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ORIGINAL ARTICLE

Correlation of the human pubic symphysis surface with age-at-death: a novel quantitative method based on a bandpass filter

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Abstract

Age-at-death estimation from skeletal remains typically utilizes the roughness of pubic symphysis articular surfaces. This study presents a new quantitative method adapting a tool from geometric morphometrics, bandpass filtering of partial warp bending energy to extract only age-related changes of the surfaces. The study sample consisted of 440 surface-scanned symphyseal pubic bones from men between 14 and 82 years of age, which were landmarked with 102 fixed and surface semilandmarks. From the original sample, 371 specimens within Procrustes distance of 0.05 of the side-specific average were selected. For this subsample, age was correlated with total bending energy (calculated as summed squared partial warps amplitudes) for a wide range of plausible bandpass filters. For our subsample's 188 right-side surfaces, the correlation between age and bandpass filtered versions of bending energy peaks relatively sharply at $r = -0.648$ for ages up through 49 years against the first seven partial warp amplitudes only. The finding for left symphyses is similar. The results demonstrate that below the age 50, the symphyseal surface form changes most systematically related to age may be best detected by a lowpass-filtered version of bending energy: signals at the largest geometric scales of roughness rather than its full spectrum. Combining this method with information from other skeletal features could further improve age-at-death estimation based on the symphyseal pubic surface.

Keywords Age-at-death estimation · Bending energy · Pubic symphysis · Bandpass filter · Geometric morphometrics

Introduction

The human pubic symphysis is a strong and yet mobile joint with importance for human locomotion as it closes the pelvic girdle. It allows for a small amount of movement, but at the same time, it is highly resistant to shearing and compression [1]. The symphysis consists of a fibrocartilaginous disc filling the gap between the two articular surfaces of the pubic bones. Those oval pubic surfaces are slightly convex, covered in hyaline cartilage and flanked by various tendons [1, 2]. The surfaces of a bilateral pair are obliquely oriented in the sagittal plane. They are parallel in the posterior part but might diverge on the anterior, superior, and inferior parts. In young adults, the articular surfaces are irregular, but they

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become smoother around the third decade of life. After a period of subtle changes, degenerative processes appear around 50 years of age [3]. These late changes include joint narrowing, sclerosis of the subchondral bone, and surface irregularity. Such features have been used by anthropologists to estimate the age-at-death of the skeleton [2, 4–7].

As soon as the changes in the pubic symphysis were described, they were classified into "phases." Todd, in 1920, established 10 phases [2]. Suchey and Brooks, in the method still most used by today's forensic efforts, revised Todd's method, leaving only 6 phases with overlapping age groups [4]. In 2012, however, Garvin and Passalacqua [8] exposed the problems derived from subjectivity and increased observer error in the phase-based methods. They noted that almost half of the experts chose the pubic symphysis and preferentially the Suchey and Brooks method based on expertise and experience instead of the methodology itself [8]. Nowadays, age-at-death estimation is highly dependent on the training of the experts in the field for visually comparing bone morphologies to photographs of forms of known age [9, 10]. Hence, a comparison of age distribution, sex, and ancestry between the sample in hand and the sample used for erecting the method must be a component of any reliability claim [11].

Recently, computational methods have appeared [12, 13] that attempt to correct some of these problems. Perhaps the most prominent of these was published by Stoyanova et al. [14, 15] and implemented in the software package named ForAge. From a 3D model of a pubic symphysis surface, ForAge calculates three shape scores: The Slice and Algee-Hewitt score (SAH), a Bending Energy (BE) score, and a Ventral Curve score. BE measures the minimum energy needed to transform a perfectly flat, infinitely thin plate into the 3D surface model of the pubic symphysis. Together the set of three scores helps to quantify the transformations that take place on the surface of the symphysis [14, 15].

Even at the time this method was announced, however, there were some reasons to be cautious about its use of bending energy. Degenerative changes that occur after age 50, such as lipping along the borders, increased porosity or the breakdown of the margins, and the possible gap that appears on the top ventral half of the symphysis of some individuals [16] can result in high bending energy scores and thus the underestimation of ages of some old individuals.

Another reason why using bending energy with individuals past age 50 is inappropriate was described already by Todd in regard to phases 8 through 10. Among these late changes of the symphysis is the change from granular bone to a smoother one, especially posteriorly. What Meindl in 1985 [6] described as "predegenerative phases" signals the end of the role of the pubic symphysis as an age indicator of the human skeleton.

The aim of this study is to develop and test a new objective quantification of the symphyseal surface of the pubic bone for age-at-death estimation coherent both biologically and statistically. This new method removes inter-observer variation inherent to the traditional phase-based methods. One particular concern of this study is to identify an upper bound for the applicable age range. As the present study is an exploratory analysis of a new multivariate technique, it was necessary to restrict the study sample to a subset matching the assumptions of the statistical toolkit.

Material and methods

Sample

The pubic bones used in this study came from the osteological collection of the Laboratory of Anthropology of the University of Granada in collaboration with the Institute of Legal Medicine and Forensic Sciences of Granada. The sample comprised pubic bones (almost always both left and right side) of 230 male individuals, totaling 440 specimens as some hemipelves were broken or missing, from forensic cases of the twentieth and twenty-first centuries, of Spanish ethnicity and of known sex and age. Age at death, ranging between 14 and 89 years, had been confirmed by a forensic doctor in all cases by reference to legal records.

Each pubis was scanned with the Artec Spider surface scanner (Artec group; Luxembourg, Luxembourg), with a 3D resolution of 0.1 mm and a 3D point accuracy of 0.05 mm. Each bone was scanned in one pass on a rotary table, and any postprocessing needed (to delete noise from the scans or artifacts and the turntable) was done with the Artec Studio 11 software. The elapsed time between positioning each pubis and its export in.ply file format for digitization averaged 5 min. All postprocessing was conducted in orthographic view, as well as the subsequent template and landmarking process. No damaged, broken, or incomplete symphyseal surface was scanned.

We used Viewbox 4 (Viewbox 4, created by D. Halazonetis, dHAL software; Kiffissia, Greece) for landmarking of the PLY files. This software produces lists of landmarks and curves and patches of semilandmarks from PLY files. At the outset, a template is created that will be warped onto every subsequent specimen, greatly reducing the risk of errors in the order or placement of the points.

For this sample of symphyses, there were two fixed landmarks, a superior one where the margin of the symphyseal surface forms an edge with the upper surface of the pubis and an inferior one at the edge of the symphysis where it falls away from the insertion of the subpubic ligament. Between these two points, a patch of 100 surface semilandmaks collected the information about surface ridges (Fig. 1).

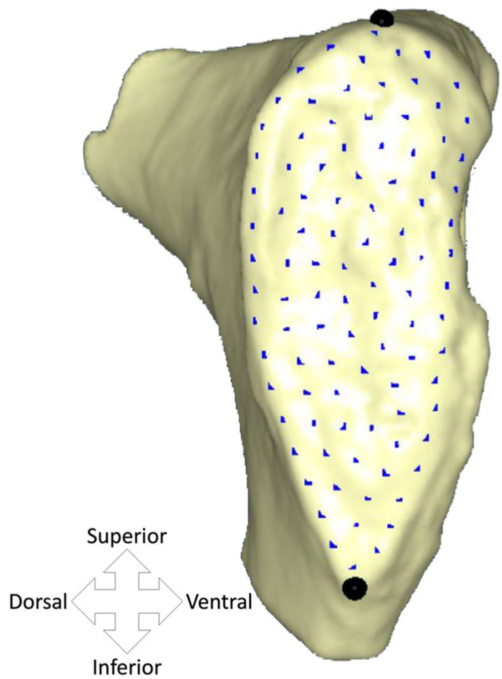

Fig. 1 3D model of a left pubic symphyseal surface. The template projected into it is based on 2 fixed landmarks (in black), one in the superior border and another in the inferior part of the symphysis. There is a patch of 100 semilandmarks (in blue) that covers the pubic surface and is limited by the ventral and dorsal borders

We did not use Viewbox's own estimate of bending energy, as it depends on the chosen template; instead, we referred our quantification to our own sample surface average.

All coordinates extracted via Viewbox were exported for analysis in R.

Todd method

The same 3D scanned sample was classified following the Todd method [2] by an independent, highly experienced expert, an assistant professor in physical anthropology at the University of Vienna who has taught sex and age determination using skeletal morphological traits in courses at all levels for more than 20 years. The ranges that Suchey-Brooks provide are, sometimes, too big for a forensic case; that is why, the Todd method is still in use. The expert was allowed to move the fully anonymized 3D scans freely, without any time limit, using Artec Studio 11 software in orthographic view and with no information beyond the specimen's sex. When the left and right hemipelves differed in assessment of Todd phase, following the recommendation in the literature [17], the older of the two was the phase assigned. The expert considered that using the 3D models was appropriate except for when senile porosity was present, as this was not reflected appropriately on the scans. Such specimens were not included for the Todd sample.

The method of bandpass filtering

The analysis in this paper improves upon the age estimation method of Stoyanova et al. [14] by exploiting a new morphometric method introduced by one of the authors in 2018: the method of bandpass filtering of the partial warp spectrum. This method was first applied by Peter Currie [18] to assess the form of the nasal septum [19]. The concept of a partial warp was introduced already in 1989 [20–22]. However, as the formulas for this method are quite technical, we introduce the concept of partial warps here by analogy with the Fourier spectrum.

Any periodic time-varying signal—say, one note of a bird song—can be decomposed into an infinite sum of simple trigonometric functions, multiples of sines and cosines. The idea of the bandpass filter used here for morphometric data is analogous to acoustic filters for sounds: A *lowpass* filter (the version we will be using here) removes the high frequencies and leaves the bass range; a *highpass* filter does the opposite, leaving only the high-frequency terms.

In morphometrics, the equivalent of the sines and cosines of a Fourier analysis is the series of partial warps of a thin-plate spline decomposition. The equivalent of the signal amplitude of a sound wave is the bending energy of a deformation encoded in the positions of landmarks and semilandmarks. A Fourier analysis starts with a low fundamental frequency, while in a partial warps analysis, this "lowest frequency" is the bending of largest scale, end-to-end of a form. This corresponds to the lowest specific bending energy, defined as the first partial warp, which is calculated as the first nonzero eigenvalue of the bending energy matrix [20–22]. On the other end of the spectrum is the bending energy of the smallest scale component of deformation, which is usually the relative spacing of the most closely spaced pair of landmarks or semilandmarks of the data template.

Continuing with this analogy, we can imagine the equivalent of bandpass filters for landmark data that work the same way they work for sounds: *lowpass filters* that remove components of high bending energy, searching for fundamental patterns. In morphometrics, this would be the restriction of an analysis to the large-scale changes of forms—growth gradients, or bends along one or two major diameters. Likewise, the *highpass filters* remove large-scale bends, in a search for small-scale folds, grooves, point sources of tissue, disarrangements of bony joints, and the like.

The decision to apply a bandpass filter must be grounded in a priori domain expertise. In our case, the deformations associated with aging of the symphyseal surface are known to involve the filling-in of the grooves in the young form and the general flattening of the symphysis surface shape over the decades. The suggestion is therefore to look at the large-scale components of surface form by applying an appropriate lowpass filter.

As in Currie [18], evaluations of bending energy were limited to one Cartesian component only, bending in the direction perpendicular to the best-fitting plane of the symphyseal surface itself.

Results

The 233 male individuals (average age of 42.05 years, SD 13.14 years) are classified following the Todd method showing that the first three Todd phases include most of the young individuals (Fig. 2). No specimen was assigned to phases IV and V although there were individuals from that age range. For phases VI to X, the variance of the group's actual ages grows more and more indicating less precision (Table 1), so that phases IX and X include individuals over the full age range. When the sample is restricted only to symphyses younger than 50 years, again two subgroups of phases appear. The first corresponds to the young individuals, and the second spans the full age range of the subsample.

A first step in geometric morphometrics, mandatory for all Procrustes analyses, is to restrict the data to a subrange of specimens that fulfill the assumptions of the statistical methods that are to follow. As this study is an exploratory analysis of a new multivariate technique, the sample must be restricted to a subset matching the assumptions of the statistical toolkit, which, for geometric morphometrics, is essentially that shapes follow a multivariate normal distribution. Under this assumption, squared Procrustes distances between specimens and the mean shape follow the Mardia-Dryden distribution, which is approximately a chi-square distribution [23]. Figure 3 shows histograms of squared Procrustes distance for our data set. Clearly, the sample as a whole does not suit these assumptions as it is not chi-square distributed. In addition to the mass of specimens near the mean, there is a scattering of extreme specimens that must all be considered "outliers" for an exploratory analysis such as ours. The importance of outlier sequestration prior to linear modeling in high-dimensional multivariate contexts like ours has recently been emphasized with great vigor by Nassim Taleb [24]. (The horizontal scale is truncated in Fig. 3; Its actual range is nearly 100 times the mean squared distance).

Therefore, we cut both of the specimen samples at a threshold $\rho^2 = 0.05$, corresponding to the upper shoulder of the distribution for the left symphyseal surface, which seems to be more variable in shape than the right surface (Fig. 3). Sample sizes thereby were reduced from 206 to 183 on the left and from 215 to 188 on the right. The curves shown in Fig. 4 are lowess regressions, which are representations of a robust local smoothed scatterplot within a moving window [25].

Figure 4 indicates that only below age 50 does bending energy decrease monotonically with age. This association is not present in older individuals, which suggests that for developing an age estimation method, specimen age should be truncated at 49. This threshold corresponds to the upper limit of Todd's class IX.

Based on these truncated samples (age under 50 years, squared Procrustes distance less than 0.05 from the mean),

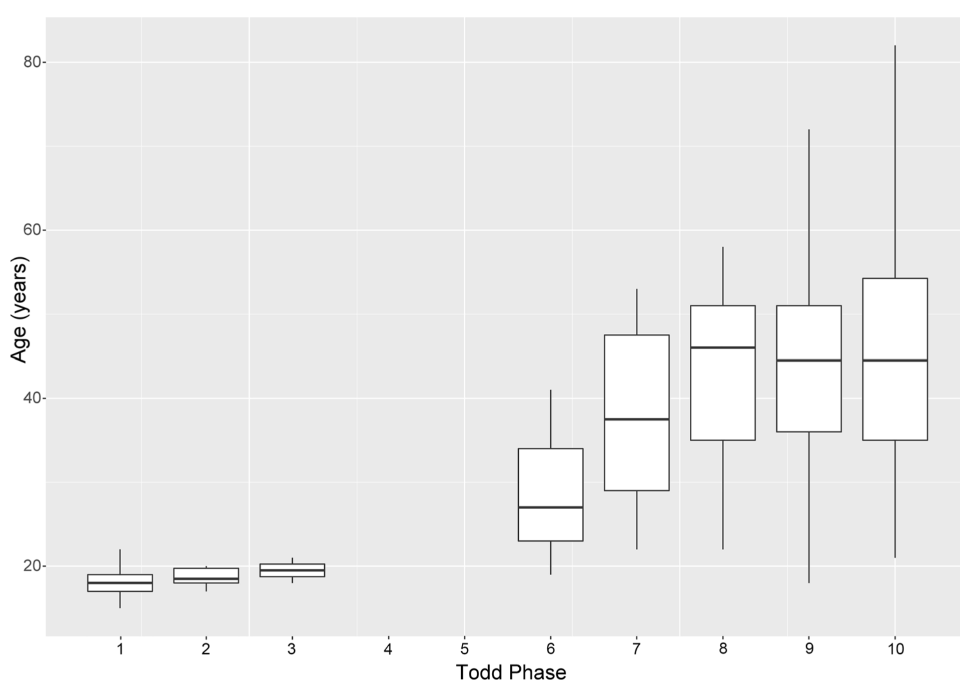

Fig. 2 Distribution of the sample along the Todd phases estimated by an expert in physical anthropology. No individual was assigned to the phases IV and V. The first 3 phases contain almost all the young individuals while the late phases (specially IX and X) contain individuals from all ages present in the sample

Table 1 Descriptive statistics for the assignments to Todd phases I to X

Descriptive statistics of the Todd phases						
	N	Minimum	Maximum	Mean	Std. Deviation	Variance
I	5	15	22	18.2	2.6	6.7
II	6	17	20	18.7	1.2	1.47
III	2	18	21	19.5	2.1	4.5
IV	0					
V	0					
VI	3	19	41	29	11.1	124
VII	8	22	53	38	11.1	122.57
VIII	45	22	58	42.8	10.5	109.91
IX	66	18	72	43.1	12.5	155.91
X	88	21	82	44.8	13	168.59

The ages of the specimen assigned to the later phases show excessive variance

we explored all the possible bandpass filters in the lower part of the bending energy spectrum. Figure 5 shows contour maps for the correlations of bandpass-filtered bending energy with actual specimen age. Clearly, the best filters start with the very first nonzero component of bending energy (partial warp 1) and stop around partial warp 7. We therefore selected this particular band for the further data analyses reported in Figs. 6 and 7.

The results under these two restrictions are summarized in Fig. 6 for the left symphyseal surfaces and in Fig. 7 for the right symphyseal surfaces. Panels (a) are replications of Fig. 5, but now for the selected bandpass filter (PW 1–7). Notice the tenfold reduction in the vertical axis range here, corresponding to the elimination of all the high-energy partial warps. The lowess regressions are consistent with those of the previous figure in indicating a major change of trend near the age of 50 years. We therefore restricted age to the range <50, resulting in subsample counts of $N=121$ (left) and $N=129$ (right) and lowess smooths that were biologically plausible (panels b). The achieved correlations are indicated in the title of the panels.

Because the problem of concern is estimating age from form, in the counter-causal direction, we modified panels (b.) by swapping the axes, placing age vertically rather than horizontally (panels c.). Results show that high bending unambiguously predicts low age, but low bending does not predict high age. After taking logarithms, which can often ameliorate such issues, we get the results shown in panels (d.), suggesting that a restriction of the domain of the technique not only to the lower age range but also to the higher bending energy range might solve this problem.

Restricting the natural logarithm of bending energy to the range >6 (implying that bending energy is greater than e^6, which is about 400) leads to the results shown in panels (e). The lowess curve for the left symphyseal surfaces in panel (e) is now adequately linear throughout its range. The curve for the right surface in panel (e), although not entirely linear, shows a correlation of -0.648 with age for the right side.

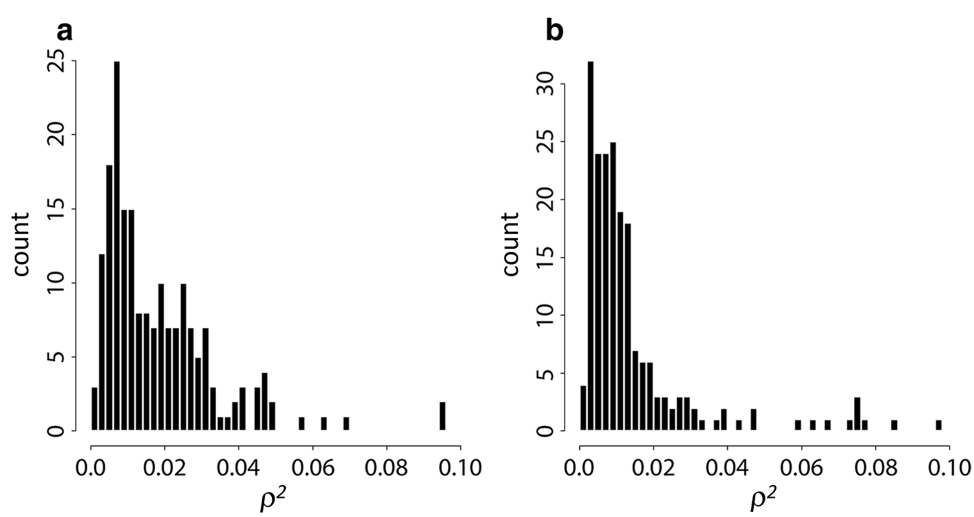

Fig. 3 Histograms of the Procrustes distance of the left (**a**) and right (**b**) symphyseal surfaces from the Procrustes mean. The charts are truncated at $\rho^2=0.1$. They suggest the threshold of $\rho^2=0.05$ used in all the analyses reported here

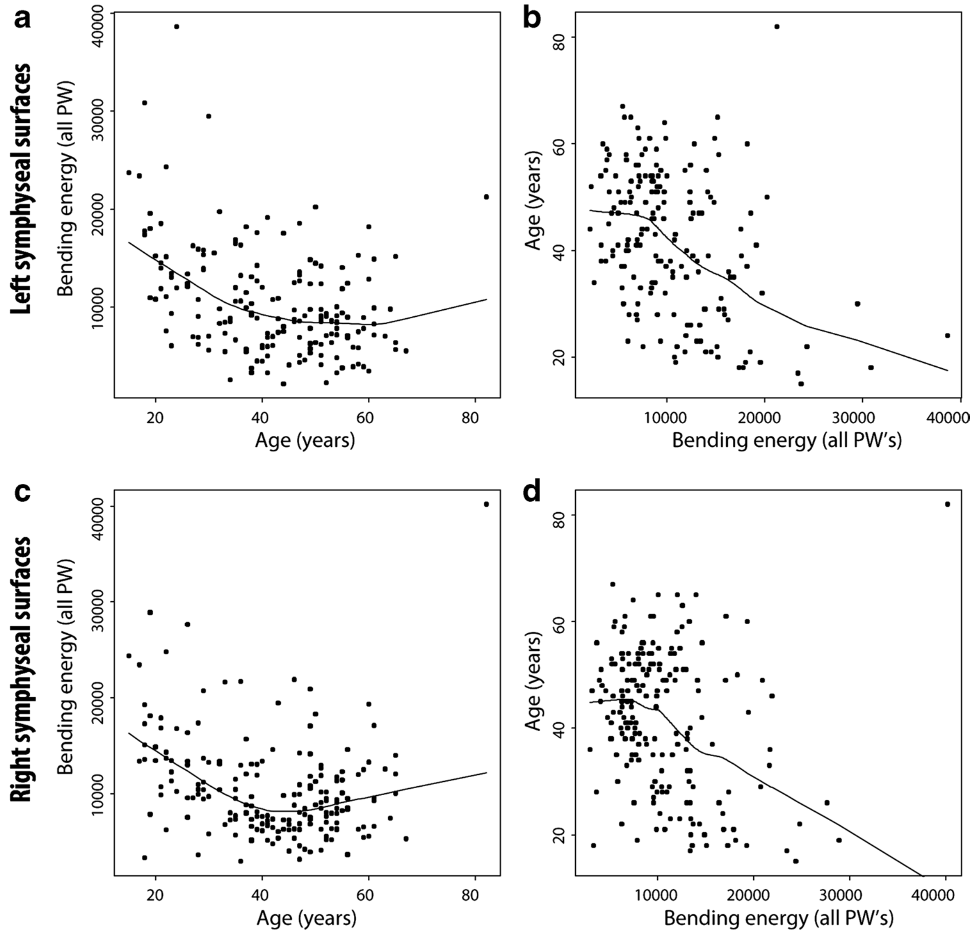

Fig. 4 Total bending energy for the male subsample of the present study, restricted to specimens with squared Procrustes distance to the mean shape of less than 0.05 (compare Fig. 3). Top row, left symphyseal surfaces, $N=183/206$; bottom row, right symphyseal surfaces, $N=188/215$. (**a**) and (**c**) Total bending energy on the vertical, age on the horizontal, with a lowess smooth of bending energy against age. (**b**) and (**d**) The reversed analysis, age on the vertical axis "regressed" on bending along the horizontal. (The analyses on the left correspond to biological processes, those on the right, to "inverse inference" in the counter-causal direction.)

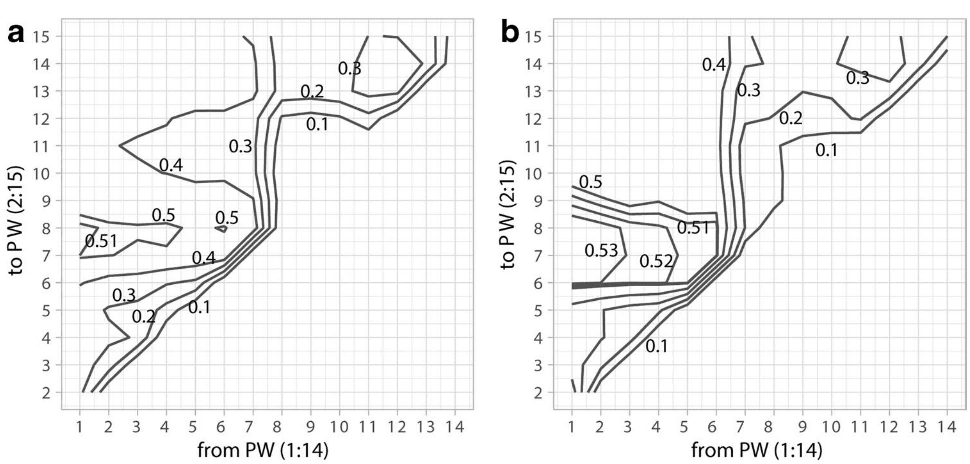

Fig. 5 Bandpass filter analysis. These are contour maps for the absolute correlation of bandpass-filtered bending energy (BE) and age for the left (**a**) and right (**b**) symphysis samples aged under 50, for all possible bandwidths between partial warps (PW) 1 and 15. Sample sizes, left, $N=121$; right, $N=129$. Left, highest contour at correlation 0.51. Right, highest contour at correlation 0.53. The selected bandpass filter for Figs. 6 and 7, common to both sides, is the band from PW1 through PW7

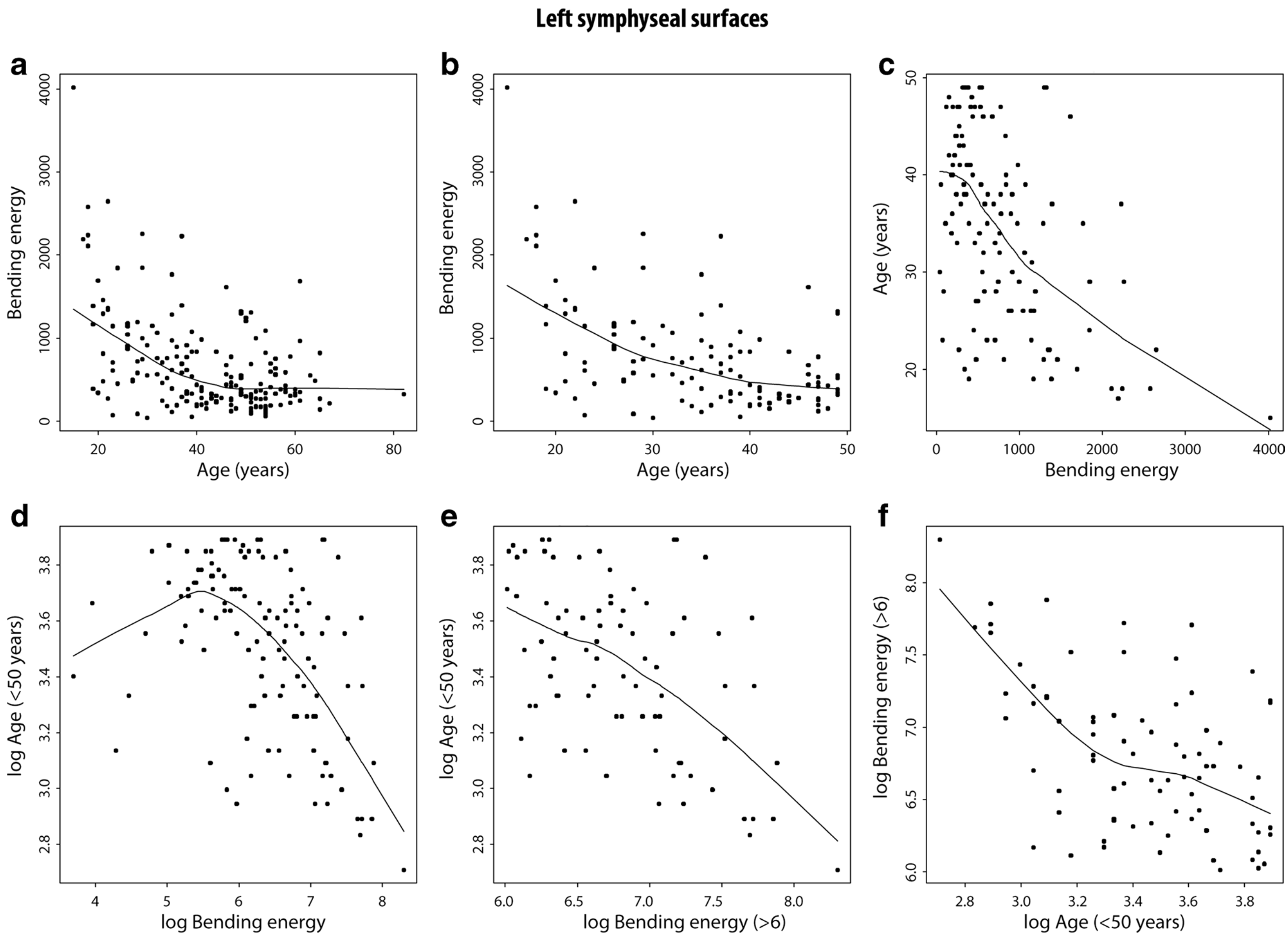

Fig. 6 Elaboration of the analysis of total bending energy, in light of the identified bandpass filter (partial warps 1–7). This figure corresponds to the left side of the symphysis. (**a**) Raw filter output (vertical) by specimen age (horizontal). (**b**) Restriction to ages under 50 (correlation of −0.51). (**c**) Reversed plots, filter output along the horizontal, age (under 50) along the vertical axis. (**d**) The same, transformed to logarithms along both axes (correlation of −0.449). (**e**) The same, restricted now only to the domains of meaningful biological trend (log bandpass-filtered bending energy greater than 6) with a correlation of −0.521. (**f**) The same, re-reversed to put the dependent variable back along the vertical axis. All curves are lowess smooths. Logarithms are to base *e* (natural logs)

Discussion

We have shown that forensic age estimation based on the quantification of the pubic symphysis of human skeletons is possible by using geometric morphometrics methods and, in particular, by applying a bandpass filter to the partial warps of the bending energy of the symphysis forms. Our ultimate finding, visualized in Fig. 7, shows that a correlation of −0.648 between age and bending energy can be achieved based on the novel method we present here. This substantially improves what can immediately be extracted from the raw data, as shown in Fig. 4, and constitutes a methodological improvement for quantitative age-at-death estimation based on the symphyseal surface.

The method presented here comprises three essential steps: (i) Restricting the age range to < 50 years, (ii) applying a lowpass filter to the bending energy of the shape data, and (iii) limiting the range of the natural logarithm of the bending energy to > 6. These limitations jointly restrict the final bending energy range to one-tenth of the range in panel (a) and hence only 1% of the original range shown in Fig. 5. Our ultimate analyses in panels (f) of Figs. 6–7, are superior to the raw analyses in panel (a) in the same figure, with which we began.

Our findings allow us to revisit the pioneering work of Todd in the 1920s and his division of symphyses into phases I–X. We confirm the validity of Todd's phases I through III, but the method we present here improves Todd's estimates for the middle range of ages. Todd's phases VIII through X all apply to symphyses that span the full age range (Fig. 2), whereas phases IV through VII seem to apply so rarely as to likely be irrelevant for forensics.

Regarding this middle range of ages, panel (e) of Figs. 6 and 7 shows that the majority of individuals that exhibit

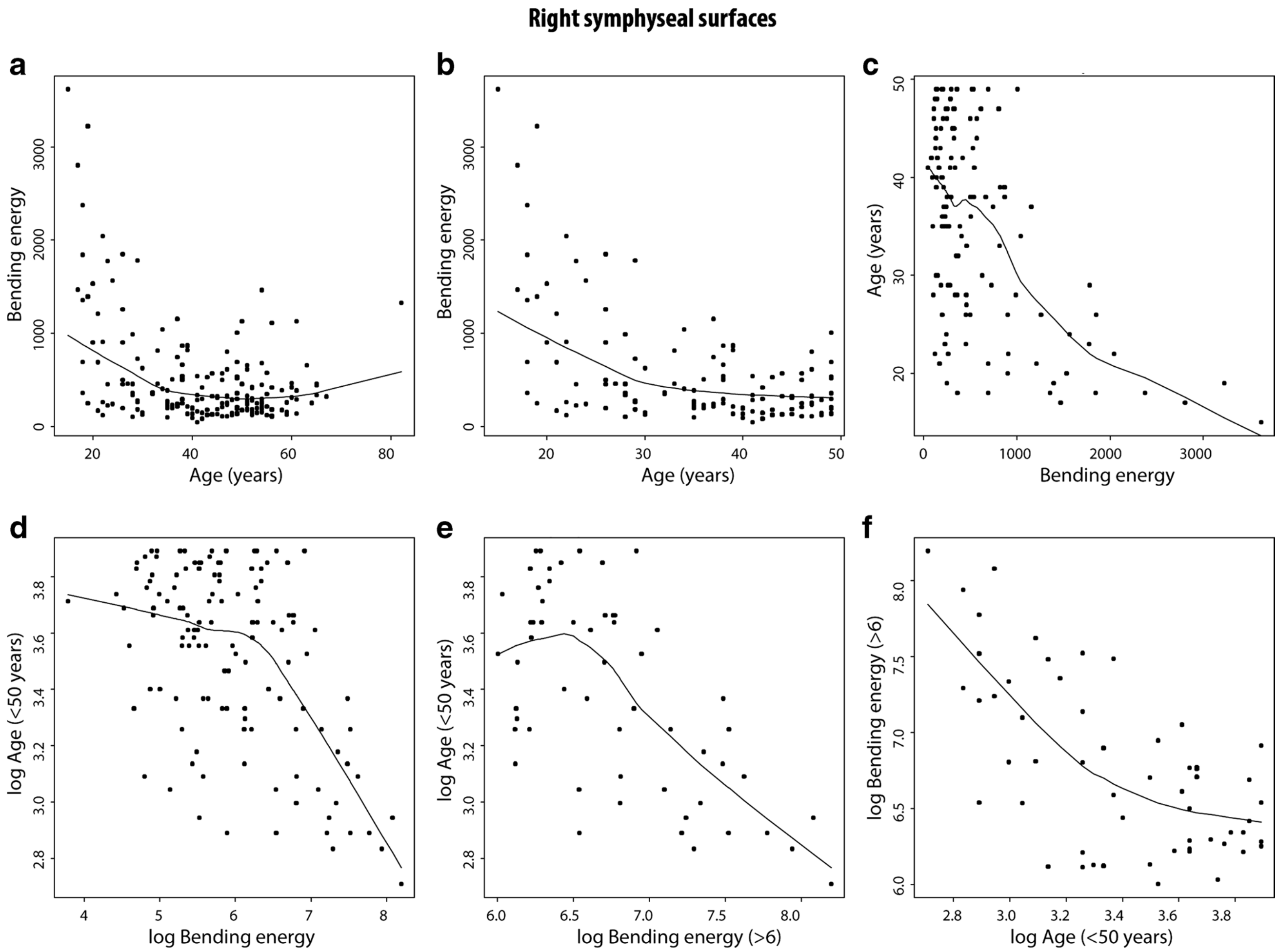

Fig. 7 Elaboration of the analysis of total bending energy in light of the identified bandpass filter (partial warps 1–7). This figure corresponds to the right side of the symphysis. (**a**) Raw filter output (vertical) by specimen age (horizontal). (**b**) Restriction to ages under 50 (correlation of −0.544). (**c**) Reversed plots, filter output along the horizontal, age (under 50) along the vertical. (**d**) The same, transformed to logarithms along both axes (correlation of −0.525). (**e**) The same, restricted now only to the domains of meaningful biological trend (log bandpass-filtered bending energy greater than 6) with a correlation of −0.648. (**f**) The same, re-reversed to put the dependent variable back along the vertical axis. All curves are lowess smooths. Logarithms are to base *e* (natural logs)

low bending energy (after application of the lowpass filter) is in the upper range of our truncated age variable (age was cut off at 49). According to panel (f), this association is a biologically meaningful one: For this age range, increasing age systematically lowers the bending energy as quantified by this specific lowpass filter.

Part of the reason for this success owes to an error in Todd's original exposition. His phases are not actual "estimates" of age. As can be seen in Fig. 2, the average ages of the symphyses in phase VIII through X are all roughly the same. Likewise, all three of the first phases have the same average age: there is no discrimination possible here [26]. Todd's phases were erroneously based on one version of the "regression to the mean" fallacy. Although several of his sample of symphyses from persons aged 40 through 44, say, looked like phase VIII, it does not follow that those symphyses that look like phase VIII should have an average age somewhere between 40 and 44. In an analysis restricted by elimination of the youngest specimens, the correlation between Todd phase VIII, IX, X, and actual age is only 0.0745. Todd's analysis, then, could be best understood as a detection of youth, not an estimation of age.

In contrast, the analysis in panels (e) and (f) of Figs. 6 and 7 is an actual biometric finding in this specific range. Both the prediction of age given lowpass bending, panel (e), and, in the opposite direction, the prediction of lowpass bending given age, panel (f), are valid biometric findings within their range of applicability. We conclude that the forensic problem in raw form, prediction of age-at-death from symphysis form across all possible age classes, does not admit to a biometrically valid solution based on our data. Methods of counter-causal "estimation" arising out of any linear multivariate computation must be restricted a priori to the domains in which those effects are linear when viewed in the causally appropriate direction.

As mentioned in the introduction, the pubic symphysis stops being an age indicator by about the age of 50. For many forensic cases, this limits what can be determined from skeletal material. The age-at-death determination of old individuals is therefore an open problem, which requires additional data. Alternative approaches try to solve this with intensive computational experiments [27, 28].

We restricted our analysis to only males because in any sample of females, potential pubic surface features may be emerging as a consequence of late pregnancy and parturition [29–32]. This might affect the age signal in a way that we were unable to assess, as information on pregnancies and births is not available for these skeletons. We do not want to speculate how parturition marks might modify bending energy. As our method requires reliable placement of many landmarks and semilandmarks, preservation of skeletal remains is an important limiting condition for the applicability of our method. Only complete adult male symphyseal surfaces under 50 years can be reliably assessed. Genetic ancestry of individuals to be aged could in addition affect the reliability of our method.

The idea of predicting age at death from symphyseal surface form is more than 100 years old. Here, we have taken a novel approach towards this problem by examining bandpass filter outputs. In this study, we exemplify an important rule of biometry: Before applying linear multivariate methods, one needs to verify first that the data under study appear to be reflecting a plausibly linear biological process in a sample for which error variance is under control [24]. Understanding the process has to precede any linear modeling. The prior explanation has to be matched to the statistical methodology that is to follow. In our work, panel (f) of Figs. 6 and 7 is coherent in this way: We achieved linearity by using the bandpass filter and thresholding it for high signal; and by cutting the age scale where the corresponding physiological process likely has ceased, meaning, before 50 years of age.

Our work offers a new objective quantification of the pubic symphysis amenable to statistical analysis that reduces the subjectivity and inter-observer variation inherent in phase-based methods of age-at-death estimation. We improved the approach of Stoyanova et al. [14, 15] by adapting some analytic possibilities offered by the spectrum associated with the thin-plate spline.

Acknowledgments This paper is dedicated to the memory of Dennis E. Slice (1958– 2019), late Professor of Scientific Computing at Florida State University and Honorarprofessor of Anthropology at the University of Vienna, whose mastery of all aspects of forensic investigations like these—not only their morphometrics but also their biology—is already sorely missed among the community he left behind. Thanks to Nicole Grunstra, Stephanie Schnorr and Lumila Menendez for the feedback that allowed us to polish the manuscript and Fernando Navarro Merino for helping with the data collection. A special mention to Martina Traindl-Prohazka for assessing the sample using the Todd method. We also want to thank the Konrad Lorenz Institute for Evolution and Cognition Research and all its members as an essential part of the intellectual and personal development needed to accomplish this work. At last, thanks to the NVIDIA Corporation (GPU-Grant).

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Data availability DOI https://osf.io/867md/.

Code availability The sample studied in this work belongs to the osteological collection of the Laboratory of Anthropology of the University of Granada, the software used for the analysis of the data is open source.

Declarations

Conflicts of interest This work is part of the doctoral dissertation of the first author, Guillermo Bravo Morante, thereby coming under the appropriate intellectual property protections of its class. University of Granada, program of biomedicine: Human evolution. Physical and forensic anthropology. Title of the thesis: “Geometric morphometrics and 3D in physical anthropology, age-at-death estimation”.

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