



Transition Analysis 3 Skeletal Age Estimations Between Social Race Groups: An Analysis of the Weathering Hypothesis



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Introduction

The weathering hypothesis, proposed by Geronimus (1992), states that marginalized people may age or “weather” faster and experience earlier health deterioration than their non-marginalized counterparts due to embodied stress. This has been documented in cardiovascular disease, infant mortality, life expectancy, telomere length, and dental health in relation to socioeconomic status, gender, and/or bureaucratic social race group (Geronimus 1992; Geronimus et al. 2001; Geronimus et al. 2006; Simons et al. 2016; Walkup et al. 2023). Relatedly, marginalized groups are susceptible to structural vulnerability and violence, which results in embodied adverse effects (Beatrice and Soler 2016; Farmer 2004; Kim et al. 2023; Winburn et al. 2022a). Theoretical considerations of structural vulnerability have recently emerged in forensic anthropology and highlight how social stressors could be embodied in skeletal and dental tissues (Kim et al. 2023; Walkup et al. 2023; Winburn et al. 2022a). **However, it is currently unknown how weathering and structural vulnerability may impact skeletal age estimations and health indicators in forensic anthropological contexts for individuals who likely experienced structural racism in the U.S., including Black, Indigenous, People of Color (BIPOC).** This study tests the weathering hypothesis and examines the biomarkers of structural vulnerability in a sample from the University of Tennessee, Knoxville’s (UTK) Donated Skeletal Collection.

Methods

A total of 118 donor individuals from UTK’s Donated Skeletal Collection were studied, **including 59 BIPOC who were age and sex matched, where possible, with 59 non-BIPOC** (e.g., “white”/European American) individuals (Table 1). Transition Analysis 3 (TA3), a freely available online program that uses body-wide indicators of biological age from a large and diverse reference sample, was used to estimate the average age of transition between trait expression stages (Boldsen et al. 2002; Getz 2020; Milner et al. 2024; Richardson and Ousley 2021). TA3 produces a median point estimate and range aggregated from a maximum of 103 age indicators. Additionally, 10% (n=12) of the sample were rescored and reassessed with TA3 at the end of initial data collection to examine intraobserver error. T-tests examined the accuracies of the age estimations between the BIPOC and non-BIPOC groups, in addition to the intraobserver error.

Structural vulnerability was assessed by examining for the presence of cribra orbitalia, porotic hyperostosis, cranial lesions, Schmorl’s nodes, spina bifida, periosteal new bone formation, lytic lesions, enthesopathies, osteoarthritis, osteoporosis, surgical interventions, and antemortem fractures as suggested by Winburn et al. (2022a). These were documented as counts per individual, meaning that total scores were associated with the overall number of repeatable indicators. To analyze differences in structural vulnerability between the BIPOC and non-BIPOC samples, chi-square analyses were run.

Table 1. Distribution of age ranges in the UTK sample.

Documented Ages	BIPOC	Non-BIPOC	Females	Males
20-24	2	1	0	3
25-29	0	1	0	1
30-34	1	2	1	2
35-39	4	2	4	2
40-44	3	4	3	4
45-49	3	3	0	6
50-54	7	7	6	8
55-59	4	4	0	8
60-64	11	11	12	10
65-69	6	6	10	2
70-74	9	9	6	12
75-79	6	6	6	6
80-84	3	3	6	0
Total	59	59	54	64

Acknowledgements and References

The authors thank Drs. Dawnie Steadman and Giovanna Vidoli at the University of Tennessee, Knoxville for access to the Donated Skeletal Collection and the Program in Forensic Anthropology at BU for providing funding.



Results

TA3 and Weathering
TA3 produced age ranges that were semi-accurate. **A total of 34 individuals (28.8%) fell outside of the estimated age range provided by TA3.** Of those, 17 individuals were from the BIPOC sample, and 17 were non-BIPOC. Additionally, 12 individuals (10.2%) fell more than five years outside the age range, with five of those being from the BIPOC sample and seven being from the non-BIPOC sample. The average difference between TA3 point estimates and the documented ages were 12.17 years for the BIPOC sample and 11.90 years for the non-BIPOC sample (Figure 1). TA3 overall performed poorly in gaining accurate point estimates in both samples, as both paired samples t-tests for the BIPOC and non-BIPOC samples produced *p*-values less than 0.001, indicating statistically significant differences in documented and TA3 estimated ages. Additionally, the independent samples t-test indicated that differences in the estimated ages and documented ages between the samples did not differ significantly (*p*-values greater than 0.05). The intraobserver error test found no statistically significant differences between the original TA3 point age estimates and the rescored TA3 point age estimates (*p*-value greater than 0.05).

Structural Vulnerability Indicators
Osteoarthritis was the only parameter of potential structural vulnerability markers that showed statistically significant differences between samples, with BIPOC experiencing more instances than non-BIPOC individuals. (Figures 2 and 3). Additionally, the BIPOC sample experienced more instances of antemortem fractures, surgical interventions, and enthesopathies than the non-BIPOC sample, but they were not statistically significant (Figure 2; Table 2).

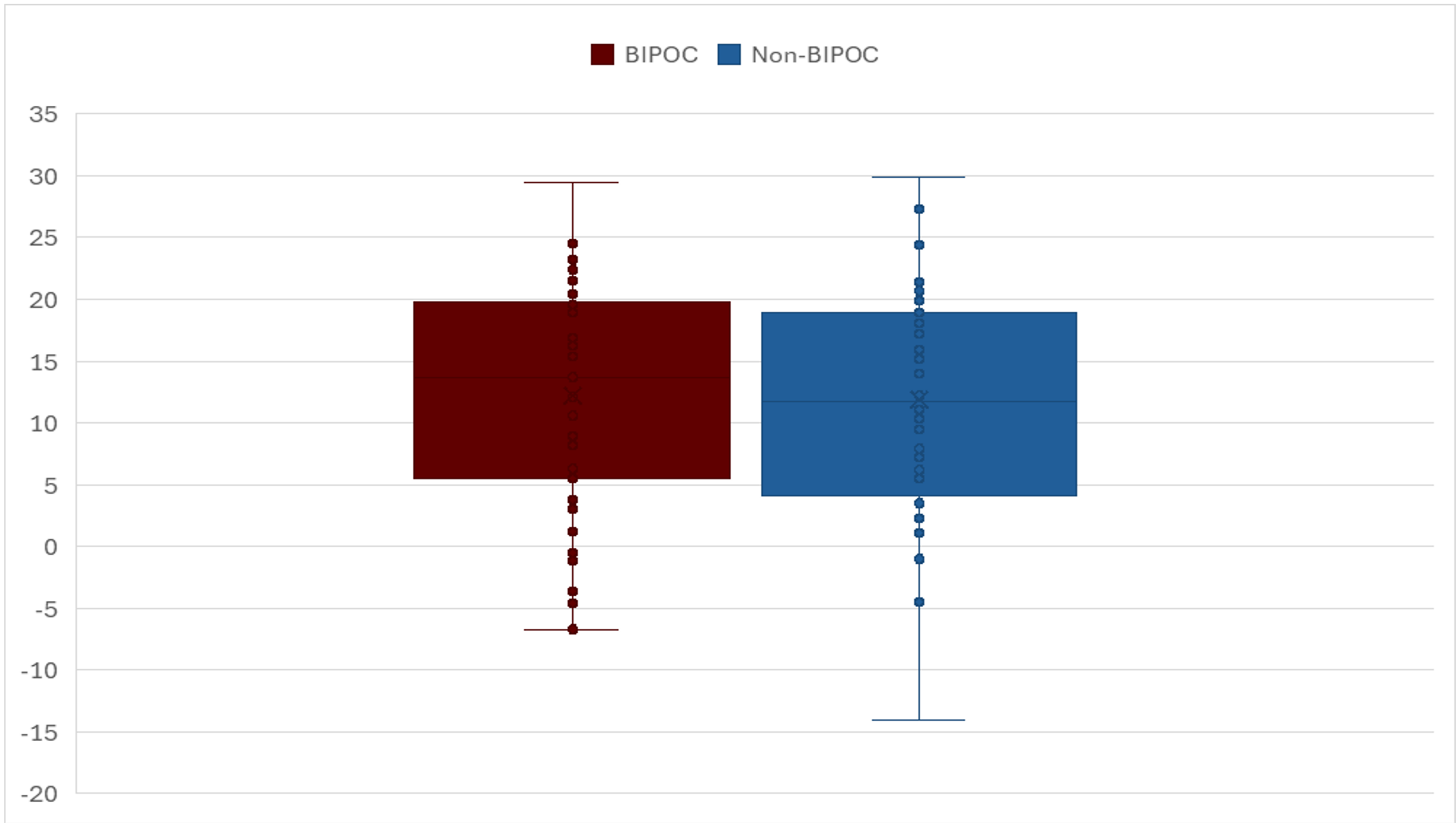


Figure 1: Box and whisker plot showing no statistically significant differences between documented ages and TA3 estimated ages in the BIPOC and non-BIPOC samples.

Discussion

Despite the incorporation of numerous body-wide biological age indicators, TA3 misclassified 28.8% of the total sample (28.0% of BIPOC and non-BIPOC). This is more inaccurate than the sole study of TA3’s accuracy investigated on a known-age sample (n=71), in which 7.04% fell outside of the TA3 estimated age range (Wonhof 2025). Additionally, TA3 did not provide accurate point estimates for either sample, making the comparisons between the two difficult. However, TA3 does provide a standardized method of estimating semi-accurate age ranges via comparison to a large embedded reference sample. Levels of accuracy in this study were higher than many studies that utilize traditional age estimation methods, particularly those using the 4th rib (e.g., Marella et al. 2025). Overall, 10.2% (n=12) of the sample had documented ages that fell more than five years outside the TA3 estimated age range.

Despite being age and sex matched, the increased presence of osteoarthritis in the BIPOC sample indicates older skeletal age than the non-BIPOC sample. While the TA3 point estimates were not statistically different between the two samples, this finding supports the weathering hypothesis. Higher rates of osteoarthritis in the BIPOC sample could also be related to exposure to different environments/occupations and reflect structural vulnerability. Additionally, while not statistically significant, the elevated frequency of antemortem fractures in the BIPOC sample could further suggest structural vulnerability, as traumatic injuries are often associated with groups that face precarious occupations and threats of violence (Winburn et al. 2022a). Paradoxically, however, surgical intervention—also higher in the BIPOC sample and seen with both treatment of antemortem fractures and joint replacements—demonstrates access to healthcare, which can be viewed as a form of privilege. However, the lack of consistent antemortem data for the donor individuals precluded determining the etiology of the interventions.

Table 2: Reported chi-square and *p*-values for the indicators of structural vulnerability showing statistically significant differences only in osteoarthritis.

SV Indicator	Chi-square value	<i>p</i> -value
Cribra orbitalia	0	1
Porotic hyperostosis	0.9091	0.76302
Cranial lesions	2.57143	0.10881
Schmorl’s nodes	3.55556	0.059346
Spina bifida	0.4	0.527089
Periosteal NB	0	1
Lytic lesions	0	1
Enthesopathy	2.77778	0.095581
Osteoarthritis	8.47059	0.003609
Osteoporosis	2.27273	0.131668
Surgical intervention	0.36364	0.546494
Fractures	1.92308	0.165518

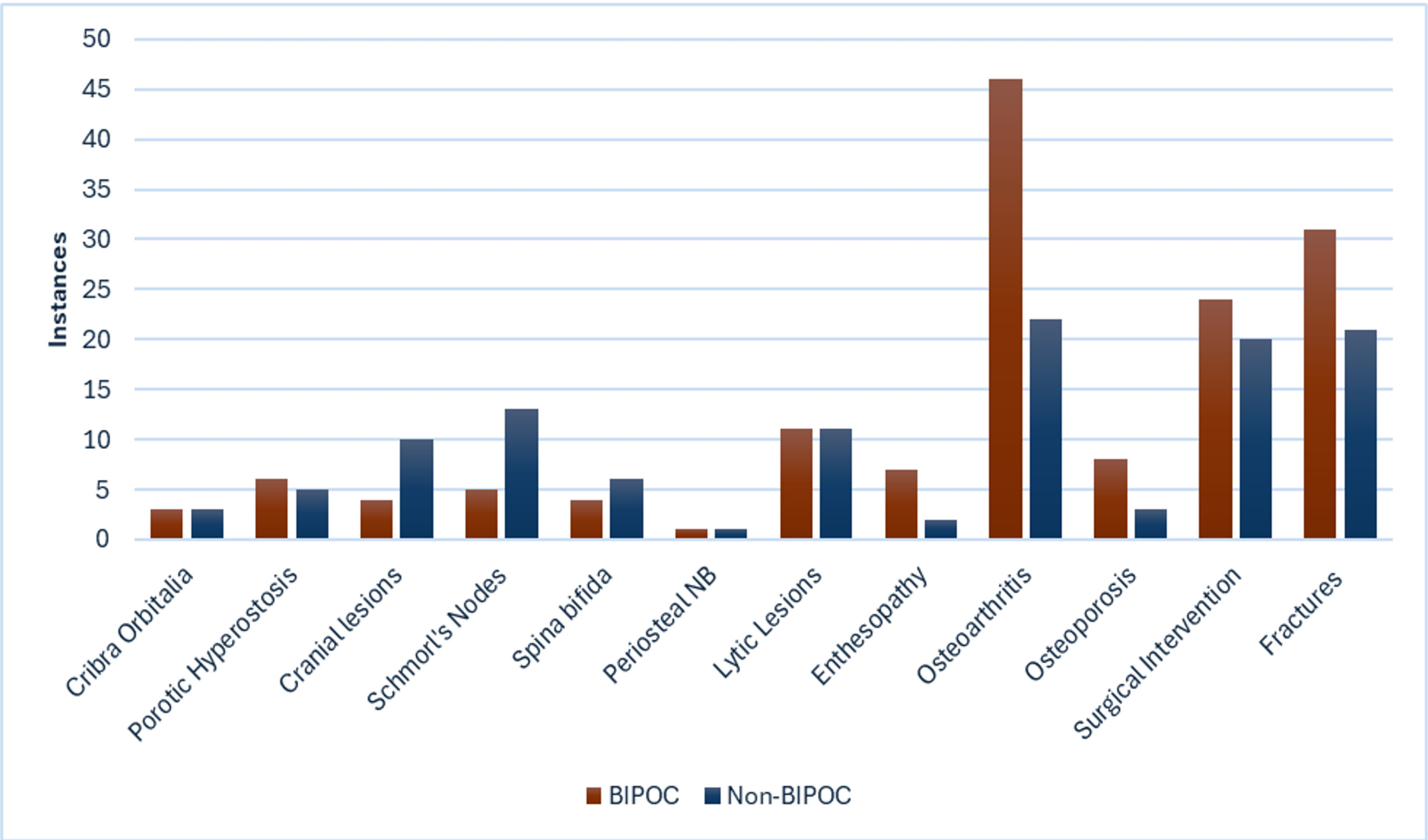


Figure 2: Bar chart of structural vulnerability markers in the BIPOC and non-BIPOC samples.

Overall, examining the evidence for **structural vulnerability was somewhat useful for visualizing health disparities between social bureaucratic racial groups, but improvements should be made before the large-scale application to forensic case reporting.** Many practices in forensic anthropology continue to contribute to the racialization of traditionally marginalized communities, including ancestry/population affinity estimation and using non-consensually donated remains (e.g., legacy and inherited collections) in research, which are rooted in colonialism (Dwyer et al. 2023; Go 2025). Additionally, the lack of BIPOC body donors due to the justified mistrust of the medical and scientific communities highlights the need for evolving, ethically situated approaches to understanding health disparities in skeletal collections (Winburn et al. 2022b). Relatedly, the association of pathological and traumatic indicators with social race is inherently problematic, especially when considering the comparison to a non-BIPOC sample as the “standard” for health. **With the wrong interpretation, structural vulnerability approaches could contribute to further racialization and harm in forensic anthropology.** The field must work to recognize the biomarkers of structural vulnerability and violence in a way that does not contribute to further marginalization, as remaining ignorant about signs of embodied injustice contributes to the harmful cycle in which forensic anthropologists have long been complicit (Beatrice and Soler 2016).

Conclusions

This project was not conducted to prove or disprove that weathering and structural vulnerability exist, as they are well documented and actively impact marginalized communities (Beatrice and Soler 2016; Geronimus 1992; Geronimus et al. 2001; Geronimus et al. 2006; Kim et al. 2023; Simons et al. 2016; Winburn et al. 2022b). Rather, this study further explores the way that stresses associated with structural vulnerability and marginalization may become embodied within the skeleton and contributes to methodology and practice in forensic anthropology. **TA3 was not refined enough as a method of skeletal age estimation to definitively visualize weathering at a level of statistical significance, which can be related to the idiosyncratic nature of human aging and the inability of current age estimation to capture that range of variation.** The weathering hypothesis was still supported by the older TA3 ages and the presence of osteoarthritis in the BIPOC sample. The examination of structural vulnerability indicators was somewhat useful for visualizing sociopolitical injustice and violence, but significant work needs to be done on a larger scale within forensic anthropology to avoid further essentializing, marginalizing, and harming historically marginalized groups before structural vulnerability can become a part of normal case reporting.