

# Cross-Validated Neural and Biophysical Models for Pediatric Fingerprint Ridge Breadth Age Estimation with Archaeological Applications

Niev Bhandare

niev841@gmail.com

Rye Country Day School

Kimberlee Moran

Rutgers University–Camden

Maria Mina

University of the Aegean

Isabella Perry

Rutgers University–Camden

Olivia Pozniewski

Rutgers University–Camden

---

## Article

**Keywords:** pediatric age estimation, fingerprint ridge breadth, neural network, reaction-diffusion, paleodermatoglyphics, Neolithic Knossos

**Posted Date:** August 26th, 2026

**DOI:** <https://doi.org/10.21203/rs.3.rs-10808097/v1>

**License:**   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

**Additional Declarations:** No competing interests reported.

---

# Abstract

Small clay figurines from Neolithic Knossos, Crete occur predominantly in domestic and residential assemblages, yet whether children participated in their manufacture remains contested. Fingerprint ridge breadth, preserved in clay at the point of contact, provides a non-destructive proxy for maker age because ridge breadth expands systematically during childhood. Existing approaches are calibrated on adult-containing samples and have never been cross-validated against a dedicated pediatric reference. We address this gap by collecting fingerprint impressions from 200 children aged 6–12 years in Rhodes, Greece, using the same clay-token protocol applicable to ancient ceramic surfaces, and evaluating three models under leave-one-out cross-validation: a logistic ordinary differential equation (ODE), a Fisher-KPP reaction-diffusion partial differential equation (PDE), and a multilayer perceptron neural network (MLP). The MLP achieved a mean absolute error of 1.382 years (bootstrap 95% CI: 1.256–1.510), reducing error fivefold relative to the adult-calibrated Kamp et al. baseline (MAE 7.09 years). Applied to 11 figurines from the Heraklion Archaeological Museum and the Stratigraphical Museum at Knossos, ridge breadth estimates across all specimens fall within the childhood age range (approximately 4–12 years depending on assumed clay shrinkage), providing the first cross-validated biometric evidence consistent with child participation in Neolithic figurine production at Knossos.

## Introduction

The small clay figurines of Neolithic Knossos are found predominantly in domestic and residential contexts, where they are modest in scale and often display surface irregularities consistent with handling by developing hands<sup>1,2</sup>. Whether children made them—or whether figurine production was an exclusively adult activity—bears directly on debates about childhood participation in Neolithic material culture<sup>3,4,5,6</sup>. That question has so far resisted direct answer because skeletal remains, grave goods, and spatial associations are unavailable for unfired clay objects recovered centuries later in fragmentary form.

Fingerprint ridge breadth—the spacing between adjacent epidermal ridges—increases as the hand grows during childhood and stabilises in adulthood, providing a biologically grounded proxy for maker age<sup>7</sup>. Kamp et al.<sup>8</sup> formalised this for archaeological use; subsequent studies applied the method to ancestral Puebloan ceramics<sup>9</sup>, Bronze Age Canaanite pottery<sup>10</sup>, and Upper Palaeolithic figurines<sup>11</sup>.

However, existing approaches share a fundamental limitation: none has been validated against a dedicated pediatric reference sample using cross-validated individual-level accuracy metrics. The Kamp et al.<sup>8</sup> regression was calibrated on an adult-containing sample and produces a mean absolute error of 7.09 years when applied to children aged 6–12. Broader attempts to identify children in the archaeological record through miniature objects<sup>4</sup>, spatial patterning<sup>3</sup>, and osteological analysis<sup>12</sup> have likewise been limited by the indirect nature of the evidence.

We address this gap through an experimental archaeology and machine-learning approach. We collected fingerprint impressions from 200 children aged 6–12 years in Rhodes, Greece, using the same clay-pressing protocol applicable to ancient ceramic surfaces, and cross-validated three models: a logistic ODE, a Fisher-KPP PDE, and an MLP. We then applied the validated models to 11 clay figurines from Neolithic Knossos to assess whether their preserved ridge dimensions are consistent with childhood manufacture.

## Results

### Reference sample characteristics

Mean SameAVG ridge breadth was  $0.491 \pm 0.077$  mm (range 0.357–0.726 mm). Male and female breadths did not differ significantly at ages 6–9 ( $p = 0.31$ ) but diverged at ages 10–12 (males  $0.528 \pm 0.063$  mm, females  $0.503 \pm 0.071$  mm), consistent with published sex differences in pediatric hand growth<sup>7</sup>.

## Intra-observer reliability

Table 1  
Intra-observer measurement reliability (n = 200).

| Metric                        | Value     | Benchmark                        |
|-------------------------------|-----------|----------------------------------|
| ICC (one-way random-effects)  | 0.829     | $\geq 0.75$ good <sup>13</sup>   |
| Pooled TEM (mm)               | 0.0280    | —                                |
| Mean rTEM (%)                 | 5.75      | < 5% excellent; 5–10% acceptable |
| Individuals rTEM > 10% (n)    | 13 (6.5%) | Flagged; sensitivity analysis    |
| Pearson r (rTEM vs MLP error) | 0.009     | No meaningful association        |

Good reliability was demonstrated (ICC = 0.829). The near-zero correlation between rTEM and MLP prediction error ( $r = 0.009$ ) indicates that measurement variability did not meaningfully drive prediction error.

## Model comparison

Table 2  
Leave-one-out cross-validation accuracy (n = 200).

| Model              | n   | MAE (yr) | RMSE (yr) | Bias (yr) | 95% CI (MAE) | ± 1 year (%) | ± 2 year (%) |
|--------------------|-----|----------|-----------|-----------|--------------|--------------|--------------|
| MLP (10-feature)   | 200 | 1.382    | 1.653     | -0.028    | 1.256–1.510  | 44.5         | 73.0         |
| ODE (logistic)     | 200 | 1.920    | 2.380     | + 0.540   | —            | 33.5         | 56.5         |
| PDE (Fisher-KPP)   | 200 | 1.900    | 2.420     | + 0.540   | —            | 34.0         | 57.5         |
| Kamp et al. (1999) | 200 | 7.090    | 7.420     | + 7.090   | —            | 0.0          | 0.0          |

The MLP achieved LOO-CV MAE of 1.382 years (bootstrap 95% CI: 1.256–1.510), outperforming all prior approaches. The ODE and PDE models achieved MAEs of 1.920 and 1.900 years without cohort-specific fitting. The adult-calibrated baseline produced MAE 7.090 years, confirming systematic error from applying an adult-calibrated model to children.

## Age-stratified and sex-stratified results

Table 3  
Age-stratified and sex-stratified MLP accuracy.

| Subgroup   | n   | MLP MAE (yr) | MLP Bias (yr) |
|------------|-----|--------------|---------------|
| Ages 6–9   | 122 | 1.180        | -0.050        |
| Ages 10–12 | 76  | 1.703        | -0.005        |
| Male       | 104 | 1.330        | -0.020        |
| Female     | 96  | 1.440        | -0.037        |

Error was lower in ages 6–9 (MAE 1.180 year) than ages 10–12 (MAE 1.703 year), reflecting growth deceleration as ridge breadth approaches its adult asymptote.

## Archaeological figurine results

Twelve friction-ridge impression areas were identified across 11 clay figurines from two museum collections at Knossos (Heraklion Archaeological Museum, n = 4; Stratigraphical Museum, n = 7). Under 0% assumed clay shrinkage, MLP point estimates ranged from 4.00 to 7.31 years. Under 15% shrinkage<sup>17</sup> the same specimens yielded 5.52 to 11.62 years. Nine of 12 impression areas fell within the empirically validated breadth range of the reference sample; three are treated as directional

classifications toward infant–toddler categories. All 95% uncertainty intervals ( $\pm 3.24$  year;  $\pm 1.96 \times \text{RMSE}$ ) encompass ages consistent with childhood.

Table 4

MLP age estimates (years) for Knossos figurines. Asterisk (\*) = extrapolation (corrected breadth below training minimum 0.357 mm). 95% CI =  $\pm 3.24$  year.

| Specimen group         | 0% shrinkage | 5% shrinkage | 10% shrinkage | 15% shrinkage |
|------------------------|--------------|--------------|---------------|---------------|
| Range across specimens | 4.00–7.31 yr | 4.48–8.27 yr | 4.96–9.44 yr  | 5.52–11.62 yr |
| Within training range  | 9/12         | 10/12        | 11/12         | 11/12         |

## Discussion

The ridge breadth dimensions preserved on 11 Neolithic figurines from Knossos fall within the childhood age range under every shrinkage scenario examined, providing direct biometric evidence consistent with child participation in figurine production. This adds a quantitative biometric line of evidence to debates that have rested primarily on contextual and analogical arguments<sup>1,2,3,4</sup>.

The MLP achieved MAE 1.382 years under LOO-CV, a fivefold improvement over the Kamp et al.<sup>8</sup> regression (MAE 7.09 years). The biophysical ODE and PDE models achieved comparable accuracy without cohort-specific fitting ( $\approx 1.90$ – $1.92$  years), demonstrating that the improvement reflects genuine information content in ridge breadth for ages 6–12, not solely machine-learning flexibility.

The near-identical ODE and PDE performance suggests that the principal age signal resides in mean breadth rather than the spatial profile at the six-landmark resolution used here. Clay shrinkage substantially affects age estimates: at 15% shrinkage, estimates shift by up to 4.2 years relative to the uncorrected value<sup>17</sup>. The sensitivity analysis demonstrates that the core finding is robust across the 0–15% range.

Limitations include single-population sampling (Rhodes, Greece), a fixed random seed per LOO-CV fold, and uncertainty in clay shrinkage parameters. Validation in additional populations and experimental firing studies are necessary before general deployment in forensic or archaeological practice<sup>17</sup>.

## Methods

### Reference sample and ethical approval

Fingerprint impressions were collected from 200 children (104 male, 96 female; ages 6–12 years; mean  $9.2 \pm 2.1$  years) attending a primary school in Rhodes, Greece. Written parental consent and child verbal assent were obtained. This study was conducted under Rutgers University IRB protocol Pro2023001527 (Non-Human Subjects Research determination, DHHS FWA00003913, approved 10 August 2023;

expanded 20 February 2026). All experiments were performed in accordance with relevant guidelines and regulations. Only age and sex were recorded; no personal identifiers were collected.

## Fingerprint acquisition and measurement

Each child pressed their right thumb into a ball of clay ( $\approx 3$  cm diameter), producing a clay token with a fingerprint impression. Impressions were photographed next to a ruler and measured in ImageJ (v.1.54f) at  $\times 10$  magnification following the protocol of Kralik and Novotny<sup>7</sup>. Ridge breadth was defined as the distance from the outer edge of one epidermal ridge to the outer edge of the adjacent furrow, perpendicular to ridge direction. Two measurement series were collected per individual: five repeated same-spot measurements (SameAVG; for reliability only) and five spatially distinct landmark measurements (Diff1–Diff5; model inputs). All values in millimetres.

## Intra-observer reliability

Reliability was assessed by Technical Error of Measurement (TEM) and relative TEM (rTEM)<sup>13</sup>, and by the intraclass correlation coefficient (ICC) from one-way random-effects ANOVA<sup>14</sup>. Thresholds: rTEM < 5% excellent, 5–10% acceptable, > 10% elevated.

## Logistic ODE model

$dB/dt = \alpha(t) \cdot B \cdot (1 - B/B_{\max}(t))$ . Phase-specific parameters derived from Kralik and Novotny<sup>7</sup> and fixed before evaluation (Phase 0:  $\alpha = 0.30/\text{yr}$ ; Phase 1:  $\alpha = 0.12/\text{yr}$ ; Phase 2:  $\alpha = 0.05/\text{yr}$ ). Solved numerically by Euler integration ( $dt = 0.01$  years). Age estimated by inverse search minimising the residual against SameAVG over  $t \in [4, 15]$  years.

## Fisher-KPP PDE model

$\partial B/\partial t = D(t) \cdot \partial^2 B/\partial x^2 + \alpha(t) \cdot B \cdot (1 - B/B_{\max}(t))$ . The diffusion term models spatial equalisation of breadth through tissue continuity. Six landmarks ( $dx = 0.2$ ), Neumann zero-flux boundary conditions, spatial profiles compared across all five Diff measurements.

## Multilayer perceptron

Input(10)  $\rightarrow$  ReLU(14)  $\rightarrow$  ReLU(8)  $\rightarrow$  Output(1), 283 trainable parameters. Features: SameAVG, Diff1–Diff5, sex,  $\log(\text{SameAVG})$ ,  $\text{SameAVG}^2$ ,  $\text{sex} \times \text{SameAVG}$ . The developmental phase variable was removed as label leakage<sup>15</sup>. Adam optimisation ( $\text{lr} = 0.008$ , cosine decay,  $\text{L2} = 0.15$ , 600 epochs); seed = fold index per LOO-CV fold.

## Baseline: Kamp et al. (1999)

The Kamp et al.<sup>8</sup> regression applied with published coefficients as adult-calibrated negative control, including all individuals (no exclusions) to give an unbiased error profile on pediatric data.

# Archaeological figurine application

Sex treated as unknown (mean of male and female model predictions). Ages estimated under four clay shrinkage regimes (0%, 5%, 10%, 15%) following Ross<sup>17</sup>. Corrected breadth =  $B_{\text{obs}}/(1 - s)$ . The 95% uncertainty interval is  $\pm 1.96 \times \text{RMSE} = \pm 3.24$  years.

## Statistical analysis

Performance evaluated by MAE, RMSE, systematic bias, and proportion of predictions within  $\pm 1$  and  $\pm 2$  years. Bootstrap 95% CIs for MAE used 10,000 non-parametric resamples of the 200 held-out errors. All analyses in Python 3.10 (PyTorch, NumPy, SciPy).

## Use of AI in manuscript preparation

During the preparation of this work the authors used Anthropic's Claude (Sonnet 4.6) to offer suggestions for revision and wording, alongside adding supplemental comments to code and to review and optimise code. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

## Declarations

## Competing interests

The authors declare no competing interests.

## Author Contribution

N.B. developed the computational models, performed all formal analysis, and wrote the main manuscript text. K.M. conceived the study, led data collection, secured funding, and contributed to manuscript writing. M.M. arranged and supervised the data collection site in Rhodes, Greece. I.P., N.B., and O.P. contributed to data collection and measurement. All authors reviewed the manuscript, although K.M and N.B. contributed to revision and editing.

## Acknowledgement

The authors thank Hillsdale Elementary School and the 2nd Elementary School of the City of Rhodes, including their students, teachers, and administrators, for their participation. The authors thank Sophia Sarantopoulou for assistance in Rhodes and Dr. Christina Nase for assistance in the United States. Additional thanks go to Kassandra Anderson, Jazlyn Carmickel, Abbie Kasoff, Megan Richards, and the staff at Say It With Clay. This work was supported by an International Collaboration Research Grant from Rutgers Global (funding travel and materials costs only; no role in study design, analysis, or publication).

# Data Availability

The data and code used for this project are publicly available at:

<https://drive.google.com/drive/u/0/folders/156R4wPlun6THjad9LDd9z2SVjBubAgtr>

## References

1. Mina, M. Figurines without sex: people or persons? In DAIS: the Aegean feast (eds Hitchcock, L. A., Laffineur, R. & Crowley, J.) 135–150 (Peeters, 2008).
2. Talalay, L. E. Heady business: skulls, heads, and decapitation in Neolithic Anatolia and Greece. *J. Mediterr. Archaeol.* **17**, 139–163 (2004).
3. Kamp, K. A. Where have all the children gone? The archaeology of childhood. *J. Archaeol. Method Theory*. **8**, 1–34 (2001).
4. Baxter, J. E. *The Archaeology of Childhood: Children, Gender, and Material Culture* (AltaMira, 2005).
5. Lillehammer, G. American Anthropological Association,. The world of children. In *Children in Action: Perspectives on the Archaeology of Childhood* (ed. Baxter, J. E.) 1–12 (2010).
6. Robb, J. *The Early Mediterranean Village* (Cambridge Univ. Press, 2007).
7. Kralik, M. & Novotny, V. Epidermal ridge breadth: an indicator of age and sex in paleodermatoglyphics. *Variability Evol.* **11**, 5–30 (2003).
8. Kamp, K. A., Timmerman, N., Lind, G., Graybill, J. & Natowsky, I. Discovering childhood: using fingerprints to find children in the archaeological record. *Am. Antiq.* **64**, 309–315 (1999).
9. Kantner, J., McKinney, D., Pierson, M. & Wester, S. Reconstructing sexual divisions of labor from fingerprints on ancestral Puebloan pottery. *Proc. Natl Acad. Sci. USA* **116**, 12220–12225 (2019).
10. Fowler, K. D. et al. The identity of potters in early states. *J. Archaeol. Method Theory*. **26**, 1470–1512 (2019).
11. Kralik, M., Novotny, V. & Oliva, M. Fingerprint on the Venus of Dolni Vestonice I. *Coll. Antropol.* **26**, 115–119 (2002).
12. Lewis, M. E. *The Bioarchaeology of Children* (Cambridge Univ. Press, 2007).
13. Ulijaszek, S. J. & Kerr, D. A. Anthropometric measurement error and the assessment of nutritional status. *Br. J. Nutr.* **82**, 165–177 (1999).
14. Norton, K. & Olds, T. (eds) *Anthropometrica* (UNSW, 1996).
15. Navega, D., Costa, E. & Cunha, E. Adult skeletal age-at-death estimation through deep random neural networks. *Biology* **11**, 532 (2022).
16. He, K., Zhang, X., Ren, S. & Sun, J. Delving deep into rectifiers. *Proc. IEEE Int. Conf. Comput. Vis.* 1026–1034 (2015).
17. Ross, J. Distorted touch: clay shrinkage experiments and the challenge of fingerprint analysis. *Archaeol. Anthropol. Sci.* **18**, 114 (2026).

18. Burchill, A. T., Sanders, A. & Morgan, T. J. H. Inferring the age and sex of ancient potters from fingerprint ridge densities. *MethodsX* **10**, 102292 (2023).
19. Fisher, R. A. The wave of advance of advantageous genes. *Ann. Eugenics.* **7**, 355–369 (1937).
20. Kolmogorov, A., Petrovsky, I. & Piskunov, N. A study of the diffusion equation with increase in the quantity of matter. *Bull. Mosc. Univ.* **1**, 1–25 (1937).
21. Verhulst, P. F. Notice sur la loi que la population suit dans son accroissement. *Corresp Math. Phys.* **10**, 113–121 (1838).
22. Kingma, D. P. & Ba, J. Adam: a method for stochastic optimization. *Proc. ICLR* (2015).
23. Penrose, L. S. Memorandum on dermatoglyphic nomenclature. *Birth Defects.* **4**, 1–13 (1968).