Age estimation using vertebral bone spurs: testing the efficacy of three methods on a European population

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Citation

Sluis, I. F. , B. , B. P. , H. , M. L. , S. , S. A. (2022). Age estimation using vertebral bone spurs: testing the efficacy of three methods on a European population. *Forensic Science International: Reports*, *6*. doi:10.1016/j.fsir.2022.100301

Forensic Science International: Reports 6 (2022) 100301

Contents lists available at ScienceDirect

Forensic Science International: Reports

journal homepage: www.sciencedirect.com/journal/forensic-science-international-reports

Age estimation using vertebral bone spurs; Testing the efficacy of three methods on a European population

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ARTICLE INFO

Keywords:
Vertebral osteophytes
Age-at-death estimation
Bioarchaeology
Forensic sciences
Forensic anthropology
Europe

ABSTRACT

Age-at-death estimation is an essential step in both bioarchaeological and forensic studies when human remains are found, as this can also contribute to the identification of the individual. It is critical that age-at-death methods be tested verified in various populations, to obtain the most accurate estimation, making research into new age-at-death methods also imperative. Since osteophyte formation on the vertebral column increases with age, this can be used as a possible method of age-at-death estimation. Snodgrass (2004), Watanabe and Terazawa (2006) and Praneatpolgrang et al. (2019) have tested this method before and have provided promising results. We test the efficacy of Snodgrass (2004), Watanabe and Terazawa (2006), and Praneatpolgrang et al. (2019) on a 19th-century archivally recorded Dutch population. A total of 88 individuals, 40 males, and 48 females were scored for the degree of osteophyte formation on the vertebral column. In addition to testing the three methods above, population-specific regression equations were developed and tested. Accuracy percentages for estimating the age-at-death based on the mean osteophyte score of the entire vertebral column were obtained for all three methods (73.86%, 76.14%, and 72.73%, respectively). In this study, a general pattern of osteophyte formation could be established, which is useful for estimating the age at death. We therefore recommend that this method can be used, cautiously as a means of age-at-death estimation.

Introduction

Estimating the age-at-death of an individual is an important step in both forensic and bioarchaeological studies as it contributes to the demographic profile of an individual and population in forensic and archaeological contexts ([16], 3). In addition, it offers an appreciation for the regional and temporal variation in the aging process ([13], 49). In forensic cases, estimating the age-at-death is crucial as it can directly contribute to a positive identification ([16], 3). For archaeology, estimating age-at-death is also very important, as this can convey paleodemographic trends and the prevalence age-controlled pathological conditions. The methods most commonly used to estimate age-at-death are cranial suture closure, dental wear, sternal rib end, pubic symphysis, and the auricular surface [1]. It is essential to investigate alternative age-at-death methods, particularly those that examine other bones to those listed above because traditional methods of age estimation often involve fragile bones (e.g., pubic symphysis, rib ends) or have been shown to have variable accuracy (e.g., cranial suture closure ([9], 9)). Additionally, it is always possible that these bones are missing either due to preservation, burial practices, or disturbance to the grave.

Osteophyte formation on the vertebral column increases with age, and the development of vertebral osteophytes has been shown to be a general indicator of age ([7], 150; [12], 1; [18], 156). Osteophytes can be defined as “abnormal bony growths or bone spurs that are bony projections formed along joints” ([3], 1) or as “a fibrocartilage-capped bony outgrowth” ([15], 237). Although osteophyte formation can occur on almost any degenerating joint, such as the hip, knee, and distal interphalangeal joints, they are most common on the vertebrae ([3], 1). Three types of osteophytes can be distinguished. First, traction spurring, which occurs at the point of tendon and ligament insertion. Second, inflammatory spurring, where the ossification of a syndesmophyte originates from the annulus fibrosis of the intervertebral discs and the spinal ligaments. This occurs, for example, in ankylosing spondylitis. A syndesmophyte can be defined as paravertebral ossification that is usually orientated vertically, whereas the osteophyte is usually orientated horizontally ([4], 1017). And finally, the genuine osteophyte or

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https://doi.org/10.1016/j.fsir.2022.100301
Received 14 June 2022; Received in revised form 26 October 2022; Accepted 11 November 2022

osteochondrophyte (chondro-osteophyte) that arises in the periosteum overlying the bone at the junction between the cartilage and the bone (van der Kraan et al., 2007, 237). This research will focus on the syndesmophyte and osteophyte formation on the vertebral column, as this is most commonly seen in the ossified ligamentous attachment of the vertebral column ([12], 2). The bony outgrowths occur in various stages. Initially starting small, bony outgrows eventually become bigger and more severe. Ultimately, it can become so severe that it can lead to ankylosis.

Previous studies—conducted on African-Americans, Japanese, and Thai populations—have indicated that vertebral degeneration is a viable method of age-at-death estimation [7,12,18]. However, the living conditions, social status, and occupations of the skeletal collections used in these studies all vary and can have a direct impact on osteophyte growths ([6], 79). Additionally, because age-at-death estimation via osteophyte formation is thought to be population-specific, it is important to expand populations under study. Here, we test the reliability of the methods developed by Snodgrass [12], Watanabe and Terazawa [18], and Praneatpolgrang et al. [7] on a 19th-century Dutch population with known age-at-death. This method has never been tested on a Western European population and, thus, will provide new, population-specific data, that can later be applied to genetically similar populations. Besides, by using three different scoring methods, it becomes possible to compare the results and to conclude which method is most accurate when studying Western European populations.

Materials

The collection that was used for this research is a 19th-century population from the Middenbeemster cemetery, which is located in northern The Netherlands (n = 412), see Fig. 1. Middenbeemster is located in the Beemsterpolder, which originated in the early 17th century, after the Beemsterlake was drained. The church, called the Keyserkerk, was built in 1618. From 1638–1829 CE burials took place both inside and outside the church. The Middenbeemster cemetery was in use form 1612–1866 CE. The population of Middenbeemster were primarily dairy farmers living in a rural environment ([5], 13). Archival records of the burials have been located, making it possible to link vertebral degeneration to known age-at-death ([5], 35; [19], 244). Individuals under 18 years of age were not included because osteophyte development in juveniles may be indicative of other conditions, such as trauma, infection, or metabolic disease [10]. This initially left 120 individuals to score for this study. However, individuals with pathological conditions, such as kyphosis, scoliosis, and Diffuse Idiopathic Skeletal Hyperostosis (DISH), were excluded (after the recommendation of [12], 1). This eventually made it possible to use a samples size of $n = 88$ individuals for this study. Age-at-death, for those individuals included in this study, ranged from 19 to 84 years (Table 1). The mean age of males is 52.3 ± 21.0, with a range of 19–84. The mean age of females is 46.9 ± 17.5, with a range of 20–80. The mean age of a combination of sexes is 49.3 ± 19.3, with a range of 19–84.

Methods

Vertebrae C2-L5 were scored for the presence and degree of osteophytes. The atlas (C1) is not included due to the lack of a vertebral body ([7], 152). In addition, vertebrae were only scored if more than 50% of the vertebral body was present. There was no minimum number of vertebrae that had to be present for observation, as one of the question to be investigated was whether the number of elements scored influences the accuracy of the model. The stage of osteophyte formation of the superior and inferior margins of the vertebral body was scored using three classification systems, namely Snodgrass (five-stage classification), Watanabe and Terazawa (four-stage classification), and Praneatpolgrang et al. (six-stage classification) ([7], 151; [12], 2; [18],

Table 1
Demographic sample size.

Sex	Age category	Number of individuals
Males (n = 40)	18 +	1
	20 – 29	7
	30 – 39	6
	40–49	3
	50 – 59	6
	60 – 69	6
	70 – 79	7
	80 – 89	4
Females (n = 48)	18 +	0
	20 – 29	12
	30 – 39	6
	40–49	8
	50 – 59	10
	60 – 69	7
	70 – 79	4
	80 – 89	1

Fig. 1. Middenbeemster cemetery, northern The Netherlands. The research area is indicated by a red dot.

157). These classification systems are shown in Table 2. Fig. 2 shows examples of no osteophyte formation (1 A/F), minor osteophyte formation (1B/G), moderate osteophyte formation (1 C/H), major osteophyte formation (1D/I), and the fusion of some vertebrae together (1E/J) ([11], 26; [12], 2). The three methods were compared to assess which method is most accurate when studying Western European populations.

After all vertebrae present were scored according to all three methods, a mean osteophyte score was calculated for the separate regions (cervical, thoracic, and lumbar) as well as the combined regions as recommended by Snodgrass, Watanabe and Terazawa, and Praneatpolgrang et al. The mean osteophyte score was calculated by dividing the sum of scores by the total number of vertebrae of that specific region ([7], 151; [12], 2; [18], 156).

The statistical analysis was performed using R, version 4.1.1 (R [8]). Age-at-death estimation equations were developed using weighted least squares (WLS) regression, due to the residuals violating the homoscedasticity assumption. Weights were estimated with a standard deviation function regressing the absolute values of the residuals from an ordinary least squares (OLS) regression on the predictor (i.e. known age). The weights were then calculated as the inverse of the squared standard deviation function. Model evaluation was conducted using R-squared (R^2), standard error of estimate (SEE), Akaike's information criterion (AIC), and accuracy of the estimate with leave-one-out cross-validation (LOOCV). Here, the accuracy was calculated as the percentage of prediction intervals that contained the known age-at-death, as well as the percentage of predictions falling within 5, 10, and 15 years of the known age-at-death.

In addition, we investigated whether the number of elements scored influences the accuracy of the model, by plotting the number of elements against the residuals. Finally, age bias tables were obtained by grouping the sample into age intervals of 10 years and calculating the mean residual error for each interval.

Results

The age distribution between males and females was examined, which is very similar in mean and curve and there are no differences between the mean scores of males and females (see S1.2 in the Supplementary Material). Because of this, we decided to combine males and females when developing regression equations to increase the sample size. The correlation between the mean osteophyte score and the known age-at-death of the males and females is a strong positive; 0.72,95%CI [0.545; 0.832], for females and 0.87, 95%CI[0.760; 0.928], for males (see Fig. 3 and Table S2.1 in the Supplementary material). The points in the scatter plots of the males and the females are virtually indistinguishable and overlapping with each other, which gives more reason to keep them grouped.

Based on the WLS regression, the entire column has the highest R^2 value, and the lumbar region the lowest for all three methods. The method from Praneatpolgrang et al. [7] performed best under AIC, with the lowest score. The Watanabe and Terazawa [18] method had the highest accuracy for the combined regions with 76.14%, followed by Snodgrass [12] with 73.86%, and Praneatpolgrang et al. [7] with 72.73% (Table 3). Age estimation for the cervical region has an accuracy of 67.74%, 66.13%, 69.36%, according to Snodgrass, Watanabe and Terazawa, and Praneatpolgrang et al., respectively. For the thoracic region this is 72,15%, 72,15%, 70,88% and for the lumbar region 79, 07%, 77,91%, 73,26%. In short, for the cervical region the method of Praneatpolgrang et al. [7] has the highest accuracy, for the thoracic region Snodgass (2004) and Watanabe and Terazawa [18] are equally reliable, and for the lumbar region Snodgrass [12] outperformed the others. Table 3 contains the regression equations that can be used to calculate an age-at-death from an osteophyte score.

We found no relationship, positive or negative, between the number of elements and the absolute value of the residuals for the combined regions; however, the accuracy of separated regions increased as the number of scored elements increased (see Figs. S4.1-S4.4 in the Supplementary Material). Therefore, we recommend scoring at least 3 elements, and preferably more, to obtain more reliable results.

Figs. 4, 5 and 6, depict the residual error by age-at-death of the entire vertebral column for the Snodgrass [12], Watanabe and Terazawa [18], and Praneatpolgrang et al. [7] methods. Here it was decided to narrow the age categories to reflect general trends in mean scores and age bias of the methods, which does not affect the robustness of our analysis. All methods display an increasing residual error with increased age-at-death. Initially, at lower ages-at-death, the points are close to the line, and somewhat evenly distributed on either side, indicating that there is little variation and relatively high accuracy. This pattern is consistent across all regions and methods (see Fig. S4.5-S4.8 in the Supplementary Material). The age bias of the methods shows an overestimation (negative residual error) of ages-at-death in younger age groups, while the older age groups are underestimated (positive residual error). The cervical region showed the largest overall age bias, while the combined regions showed the lowest bias across the majority of age groups (Table 4 and Table S4.1-S4.4 in the Supplementary Material).

The mean osteophyte score was calculated for each individual by dividing the sum of the osteophyte score by the number of vertebrae present for examination. The following applies here; the higher the osteophyte score, the more osteophyte formation was present and thus the older this individual should be. Individuals under the age of 40 never had a mean osteophyte score higher than 1.0 for all vertebral regions and the entire vertebral column. There was one exception of a female individual who had a mean osteophyte score of 1.5 for the lumbar region, while this individual was younger than 40 years old. In addition, a mean osteophyte score higher than 2.0 for all vertebral regions and the entire vertebral column never occurred in individuals under 50 years of age. Both findings could be observed by all three methods tested.

Table 2
Classification systems used to score the degree of osteophyte formation of the superior and inferior margins of the vertebral body.

Score	Snodgrass 2004 [12]	Watanabe and Terazawa 2006 [18]	Praneatpolgrang et al.[7]
0	No degenerative change	No rugged surface	No rugged surface
1	Slight lipping	Slightly rugged surface	Rugged surface prominent by less than 2 mm in length
2	Moderate lipping	Degree between score 1 and 3	Rugged surface prominent between 2 and 4.99 mm in length
3	Severe lipping	Rugged surface prominent by more than 0.8 cm in height	Rugged surface prominent between 5 and 8 mm in length
4	Ankylosis of adjacent vertebrae	–	Rugged surface prominent by more than 8 mm in length
5	–	–	Fusion of adjacent vertebrae

Discussion

It is very important to estimate the age-at-death when human remains are found in forensic or bioarchaeological contexts, as this can contribute to the identification of the individual. In order to estimate this as accurately as possible, it is critical that age-at-death methods be tested verified in various populations. Previous studies have estimated age-at-death using vertebral osteophyte formation. Similarly, other researchers have used the methods of Snodgrass [12], Watanabe and Terazawa [18], and Praneatpolgrang et al. [7]. However, these methods have been applied to non-European populations, namely African American, Japanese and Thai samples ([7], 158; [12], 6; [18], 159). This study expands the application of vertebral osteophyte formation for

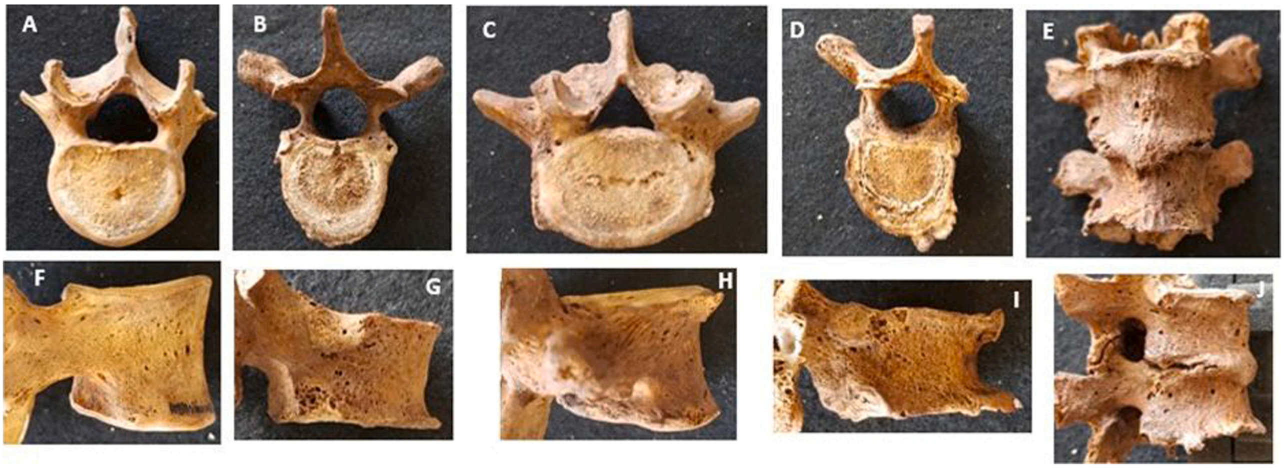

Fig. 2. The stages of osteophyte formation on the margins of the vertebral body. A/F: no osteophyte formation present. B/G: Minor osteophyte formation. C/H: Moderate osteophyte formation. D/I: Major osteophyte formation. E/J: Fusion of vertebrae due to severe osteophyte formation ([11], 26; [12], 2).

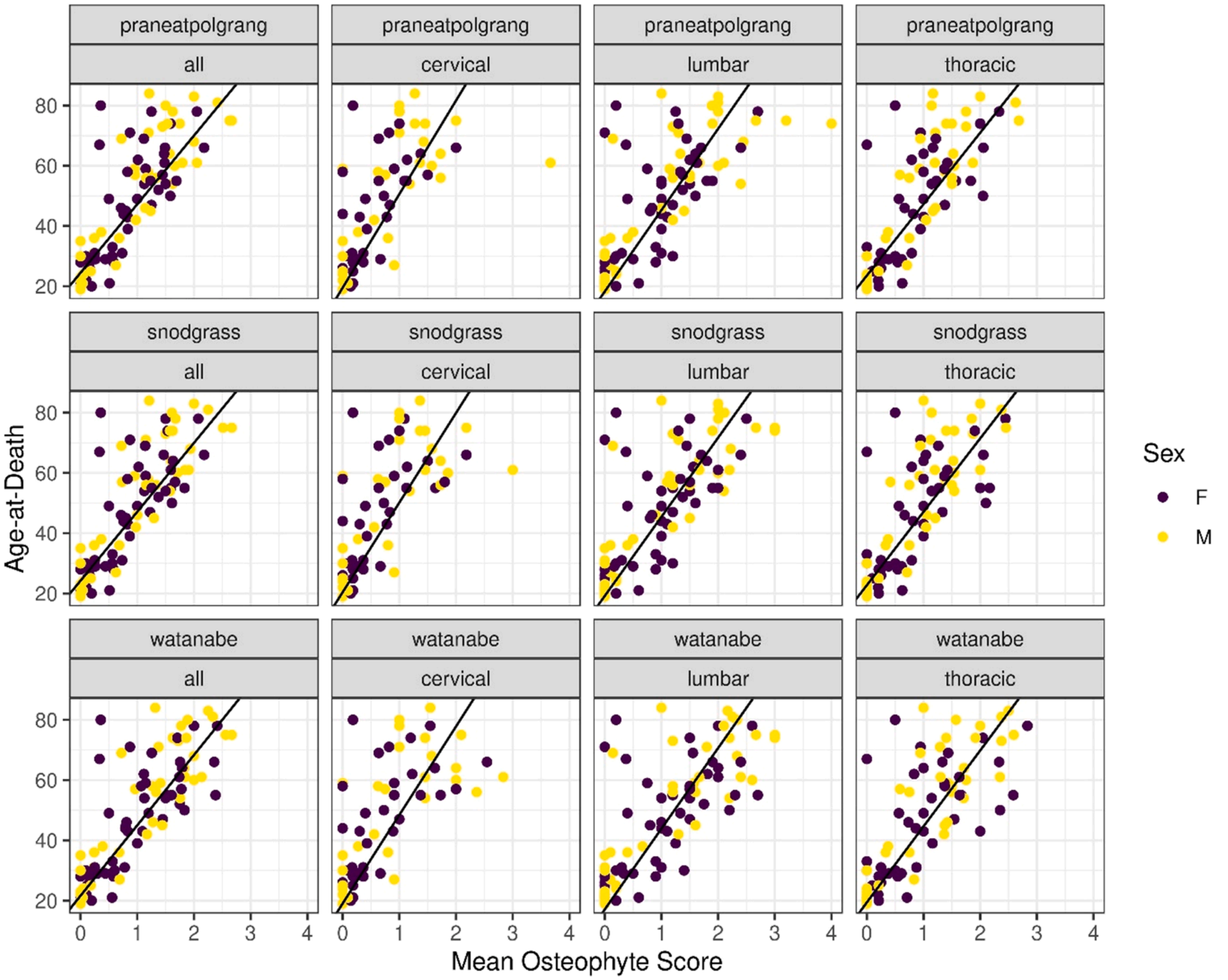

Fig. 3. Correlation scatter plots.

age-at-death estimation to, the first Western European population to be studied, a Post-medieval Dutch sample.

Regression equations were developed for each section of the vertebral column and for the combined sections, to estimate age-at-death from the degree of osteophyte formation. Overall, high correlations between the age-at-death and the mean osteophyte score were found. Accuracy percentages for estimating the age-at-death based on the mean osteophyte score of the entire vertebral column could be obtained for all three methods and are 73.86% for the method of Snodgrass, 76.14% for the method of Watanabe and Terazawa, and 72.73% for the method of Praneatpolgrang et al. Based on the R-square (R^2), the standard error of estimate (SEE) and the age bias plots, the most accurate age-at-death

Table 3

Model evaluation and weighted least squares regression. Models were built using weights estimated with a standard deviation function regressing the absolute values of the residuals on the predictor, i.e. known age. The weights were then calculated as the inverse of the squared standard deviation function.

Method	Part of spine	Number of individuals (n)	R^2	SEE	AIC	Accuracy	Regression equation
Snodgrass	Cervical	62	0.495	15.246	503.74	67.742	$y = 29.81 + 20.40x$
	Thoracic	79	0.637	13.548	615.90	72.152	$y = 24.54 + 22.62x$
	Lumbar	86	0.631	13.780	673.34	79.070	$y = 26.30 + 19.17x$
	Entire column	88	0.741	11.989	655.32	73.864	$y = 22.93 + 24.22x$
Watanabe and Terazawa	Cervical	62	0.509	15.246	501.82	66.129	$y = 29.43 + 19.04x$
	Thoracic	79	0.616	13.763	620.57	72.152	$y = 25.39 + 19.29x$
	Lumbar	86	0.621	13.807	675.54	77.910	$y = 26.77 + 17.10x$
	Entire column	88	0.738	11.888	656.47	76.136	$y = 23.41 + 21.60x$
Praneatpolgrang et al.	Cervical	62	0.454	15.598	508.71	69.355	$y = 31.05 + 19.54x$
	Thoracic	79	0.664	13.124	609.78	70.886	$y = 23.87 + 23.47x$
	Lumbar	86	0.606	14.310	678.91	73.256	$y = 27.02 + 18.27x$
	Entire column	88	0.743	12.032	654.47	72.727	$y = 22.80 + 24.50x$

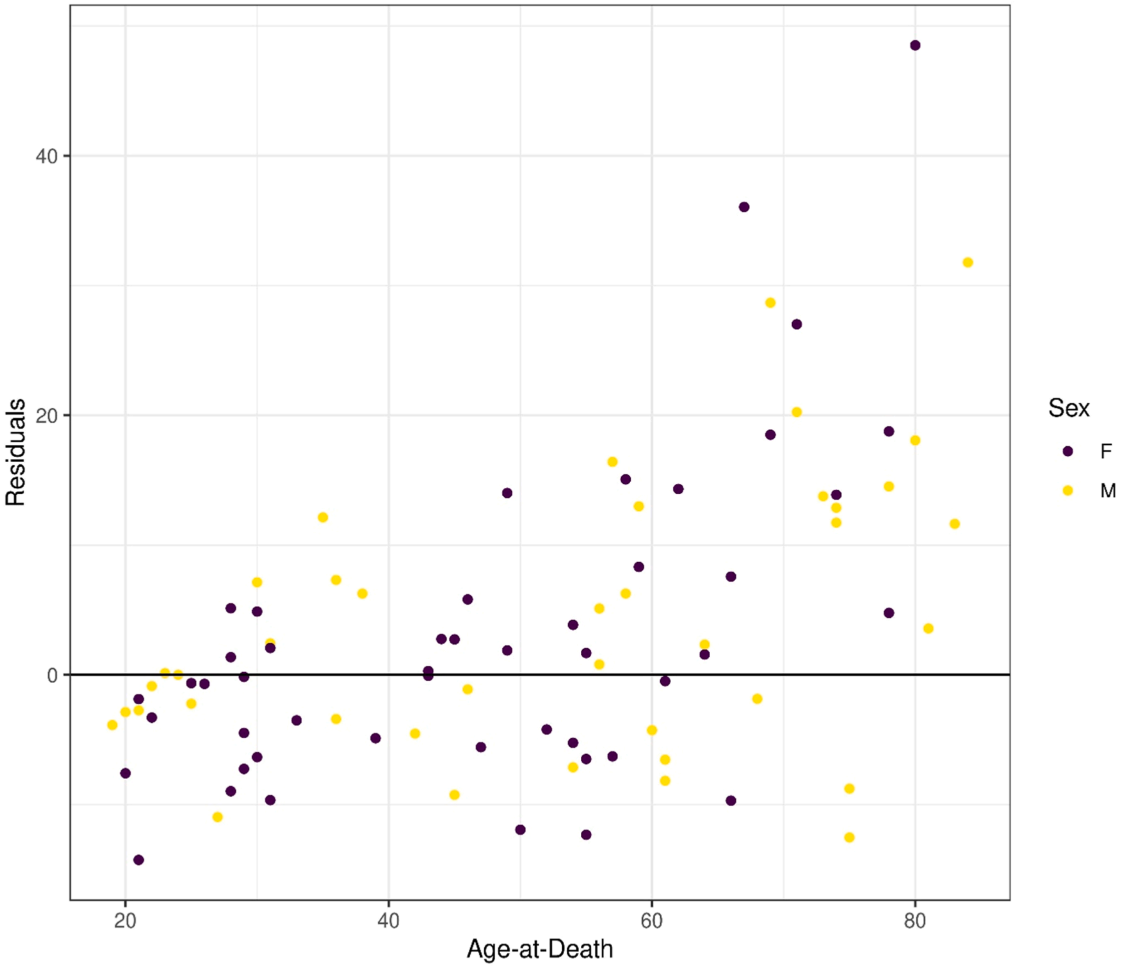

Fig. 4. Age bias plot of the entire vertebral column for the method of Snodgrass.

result will be obtained using the entire vertebral column. However, if the entire vertebral column is not available, the most accurate age-at-death result will be obtained using the thoracic region, followed by the lumbar region. There will be under- and overestimation of the age-at-death using the cervical region, in contrast to the other regions, with the entire vertebral column giving the least under- and overestimation. This result is inconsistent with the findings made in the study by Snodgrass [12]. Here the most reliable result was obtained by using the lumbar region and this region also showed less variation than the thoracic region. Additionally, in contrast to the study by Snodgrass, the use of these regions together yielded a less accurate age-at-death result ([12], 3).

The study by Van der Merwe et al. [14] looks at the different regions of the vertebral column in relation to osteophyte formation and concludes that the thoracic part of the vertebral column shows the least osteophyte formation in contrast to the cervical and lumbar parts. This can be explained by the expectation that more osteophyte formation will occur in the cervical and lumbar region because the regions are more mobile and weight-bearing. The cervical region is the most mobile region, and in addition, this region is responsible for supporting head-bearing and shoulder movement. The thoracic region guides the ribs and internal organs but is not overloaded, resulting in less osteophyte formation. The lumbar portion, on the other hand, carries the

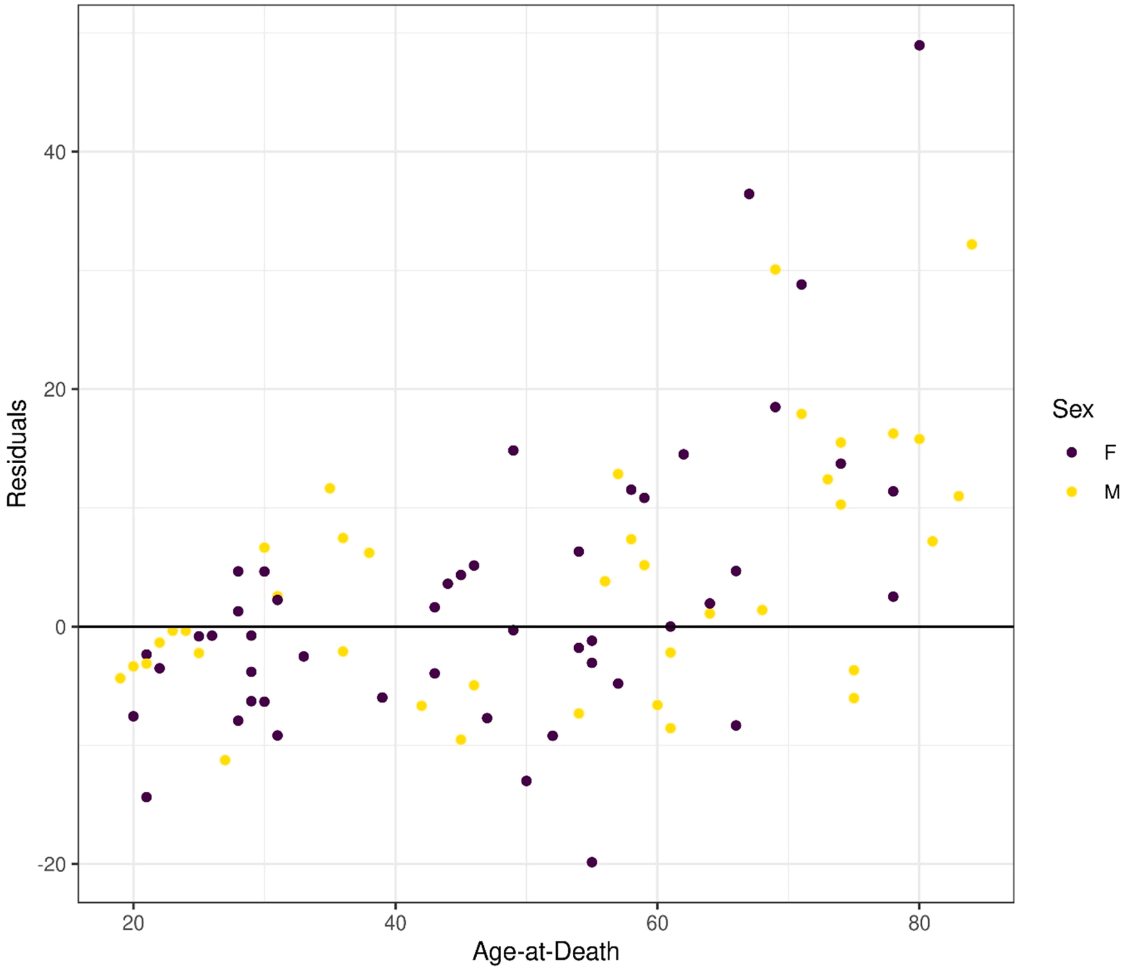

Fig. 5. Age bias plot of the entire vertebral column for the method of Watanabe and Terazawa.

most weight since this region is located at the bottom and therefore has to bear most of the thorax. It is therefore considered that the lumbar portion is under more pressure than the other regions, which can also be seen in the osteophyte pattern ([14], 463). However, the Watanabe and Terazawa's [18] study concluded that the least osteophyte formation should be observed in the cervical part, as this is where the least weight is supported in contrast to the thoracic and lumbar regions. In our study, it was found that the most osteophyte formation could be observed in the lumbar region. In addition, the cervical region showed the most osteophyte formation thereafter, with the thoracic region the least osteophyte formation, based on the mean osteophyte scores (Fig. 3). That the lumbar and cervical parts show the most osteophyte formation is in line with the expectations according to the research by Van der Merwe et al. and partially of that of Watanabe and Terazawa ([14], 463; [18], 159). Besides, the living conditions, social status, and occupations can have a direct impact on osteophyte growths, for example, the elite who performed less physical work as opposed to the working class (i.e. field farmers). The same applies to the male-female distribution, where males generally perform more strenuous tasks, where more stress on the spine can result in more osteophyte formation ([6], 79). It is interesting and important to take these findings into account when scoring the degree of osteophyte formation, as the development and pattern of the osteophytes differ in each vertebral portion caused by mobility and weight-bearing differences and variation in labour patterns in life. A description of the normal pattern of vertebral osteophyte development is, therefore, important for a reliable age-at-death estimation and for the future development of accurate age-at-death techniques.

In addition, looking at the correlation scatter plots the correlation between males and females is quite similar and the points are virtually indistinguishable and overlapping with each other. The correlation between males and females is strong. However, a little difference between males and females can be noted, with the correlation between osteophyte scores and age-at-death being higher in males than in females. This is in line with the study by Snodgrass [12], where the females also showed more variation in osteophyte score and age-at-death, in contrast to males ([12], 6). This finding may be explained from a biological perspective in that males participate in more strenuous activities at a younger age as opposed to females (i.e. sexual division of labour). This results in higher levels of strain on the vertebral column, which can lead to more and severe osteophyte formation in later life ([2], 227; [3], 2; [6], 85–86; [14], 463; [20], 404–405). On the other hand, an explanation for this finding may be that males are generally heavier and more robust than females, causing in more weight on the vertebral column, which also promotes osteophyte formation ([14], 463). The importance of socio-economic and physical activities in the light of the different sexes and between different centuries should also be highlighted, as this is important for the forensic use of age markers, which can also be influenced by physical activity. Males in Middenbeemster were known to work in the field, while females were more likely to perform work around the house, such as spinning, sawing, laundry, churning butter, making cheese, and taking care of the children. In the 19th century, the division of labour was early in life, with children sometimes even employed as young as 6 years old, where the boys often helped with livestock farming and girls were more likely to help with household chores ([17], 73).

The number of elements present was also plotted against the

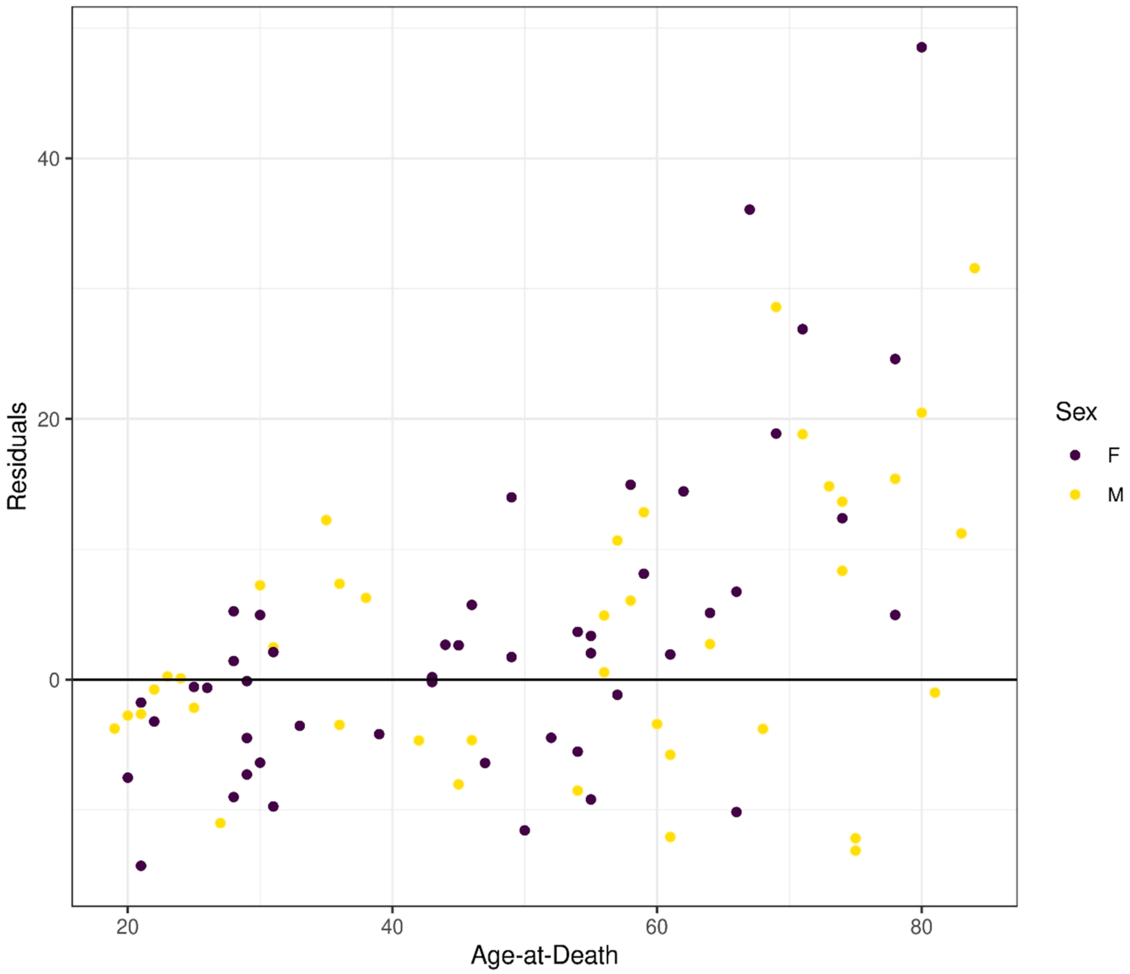

Fig. 6. Age bias plot of the entire vertebral column for the method of Praneatpolgrang et al.

Table 4
Prediction bias by age for combined regions.

Age group	Number of individuals (n)	Bias Snodgrass	Bias Watanabe and Terazawa	Bias Praneatpolgrang et al.
0–19	1	-3.9329403	-4.4137666	-3.7969539
20–29	19	3.3326893	-3.4383567	-3.2546827
30 – 39	12	1.1486175	1.2234272	1.2460393
40–49	11	0.5936718	-0.3583449	0.2461556
50 – 59	16	1.0287878	0.0678360	1.6502734
60 – 69	13	6.3261776	6.6678678	6.2793092
70 – 69	11	10.5518121	10.8119426	10.4041769
80–89	5	22.6911167	23.0021529	22.1403238

residuals, in order to determine whether the number of elements influences the accuracy. Based on this result, it can be stated that there is no relationship (positive or negative) between the number of elements scored and the absolute value of the residuals for the combined regions. However, there is a trend for separated regions, where the more elements scored result in higher accuracy. As a result, it can be concluded because of this, that the use of this aging method in cases where only a few vertebrae are available for evaluation, will yield less accurate age-at-death estimations. This finding is consistent with the study by Praneatpolgrang et al. [7] where a similar conclusion is drawn.

The results that individuals under 40 years of age almost never had an osteophyte score higher than 1.0, and individuals under 50 years of age never had an osteophyte score higher than 2.0 is in line with the findings made in the study of Snodgrass [12]. Here it was stated that for the thoracic region, a mean osteophyte score of more than 2.0 was very rare in individuals under 50 years of age and was not documented in individuals under 35 years of age. For the lumbar region, mean osteophyte scores over 2.0 never occurred in individuals under 40 years of age and were rarely seen in individuals under 50 years of age ([12], 3).

Looking at the Akaike's information criterion (AIC) and the age biases, the method of Praneatpolgrang et al. has the highest quality compared to the other statistical models and thus is recommended to use when estimating the age-at-death for Western European population using population-specific regression equations. The method is easy to apply, cheap, non-destructive, and can be learned quickly ([7], 158). Since the method Praneatpolgrang et al. method has a relatively high accuracy rate in this post-medieval Dutch population, we therefore recommend that researchers should use caution when employing vertebral degeneration as an indicator of activity.

A limitation of this study that must be mentioned is that the minimum obtained age-at-death is relatively high, resulting in the overestimation of individuals younger than this minimum age. Because the regression equations that have been developed in this study are based on the average age-at-death of the population, this becomes a problem for the ages below this average. The maximum age is also affected in the same way, resulting in an overestimation of individuals that should be classified into the age category of 18–25 (Early Young Adult) and underestimation for the individuals that should be classified into the age category of 50 + (Old Adult). However, the obtained age biases partially solve this problem, resulting in larger age biases for individuals in the above-mentioned age categories and thus less accurate age-at-death results in comparison to the other age categories. Furthermore, it should also be investigated whether the European regression equations developed in this study can also be applied to another population to investigate inter-population accuracy. It is, therefore, also recommended to use a larger sample size, as this may yield a more accurate result ([21], 51). In summary, a general pattern of osteophyte formation could be established that may be useful for age-at-death estimation, with this study and the developed population-specific regression equations contributing to age estimates in bioarchaeological and forensic studies.

Conclusion

The aim of this research was to test the efficacy of the methods of Snodgrass [12], Watanabe and Terazawa [18], and Praneatpolgrang et al. [7] on a European population. It can be stated that the osteophyte formation on the vertebral column can be a useful method to estimate the age-at-death of an individual and that the above-mentioned methods are effective. High correlations were found between osteophyte formation and age-at-death. The population-specific regression equations developed in this study will yield accurate age-at-death results, with high accuracy percentages for the entire vertebral column of 73.86% (Snodgrass), 76.14% (Watanabe and Terazawa), and 72.73% (Praneatpolgrang et al.). Population-specific regression equations are now developed for a European population and can be used for estimating the age-at-death of an individual based on the osteophyte formation on the vertebral column and, in this way, to contribute to bioarchaeological research and forensic studies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

All data and code used in the analysis are available at: https://doi.org/10.5281/zenodo.7320251.

Acknowledgements

The authors are grateful to the Middenbeemster Historical Society for their diligent archival research. Additionally, we would like the thank the community of Middenbeemster for allowing us to research the Middenbeemster collection. The skeletal collection is curated at the Faculty of Archaeology, Leiden University, The Netherlands. Finally, we would like to thank The Laboratory for Human Osteoarchaeoloy, the Faculty of Archaeology, Leiden University, The Netherlands, for enabling the examination of the human skeletal remains and providing a location to conduct the study.

Author contributions

First author: Conducted the research, scored all the vertebral elements and wrote the article. This research was conducted as part of the Master's thesis at the Faculty of Archaeology, Leiden University. Second author: Conducted the statistical research and contributed to writing the article. Third author: Contributed to the original excavation and the first age and sex estimations of the Middenbeemster collection. Fourth author: Was the supervisor of the research and contributed to writing the article.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fsir.2022.100301.

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