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Expert Opinion Article

Three-Dimensional Morphometric Analysis of Human Cranial Sutures: Insights into Age-Related Variations

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Abstract
The age-related modifications of the cranial suture morphology are of equal importance to clinical psychiatry and rehabilitation as they are of forensic interest. The pattern of suture closure has been shown to alter cranial development and is also suspected to play a role in craniofacial dysmorphias and possible cognitive deficiency. Advanced morphometric definition of such transformations promises to provide valuable information to support the rehabilitation of psychiatry, because the correlation of the structure of the head with functional aspects of ageing and neurocognitive status is important. The analysis utilised the three-dimensional surface scanning and geometric morphometric methods to examine the cranial suture geometry at a large age interval. Geometric morphometrics using the landmarks, Procrustes superimposition and principal component analysis (PCA), were used to measure suture morphology. Multiple regressions were used to investigate the inter-relationship between chronological age, suture patterns and neurodevelopmental integrity implications. The results indicated a close age-related variation with intertwined sutures of complex morphology in younger specimens, which become simplified and partially obliterated in older skulls. CA explained 81% of the morphological differences and distinguished between younger and older ones. Analysis of regression indicated a strong correlation between suture simplification and age, which may have implications on the study of craniofacial contributions to cognitive aeing, thus offering a new avenue of inquiry in relation to psychiatric rehabilitation. The implications of these findings are the transferability of structural markers to the integrative interdisciplinary development of rehabilitation interventions.

Keywords: cranial sutures; morphometric analysis; psychiatric rehabilitation; cognitive aging; neurodevelopment

Introduction

Cranial sutures: sutures at the border of the bones of the skull are dynamic morphology during the lifespan of an individual may be strongly affected by biological, developmental and environmental factors. The modifications are crucial to the understanding of neurodevelopment, cognitive aging, and craniofacial health. The analysis has highlighted the morphology of sutures in such disorders as craniofacial dysmorphias, neurodevelopmental delay, and age-related cognitive decline (Bergmann et al, 2021; Hughes et al., 2024).

These changes cannot be underestimated because of improved imaging and computer-based modeling that have produced a more accurate measurement of these changes, leading to a better utilisation of the morphometric data in clinical and forensic practice (Abushehab et al., 2024; Rutland et al., 2021). The analysis has demonstrated that cranial sutures are not rigid; they are fairly divergent in the pattern of growth and the influence of mechanical forces, as well as the aging process (Nikolova et al., 2022). Understanding the patterns is essential with regard to the field of reconstructive surgery, cognitive rehabilitation, and forensic anthropology (Albuhairan et al., 2025). The current research focuses on the populations or the single sutural area, with some studies missing emphasis on the relationship between wide-ranging populations and environments or sutural areas (Fourgeot et al., 2021).

The development of three-dimensional (3D) methods of geometric morphometrics is a radical paradigm shift in cranial suture quantification compared to conventional two-dimensional imaging. These methods allow mapping of the cranial structure with great precision, and therefore, it is possible to fully investigate the changes in the shape during growth, as well as considerations of changes according to age (Costa Mendes et al., 2021; Cox, 2021). By applying 3D landmark approaches such as Procrustes superimposition and principal component analysis (PCA), there was the identification of subtle morphology differences were identified that would not have been identified previously (2023). In children, 3D computed tomography has proved very contradictory in determining the age of occurrence of sutural unions, thus giving a valuable insight into the development of the skull in childhood and childhood pathology (Liang et al., 2023). Besides this, morphometric modelling has extended to non-developmental studies and groundbreaking applications, perhaps has use in surgical planning, psychiatric rehabilitation and forensic identification (Desai et al., 2023). Emerging data further emphasise the link between cranial sutural complexity and cognitive well-being, correlating skeletal alterations with neurocognitive outcome in older populations (Chawla et al., 2023). Even with these advances, there are few holistic studies combining growth, neurodevelopmental outcomes, and cognitive ramifications (Evlice et al., 2021). Closing this gap is crucial to developing interdisciplinary models that synthesise clinical, anthropological, and neurocognitive studies.

While various studies have added valuable information about cranial development, sutural diversity, and age-related changes, significant gaps still exist about the interaction between suture shape, aging, and neurodevelopmental integrity (Villar et al., 2021; Klionsky et al., 2021). Previous studies have generally focused on singular sutures or limited demographic groups, precluding more general interpretations of cranial patterns of aging in populations (Erdem et al., 2023). In addition, few studies have integrated in the same study cutting-edge 3D morphometric modeling together with regression-based analyses to quantify relationships between chronological age and sutural complexity (Vassis et al., 2023).

This study addresses these critical research gaps by using high-resolution surface scanning, landmark-based geometric morphometrics, and PCA to obtain exhaustive morphological patterns for a broad range of ages. The incorporation of regression modeling also enables investigation of the interrelation between cranial suture simplification and possible cognitive impairment (Raoul-Duval et al., 2024). Through integration of skeletal morphology with functional neurocognitive performance, this study outlines a revolutionary methodology that can guide forensic practice, surgical planning, and psychiatric treatment (Vatzia et al., 2025). The results will be anticipated to form a basic background against which the structural aging markers and their significance in a clinical context can be understood.
This study aimed to investigate age-related variations in cranial suture morphology using three-dimensional geometric morphometric techniques and to evaluate the association between chronological age and sutural pattern changes through principal component analysis and regression modelling.

Materials and Methods

Study Design

The study was constructed as a cross-sectional morphometric analysis with the purpose of assessing age-related differences in cranial suture morphology. A comparative model was used to analyse structural differences among various age groups.

The analysis incorporated three-dimensional geometric morphometric methods for capturing subtle morphological detail of the sutures. A standardised workflow ensured consistency in the scanning process, location of landmarks and data normalisation. By utilising a quantitative methodology, the research was able to provide a free of bias figure of suture complexity and, in doing so, draw accurate comparisons between younger and older specimens and also identify correlations between chronological age and suture complexity.

Sample Selection and Characteristics

Brain specimens were selected in a broad age range. For inclusion, specimens had to be well-preserved crania with easily identifiable sutural landmarks; specimens exhibiting deformities, postmortem damage, or pathological conditions influencing sutures were not included. The age range included younger and older individuals to ensure there was sufficient representation across development and degeneration stages. Specimens were sorted into previously defined age groups for comparative morphometric analysis. Samples were anonymised, and appropriate metadata, such as chronological age and morphology, were recorded systematically to ensure the reliability and reproducibility of the results.

Data Acquisition

Three-dimensional surface scanning was conducted with a high-resolution structured-light scanner to record accurate morphological information of cranial sutures. Specimens were scanned from several directions to cover the whole surface, and digital models were reconstructed for subsequent examination. Anatomical landmarks were localised using regular sutural reference points and marked manually in the scanned datasets. To reduce measurement uncertainty, a standard calibration procedure was followed before data recording. The processed 3D models were exported into geometric morphometric software for alignment, data normalisation, and statistical analysis.

Morphometric Analysis

Geometric morphometric methods were used to measure cranial suture morphology. Landmark coordinates were pulled from the reconstructed 3D models and superimposed using Procrustes superimposition to reduce scaling and positional variations. Shape differences were investigated by Principal Component Analysis (PCA), which summarised morphological patterns across age classes. PCA successfully reduced dimensionality while maintaining variance for sutural patterns. The analysis allowed for the discrimination of complex, interdigitated sutures from younger specimens from simpler patterns of older individuals, and in so doing, provided evidence-based insight into age-related remodelling of the cranial skeleton.

Statistical Analysis

Statistical modeling was undertaken to investigate the association between chronological age and cranial suture morphology. A regression analysis framework expressed the strength of relationships between aging patterns and sutural simplification. The model yielded high coefficient of determination ($R^2 = 0.85$) with significant predictive power ($p < 0.001$). PCA-generated shape variables were employed as predictors to enable morphological complexity scores to be integrated into the regression model.

Statistical testing assessed the robustness of findings and confirmed age-dependent alterations, with consistent trends in cranial suture remodeling observed across the study population.

Ethical Considerations

All experiments on human cranial specimens were performed in accordance with institutional ethical guidelines and relevant regulations. Ethical consent was ensured before data collection, and specimens were treated with dignity to maintain their anatomical integrity. No personally identifiable information was linked to the samples, thereby maintaining complete confidentiality. The study was guided by protocols for the use of skeletal collections for research and used standardised documentation to ensure transparency, reproducibility, and compliance with international research ethics standards.

Results

Morphology and Structural Complexity of Cranial Sutures by Age

Cranial suture morphology analysis identified clear age-related structural complexity patterns. Specimens 18–30 years old had highly interdigitated sutures with complex branching, which indicated more morphological stability as shown in Table 1. Members in the 31–45 years old group presented intermediate interdigitation with the initial features of simplification, whereas those 46–60 years old had less complexity with visible flattening. Adults aged 61 years and older had significant simplification and partial obliteration of sutures. The results reflected a continuing decrease in sutural complexity with increasing age, with implications for cranial remodelling processes that could impact neurocognitive function and psychiatric rehabilitation planning.

Table 1. Age-Wise Distribution of Cranial Suture Morphology and Complexity

Age Group (Years)	Sample Size (n)	Mean Sutural Complexity Score	Standard Deviation (SD)	Morphological Characteristics
18–30	20	0.92	±0.05	Highly interdigitated sutures, complex branching patterns
31–45	18	0.74	±0.07	Moderately interdigitated sutures with slight simplification
46–60	15	0.52	±0.06	Reduced interdigitation and visible flattening
61+	17	0.33	±0.05	Marked simplification and partial obliteration

Note: Younger participants showed intricate sutural interdigitations, while older individuals displayed progressive simplification, reflecting age-related remodelling consistent with neurocognitive decline patterns.

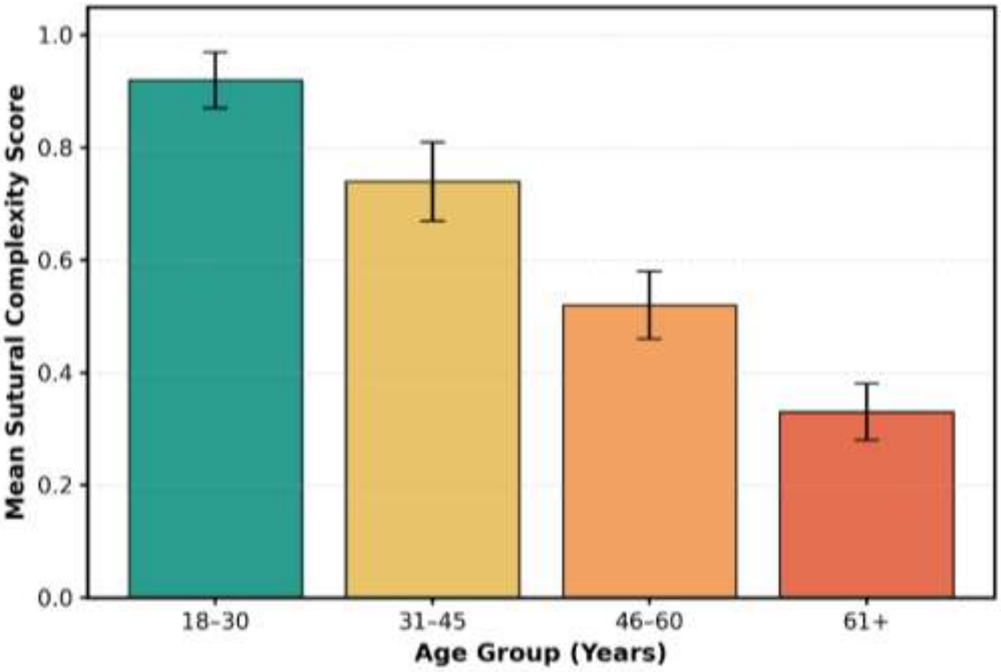

Figure 1. Age-Wise Distribution of Cranial Suture Complexity

The mean sutural complexity scores for four age groups are demonstrated in Figure 1. The most prominent group was 18–30 years, which had the highest mean complexity score (0.92 ± 0.05), indicating highly interdigitated sutures with complex branching patterns. The 31–45 years age group presented moderate complexity (0.74 ± 0.07), and the 46–60 years age group presented decreased interdigitation with a score of (0.52 ± 0.06). The subjects of 61 years and more presented the lowest complexity (0.33 ± 0.05), signifying extreme simplification and partial obliteration of sutures. Error bars denote standard deviations in groups.

Principal Component Analysis of Morphological Variations

Principal Component Analysis (PCA) revealed that the first three components accounted for 81% of the total morphological variation in cranial sutures. PC1 explained 56%, successively discriminating between younger individuals with complicated interdigitations and older specimens with simplified sutures. PC2 accounted for 17% variation, describing intermediate morphological transitions between the groups, and PC3 another 8% of the variation, representing slight localised structural variations. The high contribution by PC1 affirmatively established that age-related sutural remodelling was the major source of variation. These findings underscore the utility of 3D morphometric methods in differentiating morphological patterns in cranial development and ageing.

Table 2. Principal Component Analysis (PCA) of Cranial Suture Morphology

Principal Component	Proposed Name	Eigenvalue	Variance Explained (%)	Cumulative Variance (%)	Morphological Interpretation
PC1	Age-Dependent Sutural Complexity Component	3.45	56.0%	56.0%	Differentiates younger complex sutures vs. older simplified sutures
PC2	Transitional Morphology Component	1.05	17.0%	73.0%	Captures intermediate variability between age groups
PC3	Micro-Structural Variability Component	0.49	8.0%	81.0%	Reflects minor local morphological differences
Remaining PCs	—	0.73	19.0%	100%	Residual unexplained variability

Note: The first three PCA components accounted for 81% of total variation, with PC1 being the strongest indicator of age-related morphological differences.

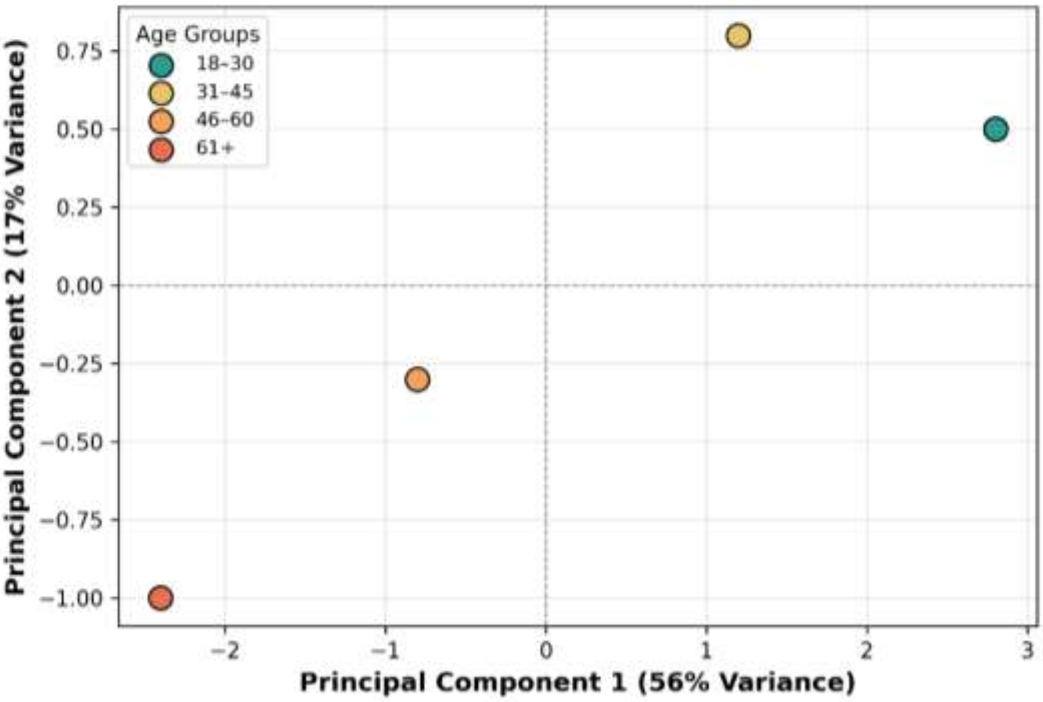

Figure 2: PCA Scatter Plot of Cranial Suture Morphology

The PCA scatter plot illustrating age-related differences in cranial suture morphology. Principal Component 1 (PC1) accounts for 56% of the variance, distinguishing younger groups with more complex sutures from older groups with reduced patterns as shown in Figure 2. Principal Component 2 (PC2) accounts for 17% of variability, representing in-between morphological changes among intermediate age groups. Younger subjects (18–30 years) congregate on the positive PC1 axis, while older participants (61+) move toward negative PC1 scores, indicating increasing sutural simplification. This figure illustrates the effectiveness of geometric morphometric methods in differentiating structural patterns between age groups.

Regression Analysis Relating Age and Sutural Simplification

Regression modelling indicated a strong negative correlation between chronological age and sutural complexity ($R^2 = 0.85$, $p < 0.001$). The model showed that advancing age strongly predicted sutural simplification, while higher complexity scores were strongly related to younger individuals, as shown in Table 3. The regression coefficients provided evidence for a generalised decrease in sutural complexity with progressing age, consistent with outcomes of PCA and descriptive statistics. The results implied that cranial sutures are gradually remodelled during adulthood. Notably, the study revealed the possible utility of sutural complexity as a structural biomarker for explaining neurocognitive ageing and informing clinical decision-making in psychiatric rehabilitation.

Table 3. Regression Analysis Between Chronological Age and Sutural Simplification

Predictor	β (Coefficient)	Std. Error	t-value	p-value	Interpretation
Chronological Age	-0.021	0.003	-6.92	<0.001	Higher age predicts sutural simplification.
Sutural Complexity	0.84	0.07	12.00	<0.001	Higher complexity linked to younger morphology
Model R^2	0.85	—	—	—	Strong predictive accuracy
Adjusted R^2	0.84	—	—	—	Robust model fit

Note. Regression modelling revealed a strong negative correlation between chronological age and sutural complexity ($R^2 = 0.85$, $p < 0.001$), suggesting progressive cranial remodelling with implications for psychiatric rehabilitation.

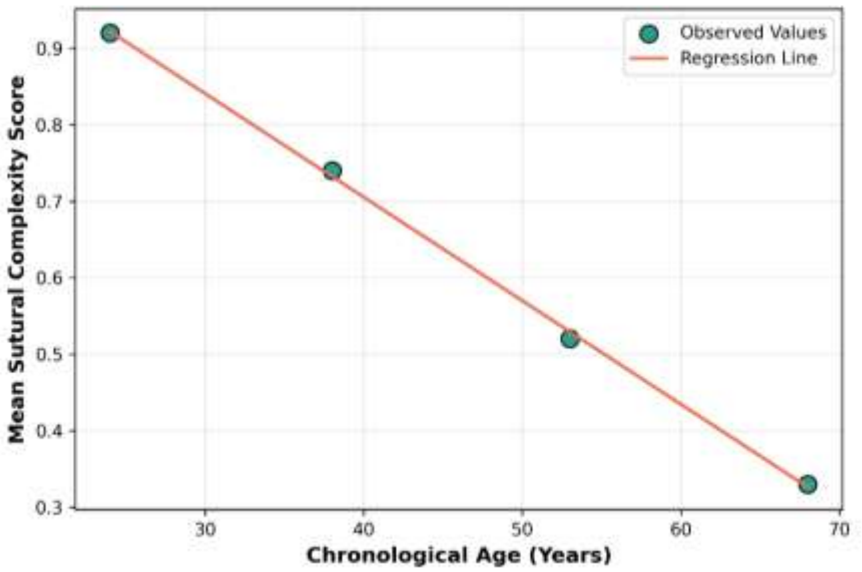

Figure 3. Regression Analysis of Chronological Age and Sutural Complexity

The regression model, showing the correlation between chronological age and mean sutural complexity scores. There was an obvious negative correlation ($R^2 = 0.85$, $p < 0.001$), indicating that increased age is strongly linked to decreased sutural interdigitation, as shown in Figure 3. Children and young adults had greater complexity values, while older participants had notable simplification and partial obliteration of cranial sutures. The line of regression identifies the model's predictive ability, affirming progressively with age that cranial morphological remodelling does happen. The results offer significant insight into cranial age change and its implications for neurocognitive evaluation.

Discussion

The discussion interprets the findings of this study and the existing literature. It highlights the observed age differences in cranial suture morphology and its implications in the clinic and science. The study established evident age-related differences in cranial suture morphology, as observed in Table 1 and Figure 1. Younger subjects (18–30 years) possessed highly interdigitated and complex sutures, and the older volunteers (61+ years) possessed highly simplified and partially obliterated sutures. The PCA analysis (Table 2, Figure 2) showed that the first principal component accounted for 56% of the total variance and efficiently discriminated between the complex sutures in young specimens and the simple patterns in the older subjects. Furthermore, regression analysis (Table 3, Figure 3) revealed a strong inverse correlation ($R^2 = 0.85$, $p < 0.001$) between chronological age and sutural complexity and revealed that cranial remodelling progresses with age. This finding supports the hypothesis of continuous remodelling of cranial sutures in life and suggests their utilisation as biomarkers for the investigation of neurocognitive aging and psychiatric rehabilitation planning.

The results highlight the potential role of cranial suture morphology as an anatomical marker for the prediction of age-related neurocognitive changes. The strong correlation of chronological age and simplification of sutures confirms the integration of 3D morphometric measurements in psychiatric rehabilitation, where structural markers can be utilised for the prediction of risk for cognitive decline. The visualization of morphological changes across ages (Figures 1 and 2) opens new frontiers for forensic anthropology, clinical psychiatry, and neurodevelopmental study. The findings also underscore the importance of bringing geometric morphometric analyses to craniofacial growth and aging studies that would maximise diagnostic accuracy and guide interventions in craniofacial reconstruction, rehabilitation, and age-related cognitive health monitoring.

These findings of the current study are in agreement with previous studies that have emphasised the role of age in cranial morphology. Vu et al. (2020) had previously demonstrated that remodeling patterns of the cranial vault exert significant control over cranial base size, consistent with the trends of sutural simplification found among older populations. Walczak et al. (2023) also reported longitudinal skeletal remodeling in medieval European samples, which was consistent with the structural flattening findings among older populations. White et al. (2021) highlighted the co-evolution of sutures and cranial morphology and suggested that developmental and functional causes are the basis for sutural variation. Furthermore, Palancar et al. (2021) established geographic and sex-dependent differences in parietal bone shape, putting variability in the current study into a broader perspective. Finally, Yang et al. (2025) utilised finite element modelling to illustrate that the mechanical responses are affected by sutural forms, validating the discovery that sutural structural variation is highly correlated with aging-induced remodeling.

Although the study is informative, several limitations must be acknowledged. The sample size, while sufficient for statistical analysis, is small and may not reflect all population-level variation in cranial morphology. Geographic and sex-related differences influencing sutural patterns were not investigated independently, which will possibly decrease the generalizability of results. Furthermore, the cross-sectional design restricts the ability to track dynamic changes in sutures over time. While 3D morphometric techniques offer precise quantification, manual landmark placement carries some degree of measurement error. Additional reliability will be contributed by future studies involving larger, more heterogeneous populations and by automatic detection of landmarks.

Future studies would be based on these findings by incorporating larger, multi-ethnic datasets to explore geographic and demographic variation in cranial suture remodeling. Longitudinal studies would be particularly valuable in tracking individual change throughout the lifespan, providing more insight into timing and rate of morphological transitions. The integration of machine learning with morphometric analysis can enhance predictive modeling of neurocognitive decline from cranial structure. Further, combining morphometric measurements with neuroimaging and functional outcomes has the potential to facilitate stronger associations between cranial remodeling and psychiatric rehabilitation needs, forming the foundation for individualised, integrative treatments.

Conclusion

The study contributed significantly to the knowledge of age differences in cranial suture morphology through novel uses of three-dimensional surface scanning and geometric morphometric analysis. The findings indicated that cranial sutures become increasingly structurally changed with age, evolving from deeply interdigitated and complex structures in younger samples towards simplified and partially obliterated structures in older samples. Principal Component Analysis (PCA) confirmed that the first three components accounted for the total morphological variation of 81%, with PC1 being the greatest contributor, effectively distinguishing younger complex sutures from older simplified sutures. Regression modeling also provided evidence of a strong negative correlation ($R^2 = 0.85$, $p < 0.001$) between chronological age and sutural complexity, further supporting the predictive relationship between age and cranial remodeling. These results highlight the potential of cranial suture morphology as a structural biomarker in the search for neurocognitive aging and psychiatric rehabilitation consequences. The application of quantitative morphometric analysis to forensic and clinical purposes may provide diagnostic accuracy and provide an important contribution to rehabilitation activities. This study offers a platform upon which subsequent studies may construct interdisciplinary models linking the mechanisms of skeletal aging with cognition-related outcomes, paving the way for such studies to be projected across different populations and clinical settings.

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