques.

Forensic anthropological analysis of Australian individuals is constrained by a paucity of population-specific standards for adult age-at-death estimation using the pubic symphysis. The present study investigates the application of the Suchey-Brooks (S-B) method for age estimation of the pubic symphysis in an Australian sub-population. Specifically, this study aims to (i) establish probability distributions for estimating individual male and female ages-at-death in an Australian Caucasian sub-population using a Bayesian statistical approach; (ii) report the probability of correct age classification utilizing the S-B method in an Australian sub-population and assess inter-population variation on bias and inaccuracy values of age estimation; (iii) investigate the age range in which the morphological S-B descriptors are observed in our population; and (iv) assess the impact of asymmetry and sex on the S-B phase allocations for age estimation. In this paper new probability estimates for calculating individual ages-at-death are provided for independent analysis of the left and right surfaces to increase the efficiency of medico-legal investigation of Queensland individuals based on the evaluation of the pubic symphysis.

The symphyseal surface of the pubic region of the os coxa is anatomically located at the interface between the fibrocartilage of the joint and the body of the pubis. The pubic symphysis is considered a frequent and established skeletal aging site (Aykroyd et al., 1999) as it exhibits a series of distinct morphological changes with age (Brown, 2009). Early age estimation techniques of the symphyseal surface developed by T.W. Todd (1920) were superseded by the construction of the Suchey-Brooks (S-B) method (1990). The S-B method was constructed using a large multi-racial sample from the Los Angeles County Medical Examiner's Office (n = 1012). Re-analysis of the Todd system using regression analysis by Katz and Suchey (1986) demonstrated that the combination of Todd phases I, II and III, phases V and VI and phases VII and VIII increased model performance in comparison to the original ten phase system. Consequently, the less ambiguous S-B method uses this six-phase

archetypal cast system, encompassing early and late phases, to assess age-related changes of osteological features of the male and female pubic symphyseal surface. In an assessment of the accuracy of major symphyseal age determination techniques using retrospective Joint POW/MIA¹ Accounting Command – Central Identification Laboratory Hawaii (JPAC-CIL) data derived from deceased military personnel between 1972-2008, Brown (2009) verified that the S-B method demonstrated the highest correct age classification (97.9%) in comparison to the McKern and Stewart (82.3%) and Todd (70%) methods.

Despite the ubiquitous use of the S-B method in forensic casework, limitations including sample composition, inter-population variation and high observer error have been frequently cited in current literature (Pasquier et al., 1999; Kimmerle et al., 2008a; Berg, 2008; Hartnett, 2010; Tocheri et al., 2002). Application of the S-B method to contemporary Balkan (Djurić et al., 2007; Kimmerle et al., 2008b) and Asian (Schmitt, 2004; Sakaue, 2006; Chen et al., 2008) populations demonstrate that a single standard of senescence for populations of different geographic locations is not appropriate for age determination due to reported variation in the magnitude of error. For example, Sakaue (2006) reports that the S-B method can be reliably applied to Japanese osteological material while Schmitt (2004) recommends that the application of the S-B method to Asian archeological remains should be avoided due to high inaccuracy values.

Furthermore, the representativeness of the S-B standards to contemporary populations has been questioned (Hoppa, 2000) due to secular trends, increase in longevity and the influence of factors including nutrition, physical activity type and frequency, health care access and socio-economic status (Lai et al., 2008; Langley-Shirley and Jantz, 2010). However, evidence is lacking in the current field of literature as the methodological approaches for the majority of studies evaluating S-B methodology are limited to historical

osteological skeletal collections. This promotes the importance of calibrating current aging techniques to model a contemporaneous population.

The S-B system does not account for bilateral asymmetry associated with genetic determinants, biomechanical factors and environmental stress (Albert and Greene, 1999; Halgrimsson, 1999; Boulay et al., 2006; Overbury et al., 2009) with phase allocation originally constructed from left symphyseal surfaces. Both Schmitt (2004) and Overbury et al. (2009) have reported asymmetries in phase allocation for left and right symphyseal surfaces attained from the same individual. Refinements of the S-B method based on asymmetry have not been developed despite the findings of these recent studies. Current studies either (i) provide an average age estimate for the pair of surfaces (Schmitt, 2004; Djuric et al., 2007; Kimmerle et al., 2008b) or (ii) incorporate the left (Godde and Hens, 2012) or right (Sakaue, 2006) surface in isolation, in their methodological approaches. The present study acknowledges the influence of bilateral asymmetry on age estimation, thus reporting independent statistical analysis and age parameters for the examination of the left and right surfaces of Australian individuals.

Utilizing contemporary post-mortem computed tomography (CT) for data acquisition, the methodological approach of this study advances Australian forensic anthropological research capabilities, which are constrained by an absence of osteological collections and lack of skeletal reference material. In this study visualization protocols for non-destructive, three dimensional (3D) examination of the symphyseal surface have been formulated utilizing CT imaging. Similar methodological approaches are utilized by the Centre of Forensic Science, The University of Western Australia (Franklin et al., 2012) and The Victorian Institute of Medicine, Melbourne (Bassed et al., 2011). The accuracy attributed to age estimation using visualization modalities such as CT has been validated through baseline studies in our laboratory and several published studies (Pasquier et al., 1999; Telmon et al., 2005; Ferrant et

al., 2009 and Tocheri et al., 2002). For example, Telmon et al. (2005) applied the S-B method to 3D CT reconstructions of the pubic symphysis and demonstrated no statistically significant difference between the application to physical bone samples and high-quality images. The scanning resolution (0.5mm/0.1mm) utilized in our study is the finest to date for any aging study, demonstrating the potential for CT imaging in routine casework proceedings specifically for high-quality visualization of fragile and decomposing material.

More recently, forensic anthropological journals have seen an influx of research implementing transition analysis coupled with Bayesian statistics for age-at-death determination (Kimmerle et al., 2008b; Langley-Shirley and Jantz, 2010; Godde and Hens, 2012.) This is the first Australian anthropological study to utilize a Bayesian statistical approach to publish calibrated age parameters for each S-B phase to reflect the senescent changes in a Queensland population.

MATERIALS AND METHODS

Population sample

The sample consisted of computed tomography (CT) scans of left and right pubic symphyseal surfaces (scanned simultaneously) obtained from 195 anonymized autopsy patients of Caucasian ancestry aged 15-70 years (male n = 119, female n = 76; Fig. 1). Samples were collected from the Queensland Health Forensic and Scientific Services (QHFSS) – Forensic Pathology Mortuary, Coopers Plains, Queensland, Australia across a seven-month duration in 2011. Ancestry data was obtained as per the ‘Queensland Health Coronial Form 1’ (determined through visual inspection and family interviews by the reporting police officer) lodged with the deceased upon arrival at the mortuary. Ethical approval for this research was granted by the Queensland Health Forensic Scientific Services -

Human Ethics Committee (FSS-HEC AU/1/1188012) and ‘Genuine Research Approval’ was granted by the Queensland State Coroner. The sample size was reliant on autopsy data and thus dependent upon unpredictable Queensland mortality rates within the study period. This resulted in a sampling bias in the older age categories in both the male and female sample.

Exclusion Parameters: Due to ethical parameters associated with this study, data collection was limited to a seven-month duration. All individuals autopsied during this period were included with the exception of Australian Aboriginal and Mongoloid individuals; individuals which exhibited pelvic fractures across the symphyseal surface or exhibited foreign bodies within the scan field; children under the age of 15 or individuals over 70 years of age.

Data acquisition and Processing

Computed Tomography scans were conducted using a Toshiba[®] Aquilion LB[™] Computed Tomography 16 slice multi-detector scanner (Toshiba Medical Systems, Minnetonka, Europe) at a 0.5mm/0.1mm slice thickness and overlap (135kV, mA varied according to Toshiba ‘Sure Exposure’). Scans specific to the anterior pelvic region with soft tissue subtraction were isolated and saved in Digital Imaging and Communications in Medicine (DICOM) format. This region of interest extended from the pubic symphyseal surface to the medial border of the obturator foramen. An independent operator (M.M) managed data acquisition prior to data processing and analysis, such that the S-B technique was applied blind to the documented age-at-death of each individual.

Amira[®] (Visage Imaging GmbH, San Diego, USA) was used as an interface for the conversion of binary DICOM data. A global threshold technique was performed to extract the bone surface from extraneous background material. The isosurface² model was converted to a stereo lithography (stl) file for Rapidform[®] XOS (INUS Technology Inc., Seoul, Korea)

processing. Rapidform[®] XOS was utilized for three-dimensional (3D) reconstruction of the symphyseal surface and subsequent morphological assessment. Utilizing the automated wire-mesh manipulation tools, the polygon mesh was optimized by re-triangulating the original coordinates of the model through interpolating mesh data and smoothing image noise.

As a consequence of the high quality scan resolution, extraneous background material, specifically image noise and extra-osseous calcifications in the ligaments and muscles surrounding the pubic symphysis, were visualized for individuals over the age of 60 years. This increased the complexity of isolating the surface using the above protocol and therefore limited the breadth of samples examined in the older age categories due to compromised visibility of the symphyseal surface. These calcifications are likely to have become more severe and frequent with increasing age and hence this study was restricted to individuals up to the age of 70 using the current non-invasive CT protocol to maintain high visibility and avoid distortions of the pubic symphysis. Furthermore, since samples were sourced from standard QHFSS autopsy operating procedures, few individuals over the age of 70 years are subject to external autopsy due to the higher frequency of death by natural causes; therefore limiting the sample demographics to individuals aged 15-70 years.

Scoring and morphological analysis of the Pubic symphysis

Utilizing the S-B method, each digital pubic symphyseal model of known sex was classified into early/late stage of one of the six S-B phases, blind to the actual age of the individual (N.L). Suchey-Brooks pubic symphyseal plaster casts scanned under the same CT data acquisition protocol were used for comparative reference during scoring. The estimated age was considered as the mean age of the obtained phase using the S-B method for utilization in the calculation of inaccuracy and bias. Once age-at-death had been estimated, the actual age was provided by QHFSS and associated statistical analysis performed.

For each S-B phase, the morphological descriptors that complement the S-B method were used to aid in phase classification (Brooks and Suchey, 1990). To assess the applicability of the S-B method, the pubic symphysis of each individual (right surfaces reported only) was examined for the presence of the morphological features provided in the S-B technique's descriptors (for example, ossific nodules and ventral beveling) blind to the actual age of the individual. The percentage frequency of appearance and corresponding age ranges in which each feature was observed in each S-B phase were calculated.

Observer error

Ten percent of samples were randomly selected to assess intra- and inter-observer variation in phase classification of the S-B method. Spearman's rank correlation coefficients (r_s) and a weighted Kappa Statistic were calculated to evaluate the consistency between observer scores. Kappa measures the agreement between the observers adjusted by the amount of agreement expected by chance alone. A kappa value of 1 indicates perfect agreement, while a kappa of 0 favors chance. For the theoretical basis underlying the Kappa Statistic, refer to the work of Ferrante and Cameriere (2009).

Probit regression and Bayesian analysis

Consistent with methodology by Langley-Shirley and Jantz (2010), Kimmerle et al. (2008b) and Konigsberg et al. (2008), transition analysis and Bayesian statistics were conducted to obtain age ranges to model the Queensland population. Transition analysis was performed separately for left and right surfaces using the Fortran-based Nphases2 program developed by Dr. Lyle Konigsberg (<http://konig.la.utk.edu/nphases2.htm>), which performs a logistic regression wherein the intercept and slope are converted to the mean and standard deviation (Boldsen et al., 2002). A log-age cumulative probit model was used for the transition

analysis to calculate the mean and standard error of the ages-of-transition for each phase (Kimmerle et al., 2008b). Transition analysis and Bayesian statistical results for the left symphyseal surface will be reported in text, unless specified otherwise. As it is the intention of this paper to determine the applicability of the S-B method, results pertaining to the left side are emphasized as the S-B technique was originally designed using left symphyseal surfaces in isolation. However, independent results of the right and left surfaces are published in the tables accompanying this paper as our research team encourages independent application of the age-parameters depending on the surface recovered.

Bayes' Theorem

The probability that an individual is a specific age at the time of death is estimated from a particular phase conditional on age, using Bayes' Theorem (Konigsberg et al., 1994; Lucy et al., 1996; Boldsen et al., 2002; Konigsberg and Frankenberg, 2002; Kimmerle et al., 2008b). The posterior probability is proportional to the product of the prior probability and likelihood ratio. Bayes' Theorem is represented below:

$$\Pr(a|c_j) = \frac{\Pr(c_j|a)f(a)}{\int_0^{\infty} \Pr(c_j|x)f(x)dx}$$

$\Pr(c_j|a)$ is the probability of obtaining the observed S-B phase from someone who is exactly a years old. This probability is obtained from the transition analysis (Langley-Shirley and Jantz, 2010); and $f(a)$ is a probability density function (PDF) for age. A Gompertz-Makeham (GM) parametric model was used to estimate the age-at-death distributions. The GM model is expressed as:

$$h(t) = \alpha_2 + \alpha_3 \exp(\beta_3 t)$$

$$s(t) = \exp(-\alpha_2 t + \alpha_3 / \beta_3 (1 - \exp(\beta_3 * t)))$$

where h is the hazard rate, t is age shifted by 15 years and s represents survivorship (Konigsberg and Frankenberg, 2002; Kimmerle et al., 2008b). Due to a lack of skeletal reference material available for an Australian population, Queensland life tables and mortality data from 2008-2010 (Australian Bureau of Statistics, 2011) were used to calculate α_2 , α_3 and β_3 . The following parameters were used for our population: Male - $\alpha_2 = 0.0151$, $\alpha_3 = 0.0001$, $\beta_3 = 0.1027$; Female - $\alpha_2 = 0.0156$, $\alpha_3 = 0.0001$, $\beta_3 = 0.1194$. The GM distribution and Bayesian analysis were conducted in “R” (<http://www.r-project.org>). “R” scripts for the GM hazards and for estimating the highest posterior density regions were sourced from Dr. Lyle Konigsberg’s webpage (<http://konig.la.utk.edu>). The posterior density regions for each S-B phase are equivalent to the most likely age-at-death in each phase. These results are not “point estimates” but rather the probability estimates of the most likely age-at-death.

Estimating error and probability of age estimation using S-B

In order to assess inter-population variation, error was quantified by inaccuracy ($\sum(|\text{estimated age} - \text{actual age}|)/n$) and bias ($\sum(\text{estimated age} - \text{actual age})/n$) calculations, where n is the number of samples, *estimated age* is the mean S-B phase age and *actual age* refers to the chronological age-at-death. Inaccuracy depicts the average magnitude of absolute error and bias represents the tendency of over- or under-estimation of age in years.

Consistent with methodology by Konigsberg et al. (2008), likelihood ratios were calculated as the probability that an individual would be in the observed S-B phase conditional on the known age-at-death divided by the probability of obtaining the observed S-B phase from the “population at large”. Using an improvement Chi-square test the probability of obtaining a particular S-B phase is estimated by the observed frequency in each S-B phase dependent on mean age-at-transition calculated for our population.

In order to assess the implications of bilateral asymmetry on age-at-death estimation, left and right symphyseal surfaces were analyzed and reported as separate entities for all statistical analyses in this study. Each surface was classified into the following categories: *same-phase*, *categorical* or *greater than one phase* asymmetry as per definitions by Overbury et al. (2009).

Kolmogorov-Smirnov tests demonstrated that actual age was normally distributed in males, but not females. An improvement Chi-square test was used to assess asymmetrical differences in phase classification, while statistically significant differences in error were investigated using non-parametric Wilcoxon Signed Rank and Mann-Whitney U tests. Statistical analyses were performed in SPSS[®] v19 (SPSS Inc, Chicago, USA). Statistical significance was regarded as marginal at $p < 0.1$ and significant at $p < 0.05$.

RESULTS

Accuracy and reliability of the Suchey-Brooks method

The analysis of the application of the S-B method by a novice versus experienced anthropologist using κ statistics demonstrated that both examiners were in “almost perfect agreement” in categorization into S-B age phases ($\kappa = 0.878$), contrary to reports of high inter-observer error of the S-B technique (Kimmerle et al., 2008a). There was “substantial agreement” in intra-observer classification into S-B phases ($\kappa = 0.748$) (Viera and Garrett, 2005). The Spearman’s rank correlation coefficient demonstrated consistency of 0.92 and 0.88 for intra- and inter-observer agreement, respectively.

The Spearman’s correlation between estimated age (S-B phase) and chronological age-at-death in the Queensland cohort was 0.77 for males and 0.68 for females ($p < 0.01$) when examining the left surface of the pubic symphysis. When examining the right symphyseal

surface, the correlation coefficients were slightly higher at 0.82 for males and 0.70 for females ($p < 0.01$). The relationship between chronological age-at-death and estimated age determined by the mean of each S-B phase for both sexes are visually depicted in Figure 2 with mean and standard deviation values presented in Table 1. Figure 2 demonstrates significant error in the estimation of age using the S-B methodology on our cohort sample. Figure 2 also provides a visual representation of the prominent asymmetry in phase allocation when examining both right and left symphyseal surfaces of the same individual. In fact, bilateral asymmetry in phase classification was exhibited in 53.33% of the sample (χ^2 : 172.07(1), $p < 0.001$), with 23.59% of asymmetric surfaces exhibiting categorical asymmetry (late phase x to early phase y) and 25.64% containing asymmetry within the same phase (early phase x to late phase x). Meanwhile, significant sexual dimorphism in individuals exhibiting categorical asymmetry was noted (males: 16.41%; females: 7.18%). Asymmetry greater than one phase was noted in less than 0.85% of the population.

Population-specific mean ages-at-transition and standard error, which represent the average age at which a Queensland individual is most likely to transition from one S-B phase to the next, is provided in Table 2. Figures 3 and 4 provide a visual illustration of these distributions. The varying dispersion of each distribution is indicative of the standard deviation for each transition, reflecting the age variation among phases. Considerable overlap among phases reflects the wide range of observed ages for each phase. The degree of overlap for transition distributions is greater for females in comparison to males. Furthermore, increased clustering and overlap of these distributions was observed in the right symphyseal samples for both males and females. Figures 5 and 6 represent the probability from the log-age cumulative probit model of being classified into each S-B phase at a given age. The performance of the right versus left symphyseal surface can be visualized in these figures. From the transition ages, the highest posterior density for each S-B phase was calculated with

Bayesian analysis for the Queensland population indicating the most likely age-at-death in each phase (Tables 3-4). Four different probabilities are given for each phase (50%, 75%, 90%, 95%). Individuals attributed to phases I and VI have truncated age ranges starting at 15 years and not extending beyond 70 years of age due to methodological considerations.

By applying the age-at-transition means for our population, utilization of the S-B method on left symphyseal surfaces resulted in correct age classification for 63.9% of females and 69.7% of males in the Queensland sample (Table 5). The highest percentage classification corresponded to phases I and VI regardless of sex (>75%). To test the null hypothesis that the estimated S-B phase is just as likely to come from the identified individual of a specific chronological age as from an individual selected from random, a Chi-square likelihood ratio was determined. Due to the small sample size ($n \leq 5$) of some phases in the Queensland male and female cohorts, the Chi-square likelihood ratio rather than Pearson's Chi-square statistic was used to test the null hypothesis (Agresti, 2002). The log likelihood ratios for the left surfaces of males and females were calculated as 1.25(5), $p=0.001$ and 1.33(5), $p=0.003$, respectively. Likelihood ratios greater than 1 argue for a relationship between the two variables, with increasing ratios suggesting a more convincing relationship further away from chance. Therefore we reject the null hypothesis, confirming that the likelihood of an individual being aged correctly based on S-B phase allocation is greater than chance alone for the left pubic symphyseal analysis. Upon examination of right surfaces a log likelihood ratio of 1.05(5), $p=0.048$ for males and 1.75(5), $p<0.001$ for females was calculated. This suggests that the S-B classification of right symphyseal surfaces in males is approaching the same odds as chance.

Table 6 presents the results for bias, inaccuracy and mean estimated age sub-divided by age subsets. Statistically significant differences between chronological and S-B estimated ages ($p<0.05$) were noted for males aged 15-34 and 55-70 years, as well as the 45-54 and 65-

70 year cohorts for females in the Queensland population. Bias ranged from -8.63 to 6.45 years and -7.13 to 6.88 years in males and females, respectively. Bias was greatest for individuals aged 65-70 years, irrespective of sex. Based on left surfaces, the method overestimated age in younger males and females with average inaccuracies of 6.29 (± 3.35) and 9.92 (± 4.31) years in individuals aged 15-44 and 15-54 years, respectively. Application of the method to older individuals resulted in an under estimation of age with average inaccuracies of 7.25 (± 1.20) years and 5.00 (± 3.01) years in males and females, respectively. Greatest inaccuracy corresponded to the 35-44 year subset in both male (8.79 \pm 8.21 years) and female (14.18 \pm 5.93 years) samples. The left symphyseal surface of Queensland females exhibited significantly greater inaccuracy values for the 15-24 and 35-44 year cohorts, but significantly lower values for individuals aged 55-65 years in comparison to the male sample ($p < 0.1$). Significant sexual dimorphism in inaccuracy was recorded for the right symphyseal surface of individuals in the 15-34 and 65-70 year cohorts ($p < 0.1$). Additionally, bilateral asymmetry of inaccuracy values was observed with the right surfaces of males (6.22 \pm 5.85) and females (5.89 \pm 5.67) being substantially less than the left surface (male: 6.95 (\pm 6.82), female: 6.78 (\pm 5.93)). This suggests that the left and right surfaces may exhibit differential temporal patterns of appearance of the S-B morphological descriptors which may bias age analysis depending on the surface evaluated.

Applicability of the Suchey-Brooks morphological descriptors

Less than 20.65% of the Queensland male sample exhibited morphological features specific to S-B phases I, II and VI (Fig. 7A), whilst morphological features specific to phases III to V were prominent in 63.0% of the sample. Figure 8A illustrates significant differences in the age ranges corresponding to these morphological features in phases I – VI between the reported S-B standards and the Queensland male sample. Generally the onset appearance of

the S-B morphological features occurs earlier in the Queensland male population, for all phases. More specifically, small differences were observed in phases I to IV; however, features corresponding to phases V (8.80 ± 0.80 years) and VI (19.88 ± 2.74 years) occurred significantly earlier than the S-B reported ages. The morphological features were persistent up to the age of 70 years for most phases, with descriptors specific to phases I to III seen $28.02 (\pm 8.73)$ years later, on average, than the S-B reported age range.

Generally, 59.0% of the female sample exhibited the S-B morphological features corresponding to phases III to V (Fig. 7B). Conversely, morphological features corresponding to phases I (49.26%), II (28.57%) and VI (45.06%) were less frequent in the Queensland female population. Assessment of the age ranges associated with these morphological indicators demonstrated significantly broader timings of appearance across phases I to IV in the Queensland sample (Fig. 8B) in contrast to phases V and VI, which displayed morphological features across a narrower age range. Contrary to males, the onset of morphological features had less deviation from the S-B reported ages, occurring $2.54 (\pm 9.47)$ years later across the female sample. Intriguingly the morphological features corresponding to phases I to III were prevalent $20.22 (\pm 13.89)$ years later in comparison to the S-B standard age ranges for the Queensland female population.

DISCUSSION

Whilst the application of the S-B method to a Queensland Caucasian population demonstrated correct classification more often than would be seen if an individual was selected at random from the sample, significant error associated with this method was observed. Our study supports the findings of research on Asian (Schmitt, 2004) and Balkan (Djurić et al., 2007; Kimmerle et al., 2008a) populations, highlighting problems in the extrapolation of the S-B method to populations outside the United States. Inter-population

studies assessing the applicability of the S-B method have used the mean age and standard deviation of each S-B phase to calculate the percentage correct classification, despite the broad age ranges and significant overlap represented by the S-B phases. To account for this, this study applied transition analysis to identify mean ages-at-transition and probability density distributions to demonstrate the ability of the S-B morphological indicators to discriminate age in the Queensland sample. This complements the work of Konigsberg et al. (2008) whom affirm the use of transition analysis to provide appropriate coverage in age estimation. The transition analysis results demonstrate significant overlap between phase distributions, particularly for individuals aged 18-45 years (Fig. 3 and 4) and more distinctly so for females and when evaluating right surfaces in isolation. We report for the first time highest posterior density ages for each S-B phase for an Australian sub-population with a range of probability intervals. As purported by Langley-Shirley and Jantz (2010) posterior density tables may be advantageous in a number of industry environments including forensic anthropology casework which may lead to improved age estimation in an Australian context.

In order to provide comparative data to previously published population studies, we compare the magnitude and directionality of error between the chronological and estimated ages based on mean age and standard deviation of the S-B phases. Inaccuracy in the Queensland population did not exceed 14.18 years, therefore the magnitude of error is smaller in comparison to the Thai population (17.20 years) (Schmitt, 2004) but greater than the 3.36 and 8 year inaccuracies for Spanish (Rissech et al., 2012) and Japanese (Sakaue, 2006) individuals, respectively, regardless of gender. Furthermore, caution is recommended for the comparison of the above studies to our contemporary Queensland population, as the methodological approaches of these comparative studies are limited to historical osteological collections and/or retrospective autopsy specimens.

Such demographic variability may be attributed to two parameters. Firstly, resulting from developmental advances, the S-B collection is not representative of a 21st century population. This is supported by Hoppa (2000) who identifies that age-related changes of the pubic symphysis can be significantly different ($p < 0.001$) between target and reference samples. Specifically, in a comparison between the reference distribution for the S-B method to a 20th century autopsy sample (Dade County Medical Examiner, Miami, Florida) (Klepinger et al., 1992) and the 18th-19th century Spitalfields sample (Christ Church, Spitalfields, London) (Molleson et al., 1993), Hoppa (2000) demonstrated differential timing of age-related changes in osteological features of the pubic symphysis, with significant differences in mean ages within each 10-year-subset between the populations. Studies on secular changes in diaphyseal length, cranial dimensions and the fusion of the medial clavicle (Loder et al., 1993; Meadows and Jantz, 1995; Jantz and Jantz, 1999; Jantz and Wescott, 2002; Langley-Shirley and Jantz, 2010) illustrate that modern skeletal samples are required for the maintenance of forensic standards. Skeletal acceleration has been attributed to secular changes in height, neonate and postnatal weight, and sexual maturation (menarche and puberty) due to health improvements, improved socioeconomic status and increased life expectancy (Malina, 1979; Langley-Shirley and Jantz, 2010). As a result, the importance of using contemporary populations for skeletal aging should not be underestimated.

Secondly, the S-B collection was derived from a Californian population which has a very specific, but biased racial demographic comprised of Caucasian (65.8%), Negroid (18.9%), Mexican (10.6%) and Mongoloid (2.0%) individuals and potentially excludes appropriate inter-population variability from its analysis. A study conducted by Langley-Shirley and Jantz (2010) ascertain that no significant ethnic differences between African Americans and European Americans were detected using standard age estimation methods of the medial clavicle due to the fact that factors affecting growth are similar for the American

population as a whole. Socioeconomic status and nutritional status has therefore been reported as an influential variable in maturation differences as documented by the correlation between high levels of economic progress and medical advances with earlier ossification timings (Katz and Suchey, 1986; Kemkes-Grottenthaler, 2002; Schmeling et al., 2006). Therefore the inter-population differences observed in our study compared to S-B standards may represent secular trends and/or differences in lifestyle factors in Queensland, Australian samples. Sample acquisition and analysis from other Australian states may help to assess the presence of intra-population variability in the Australian population, thus determining whether the findings of this study may be extrapolated to model the collective Australian population or are limited to the state of Queensland.

The greatest error, defined by the measure of inaccuracy was associated with Queensland individuals aged 35-44 years in both male and female samples. Such error may be correlated to inherent confusion in distinguishing between the formation and degradation of the ventral rampart, reported in this study. According to Suchey and Katz (1998) the formation of the ventral rampart peaks in the mid/late twenties, however there are outlying cases reported in individuals in the 60+ year cohort. This potentially contributes to interpretative errors of the ventral rampart, resulting in high error rates attributed to late phase III/ early phase IV in this study. These findings also suggest a 'lag' in the appearance of morphological features in the Queensland population, as this particular contingent is more commonly reported between phases III and VI (Katz and Suchey, 1986; Kimmerle et al., 2008b).

In the Queensland sample, error rates were lower for older individuals (≥ 45 years). These findings contradict studies by Komar (2003) and Berg (2008) which suggest that once an individual reaches 40 years, the S-B technique loses precision. Instead, the error associated with aging Queensland males (mean inaccuracy of 7.24 ± 1.20) and females (mean inaccuracy of 5.49 ± 2.29) greater than 45 years of age is smaller than the error attributed to younger

individuals (<45 years: Male: 6.29 ± 3.35 , Female: 4.47 ± 11.07). Thus, greater caution should be applied when aging Queensland individuals under the age of 45 years using the S-B method.

In an evaluation of the frequency and timing of the S-B morphological descriptors, the Queensland sample exhibits a delay in surface degradation with less than 30% of our cohort exhibiting morphological features specific to phase VI such as complete rim erosion or surface disfigurement. The reduced frequency of complete rim erosion may be attributed to our sample being limited by an upper threshold age of 70 years in comparison to the S-B demographics that extend to 90 years of age. Therefore, individuals older than 70 years should be investigated in future Australian age estimation studies both in terms of morphological descriptors and transition analysis distributions. Furthermore, based on the Chi-square analysis and correct age classification of individuals in phase VI being significantly higher than phases II-V, increased investigation of individuals aged 26 to 45 years is recommended within the Queensland population, particularly pertaining to the female cohort which significantly lacked samples in these age groups in the current study. The implementation of a VII phase to the S-B method as constructed by Berg (2008) which yielded greater accuracy for aging females in a Balkan population may also prove useful, but has yet to be verified on a male population. The age-at-transition of 51.68 years for phases V/VI in the Queensland male sample supports this inclusion, which is comparatively lower than the transition age of 66.1 years for a Balkan sample and 65.5 years for the Los Angeles Coroner's Office Sample (Konigsberg et al., 2008).

Sexual dimorphic differences in mean error were prominent in the application of the S-B method to the Queensland population, where inaccuracy was significantly higher in the left surface of males aged 55-64 and significantly lower in males aged 15-24 and 35-44 compared to female samples. Percentage correct classification based on transition analysis

demonstrated that 2.8% more males were aged accurately in comparison to females, however this is likely to be the result of a biased sample pool in the female cohort with 62% of the individuals falling in the S-B phase VI. Upon exclusion of individuals classified into S-B phase VI, only 40.0% of left surfaces were correctly classified. Additionally, 27.3% of the right surfaces were aged correctly in Queensland females, which suggests that age estimation is more reliable for individuals over the age of 65. This supports the consensus that female age estimation is less reliable than males (Berg, 2008; Kemkes-Grottenthaler, 2002; Winburn and Brown, 2011), despite our observation that the female Queensland pubic symphyseal surfaces exhibited a more predictable morphological pattern of aging in comparison to males. This is evidenced by the qualitative morphological examination of the S-B descriptors in the Queensland population that demonstrated that the frequency of males exhibiting the S-B features was lower than females and displayed significant variation in the timing of appearance. The timing of appearance of features occurred significantly earlier in males (15.62 ± 6.01 years earlier) than the S-B standards compared to females (2.58 ± 9.27 years later). These morphological observations support findings by Kimmerle et al. (2008a) who report that most pubic symphyses do not appear as the S-B prototypes due to skeletal variation and the unpredictable timing of morphological change. The findings of our study suggest that the S-B age ranges reported do not provide adequate specificity for a Queensland population, as 75% of the morphological descriptors span the entire Queensland cohort, starting at the age of 15 years and extending to individuals aged 65-70 years (Fig. 7B and Fig. 8B).

Asymmetry of the pubic symphysis in relation to the application of the Suchey-Brooks method for age-at-death estimation has been reported for a Thai population (Schmitt, 2004), the Hamann-Todd Osteological Collection and now an Australian population. Overbury et al. (2009) demonstrated that 63% of the Hamann-Todd Osteological collection ($n=140$) are asymmetrical, which is comparable to the 53.33% attributed to the Queensland

population in the classification of left and right surfaces from the same individual. Consistent with Overbury et al. (2009) some directionality was found, with the right symphyseal faces being slightly older on average in female samples but younger on average in male samples. Further, regardless of gender, inaccuracy values attributed to the left surfaces were substantially greater than the right, suggesting that the right surface provides more accurate age estimates. In a breakdown of the asymmetrical samples, 23.59% exhibited categorical asymmetry, where each surface was assigned to a different phase. These results recommend that caution should be applied for age estimation using a single pubic symphyseal surface in isolation. Where possible, both symphyseal surfaces should be examined in casework proceedings in Queensland, Australia to improve age estimation.

CONCLUSION

The results of this study indicate that caution should be applied to the use of the S-B method for uni-factorial age estimation in Queensland, Australian casework. However until improved methods are developed, the present study provides a revised calibration for estimating age-at-death by reporting population-specific probability density distribution tables and mean ages-at-transition through a Bayesian statistical approach. Bilateral asymmetry and sexual dimorphism were prominent features in this population, increasing the potential for error in age estimation using the S-B method. Furthermore the appearance and timing of published S-B morphological descriptors were more consistently aligned with the female Queensland sample compared to the male sample. Ongoing development of population-specific standards for Australia necessitates further data collection to increase sample size in all age categories, as well as from other ancestral groups and Australian states.

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FOOTNOTES

¹ Prisoners of War/ Missing in Action

² A three-dimensional polygonal mesh constructed from a series of contour points in a scalar field.

FIGURE LEGENDS

Fig. 1. Age and sex distribution of the study sample of Caucasians in Queensland, Australia. The frequency of male (black) (n = 119) and female (white) (n = 76) individuals in each age cohort.

Fig. 2. Comparison of chronological and estimated ages using the S-B method for Queensland individuals (A: Male, B: Female). The degree of over- or under-estimation (bias) may be seen in estimated points that fall above or below the chronological age line of points (thick black line with shaded circles). NOTE: Individual scatter points represent estimated age (S-B mean) for left and right surfaces of each individual; open circles represent that the estimated age for both surfaces was the same, while “L” and “R” symbols connected by a vertical line demonstrate bilateral asymmetry in the age estimation of one individual.

Fig. 3. Age-at-transition distributions derived from a log-age cumulative probit model for the Suchey-Brooks phases for left and right symphyseal surfaces of Queensland males.

Fig. 4. Age-at-transition distributions derived from a log-age cumulative probit model for the Suchey-Brooks phases for left and right symphyseal surfaces of Queensland females.

Fig. 5. Probabilities of the age-at-death for Queensland male individuals being classified into each of the Suchey-Brooks phases. The probability models, represented separately for each phase, are derived from the log-normal transition analysis. Left surfaces are represented by a solid line and right surfaces by a dashed line.

Fig. 6. Probabilities of the age-at-death for Queensland female individuals being classified into each of the Suchey-Brooks phases. The probability models, represented separately for each phase, are derived from the log-normal transition analysis. Left surfaces are represented by a solid line and right surfaces by a dashed line.

Abbreviations

Commence delimit	commencing delimitation of either extremity
Hor Ridging	horizontal ridge development
Lack Delimitation	lack of delimitation of lower/upper extremities
Mod rim erosion	moderate erosion of the symphyseal rim
Prom depression	prominent depression of the symphyseal face
Prom Lig Attach	prominent/ marked ventral ligamentous attachments

Prom rim erosion	prominent erosion of the symphyseal rim
PT Sep bony knob	pubic tubercle appears as a separate bony knob
SVM Resorption	resorption of the superior ventral margin
Vent Lig Attach	ventral ligamentous attachments
VR complete	complete formation of the ventral rampart

Fig. 7. Frequency of appearance of the S-B morphological descriptors in the Queensland Population (A: Male, B: Female). NOTE: Checkered bars represent morphological features that are frequently observed in the population ($\geq 50\%$ of individuals).

Fig. 8. Timing of appearance of the S-B morphological descriptors in the Queensland Population (A: Male, B: Female). The age range (minimum to maximum) in which each morphological descriptor is observed in the Queensland population (grey lines) alongside the S-B published age ranges for each morphological descriptor (black lines).