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Trauma or taphonomy? A forensic reassessment of perimortem cranial trauma in burials from the Phaleron cemetery (Archaic Athens, Greece)

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ABSTRACT

The Phaleron cemetery was one of the most important burial sites in Archaic Attica (8th–5th centuries BCE). Its burials include individuals showing signs of captivity (i.e., evidence of physical restraints) and are believed to potentially represent executed prisoners. This study reassesses the previously proposed presence of perimortem cranial trauma in these distinctive individuals, based on independent evaluations by two experienced forensic practitioners, a comparative sample of documented forensic trauma cases from modern Greece, and multivariate statistical analysis. Of the 19 crania analyzed, only two of the distinctive (or “D-Group”) burials showed clear evidence of perimortem trauma, with only one of these presenting all diagnostic perimortem indications. However, even in these cases, the consistent location of the fractures (mainly on the side of the skull) relative to the underlying soil, along with the water-rich nature of these seaside contexts, may also likely suggest a taphonomic origin. These results highlight the importance of contextual and environmental factors in trauma interpretation, emphasizing the value of documented forensic references and multivariate approaches that can assess multiple diagnostic traits together. More broadly, our findings underscore the need for caution when attempting to link skeletal trauma to the cause of death in bioarchaeological contexts, where long-term taphonomic effects can play a decisive role.

1. Introduction

The archaeological site of Phaleron, located on a bay of the Saronic Gulf about four km southwest of the Athens’ Acropolis, contains a unique burial ground dating to the Archaic period (8th–5th centuries BCE). Over 1900 non-elite burials have been uncovered, including individuals buried in simple pits, jar burials for infants, and cremations (Chryssoulaki et al., 2014; Buikstra et al., 2023a,b; 2024). Notably, some individuals, often referred to in the relevant literature as “distinctive”, “Desmotes” (i.e., meaning “bound” in Greek), or the “D-Group” (hereafter), were buried with evidence of physical restraints, such as metal shackles (Chryssoulaki et al., 2014; Prevedorou and Buikstra, 2019; Karakostis et al., 2021; Prevedorou et al., 2024; Buikstra et al., 2023a,b; 2024). Such findings suggest that these individuals may have been executed prisoners, captives, and/or victims of political conflicts during a turbulent phase of ancient Athenian history, thus potentially offering invaluable insights into ancient Athenian society and justice.

In bioarchaeology, paleopathological analyses can provide crucial insights into past individuals’ identities and circumstances of death (e.g., Buikstra, 2023a,b). A key aspect of this process is the identification and evaluation of fractures that may have resulted from perimortem trauma. Determining whether these lesions occurred antemortem

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(before death), perimortem (at or around the time of death), or postmortem (after death) offers valuable information on the conditions surrounding an individual's death (e.g., Sauer, 1998; Komar and Buikstra, 2007; Kranioti, 2015). Perimortem injuries can occur for as long as the bone retains its natural moisture, collagen, and elasticity, the duration of which depends on various environmental conditions (e.g., Sauer, 1998; Moraitis et al., 2009; Buikstra, 2023a,b).

This classification not only indicates whether trauma may have occurred while the individual was alive but also helps reconstruct the manner and mechanism of death (Sauer, 1998). Though skeletal analysis alone rarely confirms the exact physiological cause (Sauer and Simson, 1984), it can assist in distinguishing between natural deaths, accidents, suicides, and homicides. Beyond forensic applications, such dry bone trauma investigations can potentially deepen our understanding of past populations' lived experiences.

In a previous study, Ingvarsson-Sundström and Backstrom (2019) examined fractures in the remains of 79 individuals from the Phaleron cemetery site. These burials, uncovered in 2016, were arranged in three separate rows within a sandy and water-rich environment. Their analysis reported extensive evidence of "likely perimortem" trauma, particularly in the skulls, pointing to violent causes of death for some of the "distinctive" individuals (Chryssoulaki et al., 2014; Buikstra et al., 2024). Many of these crania exhibited injuries apparently consistent with blunt force trauma, suggesting the possible use of blunt weapons or implements designed to inflict fatal blows. On this basis, they discussed that the mass graves, their uniform distribution, and the suspected injuries seem to broadly align with the proposition that these individuals may have been victims of political purges or punitive actions linked to episodes of socio-political unrest described in historical accounts of Archaic Athens (Ingvarsson-Sundström and Backstrom, 2019).

Nevertheless, that previous study also highlighted that these skulls also exhibit extensive postmortem taphonomic damage, which can make the analysis of trauma difficult as it can obscure perimortem fracture characteristics (e.g., Buikstra, 2023a,b). This challenge is expected to be even greater in these particular burials due to their water-rich soil environment (as described by Ingvarsson-Sundström and Backstrom, 2019), which may have likely influenced fracture formation in a way that reduces the distinguishability between perimortem bone reactions and postmortem damage (see Galloway et al., 1999; Samuel et al., 2016; Lobell, 2018).

In this framework, the present study re-evaluates the timing of cranial trauma in a series of skulls from the Phaleron cemetery (including those exhibiting traits previously classified as "likely perimortem"), focusing particularly on distinguishing perimortem from postmortem fractures. Our comparative analysis relies on a valuable reference sample of documented forensic cases, the use of established anthropological protocols, and multivariate analyses of scored diagnostic traits.

2. Materials and methods

Based on standard practice for evaluating the timing of skeletal trauma, biological anthropologists often rely on the so-called "green stick/dry stick" analogy. Fresh bones contain a high level of organic and moisture content, and they tend to splinter when mechanical force is acting on them. On the contrary, dry bones tend to shatter when subjected to mechanical force (e.g., Komar and Buikstra, 2007; Wieberg and Wescott, 2008; Moraitis et al., 2009; Galloway et al., 1999; Kemp, 2016; Sala et al., 2016). For the present paper, skeletal trauma analysis relied on the evaluation of seven characteristics of the following standard cranial fractures (see Table 1): fracture lines, linear pattern, edge morphology, coloration, plastic deformation, delamination, and the presence of small adhering bone fragments (e.g., Sauer, 1998; Komar and Buikstra, 2007; Moraitis et al., 2009; Sala et al., 2016; Kranioti, 2015; also see description below). The aforementioned characteristics were selected because they are included in the standard recording forms of the Forensic Anthropology Unit at the National and Kapodistrian University of Athens Medical School, which handles the vast majority of forensic anthropological cases in the country (Moraitis et al., 2015).

Table 1
Summary of fracture characteristics, definitions, and scoring criteria (for additional details, see Materials and Methods).

Characteristic	Definition	Assessment criteria
Fracture lines (FL)	Cracks extending from the point of impact or stress.	**Perimortem**: Radiating and relatively linear fracture lines. **Postmortem**: Non-radiating, irregular lines.
Linear pattern (LP)	The overall shape and orientation of the fracture.	**Perimortem**: Smooth, linear or curved fractures indicating plasticity. **Postmortem**: Irregular, angular, or fragmented breaks.
Edge morphology (Edges)	The visual appearance and tactile quality of the fracture edges.	**Perimortem**: Sharp, clean, or possibly beveled edges. **Postmortem**: Rough, brittle, jagged edges.
Coloration (Col.)	Comparison of the color of fracture surface to the surrounding bone.	**Perimortem**: Fracture coloration matches surrounding bone. **Postmortem**: Fracture appears lighter or different due to post-depositional changes.
Plastic deformation (PD)	Permanent warping or bending of bone without complete fracture, indicative of elasticity at time of injury.	**Perimortem**: When present suggests fresh bone with moisture and elasticity. **Postmortem**: When absent suggests dried bone fractures without deformation.
Delamination (Delam.)	Peeling or flaking of the cortical layer of bone near fracture edges.	**Perimortem**: Often present due to moist conditions and force transfer across bone layers. **Postmortem**: Rare or absent.
Adhering bone fragments (AFAF)	Small fragments that remain loosely attached or embedded at the fracture site.	**Perimortem**: When present, they indicate soft tissue and cohesion at time of injury. **Postmortem**: Usually absent, as fragmentation leads to separation.

More specifically, perimortem trauma typically results in fracture lines that are radiating and follow a relatively linear pattern, whereas postmortem damage tends to produce fracture lines that are non-radiating and irregular (e.g., Sauer, 1998; Moraitis et al., 2009; Kranioti, 2015; Buikstra, 2023a,b). The edges of perimortem fractures are usually sharp and may show beveling, while postmortem fractures often appear jagged and brittle. The colors of perimortem fractures generally match the surrounding bone, as the injury occurred before taphonomic processes altered its appearance. Moreover, the presence of plastic deformation, which refers to the permanent alteration of bone shape without fracturing, is characteristic of fresh bone due to its moisture and elasticity. In contrast, dried bone typically lacks flexibility and cannot absorb or redistribute force similarly to fresh bone, thus becoming more prone to shattering. Finally, delamination (i.e., the peeling of outer bone layers) along with the occurrence of small bone fragments adhering to fracture edges (e.g., see Sala et al., 2016), may also occur in perimortem injuries, again due to the presence of moisture and soft tissues in the area at the time of trauma (e.g., Moraitis et al., 2009).

To evaluate the timing of cranial trauma in this study, we relied on a comparative documented sample of 20 individuals, corresponding to 13 males and 7 females, aged between 29 and 94 years old (mean: 53 years). All these were crania with confirmed perimortem blunt force trauma or postmortem fractures, originating from identified forensic cases investigated by one of the authors (KM). The presence of parietal or temporal bone fractures (reflecting the location of most fractures deemed as "possibly" or "probably" perimortem in the Phaleron skulls) and a legally confirmed mechanism of death were prerequisites for including a forensic case in the comparative sample. Ten of the cases showed perimortem trauma (six of which involved fractures on the side of the skull, as in Phaleron), while the remaining ten cases involves crania with postmortem (taphonomic) changes (seven of which involved fractures on the side of the skull). Moreover, two of the confirmed perimortem cases were retrieved from water-rich environments (similarly to the Phaleron burial context). The recorded diagnostic characteristics were retrieved from the laboratory's formal case files, which were produced during the forensic investigation and before the individual's cause of death was legally confirmed. These files included recording forms, the forensic anthropology report, and associated photographic material taken during the examination. Each diagnostic trait was individually scored as absent or present (i.e., binary variables), with "presence" indicating the perimortem condition. For the purposes of this study, all seven traits across the 20 cases were compiled into a dataset.

Regarding the bioarchaeological sample, 19 crania from Phaleron burials were analyzed. Thirteen of these were housed at the Malcolm H. Wiener Laboratory for Archaeological Science at the American School of Classical Studies in Athens, Greece, at the time of the study, including tombs XI_1228, XI_1267, XI_1296, XI_1344, XI_1356, XI_1359, XI_1365, XI_1383, IV_76, IV_344, IV_349, IV_400, and IV_430. An additional six crania (XI_1272, XI_1316, XI_1333, XI_1336, XI_1353, and XI_1373), which were no longer physically accessible, were assessed based on existing detailed photographic materials of each skull/fracture (see Ingvarsson-Sundström and Backstrom, 2019). The 19 cases analyzed included all nine crania from the distinctive burial sector "XI" previously identified as having "likely perimortem" trauma (Ingvarsson-Sundström and Backstrom, 2019), including XI_1356, XI_1359, XI_1383, XI_1272, XI_1316, XI_1333, XI_1336, XI_1353, and XI_1373. Finally, we also included another five skulls showing potential indications of trauma (i.e., IV_76, IV_344, IV_349, IV_400, and IV_430), from burial sector "IV" (not "distinctive"). All examined skulls appear to correspond to "possible" or "probable" biological males, ranging from young to mid-adulthood (Buikstra et al. forthcoming).

The archaeological cranial fractures were scored utilizing the same seven diagnostic characteristics outlined above, enabling their statistical comparison to the forensic documented sample. All crania were independently scored by experienced forensic anthropology practitioners (IA and KM) to evaluate inter-observer error, and were subsequently photographed. For assessing the level of agreement between two independent raters in classifying items into mutually exclusive categories, the Cohen's Kappa statistic was used (Cohen, 1960; Field, 2013). Unlike a simple percentage agreement measure, Cohen's Kappa adjusts for the possibility of agreement occurring by chance, providing a more robust evaluation of inter-rater reliability. For the crania studied exclusively through photographic material, we opted to score only the four most diagnostic traits (see Results), as these were the ones providing a clear distinction between perimortem and postmortem trauma in the documented forensic sample. Also, fracture edges and coloration were recorded with as much caution as possible, relying on all information discernible in the existing photographs (Ingvarsson-Sundström and Backstrom, 2019).

For the aforementioned seven features (i.e., categorical binary variables), a series of seven Fisher's Exact tests were performed, to determine whether there is a significant association between each trait and the timing of the injury (perimortem or postmortem). This test is more appropriate for small sample sizes, compared to the chi-square test (χ^2), especially when expected frequencies can be below five (Fisher, 1922; Field, 2013). In such cases, the chi-square test may produce inaccurate results (McDonald, 2014). Additionally, to visualize within-trait variation across individual crania/fractures, we used jitter plots (Hammer et al., 2001). For each trait, each trauma case was plotted according to presence or absence, with different colors and markers distinguishing trauma categories. Perimortem forensic cases were represented by blue dots, postmortem forensic cases were marked with fuchsia dots, postmortem forensic cases from wet environments were indicated by empty fuchsia squares, and skeletal remains from Phaleron were depicted using black markers.

Furthermore, to explore combinations of traits that may vary between perimortem and postmortem fractures, the four traits showing significant differences between the two conditions in the documented sample (based on the Fisher's Exact tests) were subjected to a multiple correspondence analysis (MCA), involving all archaeological and forensic cases (e.g., as in Sala et al., 2016). No prior grouping assumptions were made, but cases were color-labeled by group/condition. Considering the very clear distinction observed between peri- and postmortem cases on Axis 1, Phaleron specimens could be directly linked to a proposed timing group depending on their Axis 1 score. All statistical analyses were performed in the software IBM SPSS version 24 (IBM inc., Armonk, NY), while PAST version 4.04 (Hammer et al., 2001) was used for generating the jitter plot figures, which were further edited in Adobe Illustrator CC 2015 version 19.0 (Adobe Systems, San Jose, CA).

3. Results

The level of agreement (κ) between the two forensic specialists for the seven categorical variables, as measured by Cohen's Kappa, ranged from 0.76 to 1.00. These values indicate substantial to almost perfect agreement across all traits assessed (Cohen, 1960; Field, 2013). Specifically, most variables exhibited strong to perfect consistency between raters (i.e., fracture line, linear pattern, edges, coloration, adhering bone fragments), while others showed to be slightly more subjective (i.e., delamination, plastic deformation). This high level of inter-rater reliability confirms the robustness of the classification process and minimizes the likelihood of observer bias affecting the results.

The Fisher's Exact tests indicated that the presence of radiating fractures, linear fracture edges, sharp fracture edges, and uniform coloration show a significant difference ($p < 0.01$) between confirmed perimortem and postmortem cases (Table 2). This trend was also visible in the jitter plots (Fig. 1), which showed that the frequency of these traits clearly varied between peri- and postmortem cases. Even though the remaining three traits (plastic deformation, delamination, and the presence of small adhering bone fragments) were exclusively observed in perimortem trauma cases (as shown by the upper row of cases in Fig. 1), their frequent absence in other such cases (as shown by the lower row) reduced their value as perimortem markers in this specific sample. This was also reflected in the Fisher's exact tests, where these traits did not reach statistical significance due to their low prevalence.

The MCA performed on the four diagnostic features produced Axis 1, with an eigenvalue of 2.61, explaining 65.2 % of the variance. The "loadings" for this axis (calculated in SPSS as each original variable's discrimination measure for this component) were 0.73 for radiating fractures, 0.60 for linear fracture edges, 0.77 for sharp fracture edges, and 0.50 for uniform coloration (Table 3), indicating that the first three traits were more strongly associated with Axis 1 compared to coloration. As shown in Fig. 2, the combined presence of multiple perimortem traits greatly enhanced the differentiation between peri- and postmortem fractures, with no postmortem fracture exhibiting three or four perimortem indicators simultaneously. In comparison, within the bioarchaeological sample, only three Phaleron crania displayed all four traits (XI_1359, IV_344, and IV_430; Figs. 3–5), while one (XI_1383) exhibited three (Table 4). Interestingly, two of the Phaleron skulls exhibited two perimortem traits, overlapping with a confirmed postmortem forensic case involving human remains from a wet context (Fig. 2). Fig. 2 also presents examples of the four perimortem traits (scored as "present") evaluated in this study, originating from the forensic documented sample itself.

The second axis of the MCA had an eigenvalue of 0.72, accounting for 18.0 % of the variance, with "loadings" of 0.05 for radiating fractures, 0.24 for linear fracture edges, 0.01 for sharp fracture edges, and 0.42 for uniform coloration. The MCA statistics are summarized in Table 3, while

Table 2
Fisher's exact test P-values showing significant differences between documented peri- and post-mortem cranial fractures in four of the seven diagnostic traits considered.

	Fracture line	Linear pattern	Edges	Coloration	Plastic deformation	Delamination	AFAF
Fisher's Exact Test (Exact Sig. 2-sided)	0.005	0.003	0.000	0.011	1.000	1.000	0.087

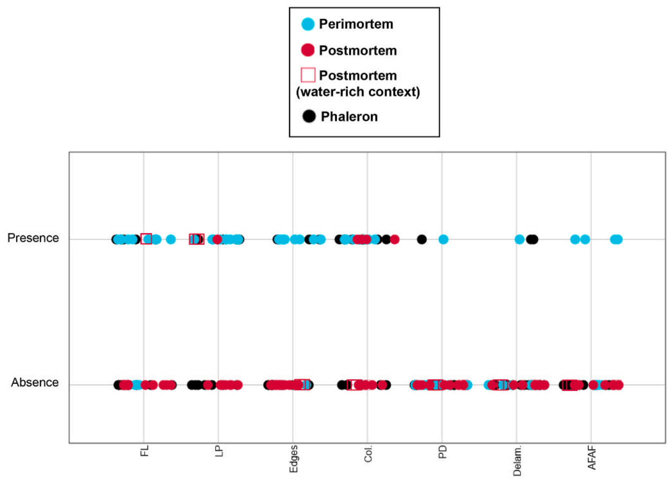

Fig. 1. Jitter plots of presence (above) or absence (below) scores for all seven diagnostic perimortem traits assessed in this study (exact specimen scores for the four significant traits are provided in Table 4). These include perimortem-like fracture lines ("FL"), linear pattern ("LP"), edge morphology ("Edges"), coloration ("Col."), plastic deformation ("PD"), delamination ("Delam."), and the presence of small adhering bone fragments ("AFAF"). The legend on the top explains the categories represented by each color. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Statistics of the multiple correspondence analysis (MCA) conducted in this study. The abbreviations are spelled out in Table 1 and the legend of Fig. 1.

Dimensions	Total variance (Eigen-value)	Variance explained (%)	Discrimination measures			
			FL	LP	Edges	Col.
Axis 1	2.61	65.20	0.73	0.60	0.77	0.50
Axis 2	0.72	18.00	0.05	0.24	0.01	0.42

the specimen scores for Axis 1 are visually represented in Fig. 2. Although the statistics of Axis 2 are described above, its specimen scores were not depicted, as it did not exhibit any clear patterns distinguishing peri- and postmortem forensic cases or any other grouping in this study. The raw data collected can be found in Table 4.

4. Discussion

The aim of this study was to use a documented forensic reference sample of confirmed trauma cases to reassess the presence of perimortem blunt force trauma in a selective series of skulls from the Phaleron cemetery, which includes burials of individuals who were held captive and were most likely executed (e.g., Chryssoulaki et al., 2014; Prevedorou and Buikstra, 2019; Ingvarsson-Sundström and Backstrom, 2019; Karakostis et al., 2021; Prevedorou et al., 2024; Buikstra et al., 2023a,b; 2024). Our forensic data showed that three of the seven traits used (namely fracture line, linear pattern, and edges) consistently differed between peri- and postmortem fractures (Figs. 1 and 2; Table 2), aligning with the established forensic and bioarchaeological literature (e.g., see Sauer, 1998; Komar and Buikstra, 2007; Moraitis et al., 2009; Kranioti, 2015; Buikstra, 2023a,b and references therein). This distinction was also evident but less pronounced in terms of fracture edge coloration, which may be likely affected by various taphonomic factors. From a methodological perspective, our findings from the documented cases highlight the importance of these four traits in determining perimortem trauma.

Combining this comparative dataset with analytical procedures conducted by two forensic experts independently (IA and KM), we found considerable evidence of blunt force trauma in only 3 of the 19 Phaleron cases (each displaying all four perimortem indicators identified by both analysts; see Figs. 3–5), while one additional case (XI_1383) showed partial evidence, presenting three of the four perimortem traits (Fig. 2). Importantly, only two of the nine "distinctive" (D-Group) burial cases previously proposed as exhibiting perimortem trauma (i.e., XI_1359 and XI_1383; see Ingvarsson-Sundström and Backstrom, 2019) showed considerable perimortem indications. Another cranium classified as perimortem by our MCA (IV_430), which had not been previously studied, does not correspond to a "distinctive" burial. Fracture patterning of this skull indicated a potentially perimortem origin due to the presence of a specific perimortem trait known as external beveling (i.e., a beveled edge on the outer table of the bone), which is most commonly associated with high-velocity projectile exit wounds (Fig. 5C; Moraitis et al., 2009). However, there are compelling reasons to suggest that the fracturing of this skull actually occurred postmortem. Upon examining the internal aspect of the skull (Fig. 5A and B), the sand filling the endocranium reveals distinct traces of a cylindrical implement, likely responsible for the inflicted fracture, possibly occurred during excavation. The "imprint" of this activity in the sand filling demonstrates that this cranial fracture is most likely postmortem. We suggest that the reason that it resembles a perimortem injury is that the excavating tool acted upon a moist and pliable cranial interior (Galloway et al., 1999; Samuel et al., 2016).

As previously stated, in distinguishing perimortem and postmortem skeletal fractures, practitioners typically consider the breakage patterning, which differs significantly between fresh and dry bone. In some contexts, though, skeletal elements can maintain their moisture for extensive periods of time. The presence of water appears to modify the mechanical properties and affects the ultrastructural behavior of bone. This change is relevant to the mechanical response of bone under different loading modes, with strain hardening in tension, and strain softening in compression. Samuel et al. (2016) have reported that water appears to modify the matrix surrounding the mineral crystals of the bone, reduces the mineral-collagen strain ratio, and induces a viscous response in the mineral phase. Thus, these water-related alterations of the bones may cause postmortem fractures to mimic the mechanical characteristics of perimortem trauma. This observation aligns with the findings of the present study, which identified certain indications of perimortem trauma (i.e., linear fracture patterns) in two confirmed postmortem cases from water-rich contexts (see fuchsia squares in Fig. 1 and detailed scores in Table 4); notably, one of these two "wet" crania also displayed perimortem-like radiating fracture lines, resulting in an intermediate score in the MCA (Fig. 2).

Furthermore, for sites where remains are buried below water tables and/or in places submerged for long time periods, minerals may eventually leach from bones. As a result, skeletal elements are found to be pliant (Galloway et al., 1999). Such malleable skeletal elements may exhibit characteristics very similar to those associated with perimortem trauma. The Phaleron cemetery is located near the ancient coastline of the Bay of Phaleron, which served as a primary harbor for Athens before the development of the port of Piraeus in the 5th century BCE. Given its

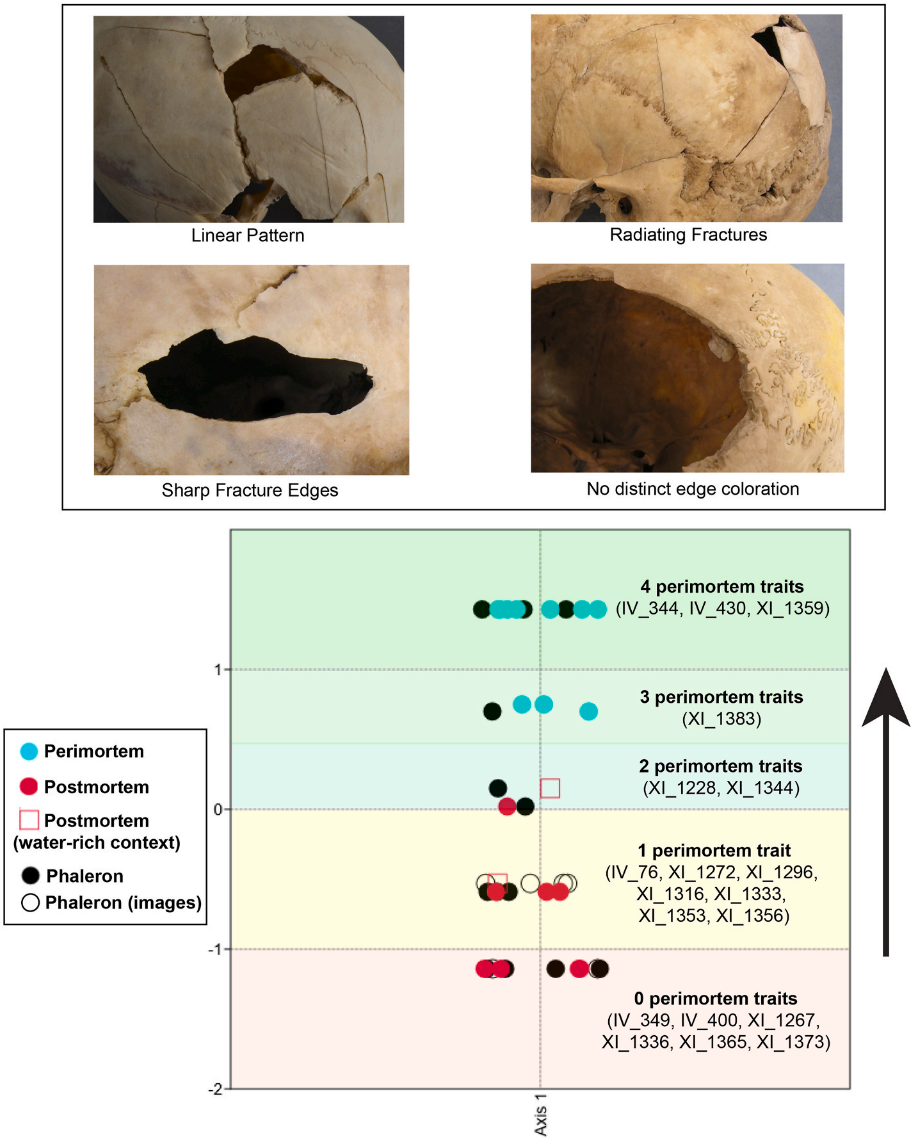

Fig. 2. Jitter plot depicting the multiple correspondence analysis (MCA) scores of Axis 1, which provided a clear separation between documented perimortem and postmortem fractures. This analysis relied on the four most diagnostic traits, involving fracture lines, linear pattern, edge morphology, and coloration (exact data for each specimen provided in Table 4). The number of perimortem traits simultaneously present in each specimen's fractures is provided within the plot (along with the corresponding Phaleron crania), while the figures above depict examples of these four perimortem features from the documented sample. The legend on the left explains the categories represented by each color, with empty black circles denoting Phaleron fractures that could only be assessed using existing photographic materials. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

coastal proximity and the sandy nature of the burial ground, it is probable that the site experienced periodic flooding over the centuries, which could have impacted the preservation and stratigraphy of the burials. Coastal sites in antiquity were often vulnerable to sea-level fluctuations, storm surges, and sediment displacement, all of which could have influenced the archaeological context of Phaleron (Chryssoulaki et al., 2014; Lobell, 2018). Additionally, evidence from other ancient cemeteries near water bodies also suggests that natural hydrological changes often played a role in burial site conditions over time (Camp, 2001).

In other respects, our findings partially align with those of the previous study (Ingvarsson-Sundström and Backstrom, 2019) regarding the distribution of perimortem and postmortem trauma in specific individuals. For instance, in burials XI_1296 and XI_1365, the earlier study identified likely perimortem trauma exclusively on the mandible (and not the skull), and our analysis also supports this conclusion by suggesting that the fractures observed on the cranial vault are actually postmortem. Additionally, our results fully agree for burials XI_1344 and XI_1228, where the previous study reported exclusively postmortem cranial vault trauma; our findings align with this assessment, reinforcing the consistency of these classifications.

However, for other skull fractures, where our observations do not align with the previous assessments, it is worth noting that Ingvarsson-Sundström and Backstrom (2019) also acknowledged that, while the presumed perimortem fractures observed in this material may have resulted from interpersonal violence, other potential causes cannot be ruled out. Notably, we believe it is important to highlight that, in the vast majority of the proposed potentially perimortem cases, linear pattern of fractures were consistently located on the cranial side facing upward, which was also frequently consistent with the posture of the skull on the underlying soil within the burial (see Ingvarsson-Sundström and Backstrom, 2019). This is also the case for the only two "distinctive" burials in our study that showed considerable indications of perimortem skull trauma (i.e., skulls XI_1359 and XI_1383; see Figs. 42 and 45 in

Fig. 3. Lateral aspect of cranium XI_1359, exhibiting breakage patterns consistent with perimortem skeletal responses.

Fig. 4. Lateral aspect of cranium IV_344, showing a comminuted depressed fracture and evidence of trephination located atop a radiating fracture (white arrow).

Ingvarsson-Sundström and Backstrom, 2019). In this framework, rather than assuming that all of these individuals happened to be injured in a highly similar manner and exact region of the skull (i.e., the side) that coincidentally reflected the posture of the cranium within the burial, it may be far more parsimonious to suggest that the observed fracture distribution likely reflects soil compression or other disturbances during deposition, particularly if the bodies and their bones, after skeletonization, were still relatively fresh and/or moist at the time of burial, which was most likely the case in this specific water-rich context. Under such conditions, even though these fractures could technically be classified as perimortem, they may likely also be in fact taphonomic in origin and unrelated to the individuals' actual cause of death.

Beyond these previously analyzed cases, our study additionally examined skull fractures from burials IV_76, IV_344, IV_349, IV_400, and IV_430, which were not included in the earlier study and do not correspond to "distinctive" burials. Among these, probable perimortem trauma was identified only in IV_344 (Fig. 4), where a comminuted depressed fracture was observed, along with a trephination situated on top of a radiating fracture. The positioning suggests that the trepanation occurred subsequent to the cranial injury, with evidence of bone remodeling potentially indicating an attempt at decompressive intervention (see Aidonis et al., 2021). Additionally, postmortem changes have affected both lesions, resulting in roughened surfaces, consistent with alterations of taphonomic origin. Nevertheless, these damages do not obscure the perimortem features in IV_344, which remain distinctive (Fig. 4).

Fig. 5. Left lateral (A, B) and posterior (C) aspects of cranium IV_430. Cranium IV_430 was initially classified in our analyses as perimortem based on the multiple correspondence analysis (MCA) but was later determined to be postmortem due to taphonomic evidence. Although the fracture exhibits external beveling that resembles a projectile exit wound (panel C), the presence of sand filling the cranial cavity (panel A) and the cylindrical imprint of a tool on the internal filling itself (panel B) suggest that the fracture resulted from excavation-related activity.

5. Conclusions

This study reassessed the presence of perimortem cranial trauma in burials from one of the most important cemeteries of Archaic Attica, including a series of distinctive interments of captives that were likely executed. Relying on a valuable comparative forensic sample, independently conducted analyses by two experienced forensic practitioners, and the use of multivariate statistics, we found limited evidence for securely assigned perimortem trauma, with only two D-Group skulls meeting the majority of the selected criteria (Fig. 2). In both these cases, however, the location of the fractures in relation to the skulls' position within the grave, combined with the water-rich burial environment, may also possibly suggest a taphonomic origin rather than trauma linked to the cause of death. Although blunt force cranial fractures are often associated with interpersonal violence, similar fracture patterns can occur after death due to factors such as deposition, transport, or burial (e.g., Komar and Buikstra, 2007; Moraitis et al., 2009; Sala et al., 2016; Buikstra, 2023a,b), potentially resembling perimortem trauma. Overall, our findings underline the importance of considering key contextual and taphonomic factors in trauma analysis, while highlighting the value of documented forensic cases and multivariate approaches that can readily evaluate the combined presence of multiple diagnostic traits simultaneously. In the future, these approaches can potentially be combined with the use of additional methods, such as fractography (e.g., Machin and Christensen, 2022), to further refine trauma analysis. We believe that the introduction and future application of such rigorous

Table 4
The scores of the four diagnostic traits used in the multivariate analysis, along with the total number of perimortem indicators per specimen. The abbreviations are spelled out in Table 1 and the legend of Fig. 1.

Group	Label	FL	LP	Edges	Col.	Total perimortem traits
Phaleron	XI_1296	0	0	0	1	1
	XI_1267	0	0	0	0	0
	XI_1359	1	1	1	1	4
	XI_1356	0	0	0	1	1
	XI_1344	1	1	0	0	2
	XI_1228	0	1	0	1	2
	XI_1365	0	0	0	0	0
	XI_1383	1	1	0	1	3
	XI_1272	0	1	0	0	1
	XI_1316	0	1	0	0	1
	XI_1333	0	1	0	0	1
	XI_1336	0	0	0	0	0
	XI_1373	0	0	0	0	0
	XI_1353	0	1	0	0	1
	IV_344	1	1	1	1	4
	IV_76	0	0	0	1	1
	IV_430	1	1	1	1	4
	IV_349	0	0	0	0	0
	IV_400	0	0	0	0	0
Documented perimortem		1	1	1	1	4
		0	1	1	1	3
		1	1	1	1	4
		1	1	1	1	4
		1	1	0	1	3
		1	1	1	1	4
		1	1	1	1	4
		0	1	1	1	3
		1	1	1	1	4
		1	1	1	1	4
Documented postmortem		0	0	0	1	1
		0	1	0	1	2
		0	0	0	1	1
		0	0	0	0	0
		0	0	0	0	0
	water-rich context	0	1	0	0	1
	water-rich context	1	1	0	0	2
		0	0	0	0	0
		0	0	0	0	0
		0	0	0	1	1

methodological approaches are essential for improving the accuracy of trauma interpretation in both forensic and bioarchaeological contexts.

CRediT authorship contribution statement

Ioanna Anastopoulou: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Jane E. Buikstra:** Writing – review & editing, Validation, Resources, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Lourdes Tamayo:** Writing – review & editing, Investigation. **Stella Chryssoulaki:** Writing – review & editing, Resources, Data curation. **Konstantinos Moraitis:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation. **Fotios Alexandros Karakostis:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Data availability

The raw data generated supporting the core findings of this study (scored traits) are provided for all samples within the manuscript itself (Table 4).

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to quickly identify and correct minor grammar and syntax issues in select sections of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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.

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