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Comparative Stature Estimation and Skeletal Robusticity in the Indus Valley Civilization Populations: Long Bone Evidence from Three Sites

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Running head: IVC STATURE AND MORPHOLOGY: RUPAR, KALIBANGAN, LOTHAL

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Abstract

This study estimates living stature, quantifies skeletal robusticity and cross-sectional bone shape, and compares three Indus Valley Civilization skeletal assemblages from Rupar, Kalibangan, and Lothal, India. Forty-six adult individuals were analysed using fragment lengths from six long bones (humerus, radius, ulna, femur, tibia, and fibula), with stature reconstructed through a validated two-step regression approach that is appropriate for fragmentary remains and consistent with population-sensitive stature estimation practice. Robusticity Index (RI) and Circularity Index (CI) were calculated to assess diaphyseal form and biomechanical patterning, which are standard approaches for interpreting skeletal loading and activity-related variation. Inter-site comparisons were performed using Kruskal-Wallis and Mann-Whitney U tests with Bonferroni correction, a suitable strategy for small archaeological samples and non-normal distributions.

The pooled weighted mean stature was 189.3 ± 20.5 cm, and site means followed a geographical gradient of Rupar > Kalibangan > Lothal, although the difference was not statistically significant ($p = 0.21$). Femoral RI also showed a non-significant inter-site trend ($p = 0.093$), with higher values at Lothal suggesting possible differences in lower-limb mechanical loading, but this remains an inference rather than a confirmed site effect. Platymeria and platycnemia were observed in subsets of the sample, but these traits should be interpreted cautiously as possible indicators of repetitive loading or postural behaviour rather than as direct proof of specific activities such as squatting or load-carrying. The results add to the limited bioarchaeological literature on Indus Valley Civilization skeletal populations and support a cautious, population-aware interpretation of stature and robusticity variation.

HIGHLIGHTS

- **Stature Estimates:** Weighted mean stature estimates were 196.9 cm (Rupar), 189.2 cm (Kalibangan), and 186.0 cm (Lothal).
- **Regional Robusticity:** A non-significant inter-site trend was found in femoral robusticity (p = 0.093), with Lothal exhibiting higher values, potentially reflecting coastal port activity patterns.
- **Habitual Posture:** Prevalences of platymeria (33%) and platycnemia (31%) suggest that habitual squatting was a common physical behaviour across all three populations.
- **Population Heterogeneity:** Lothal showed the highest intra-site morphological variability (*CV*=13.3%), consistent with its role as a cosmopolitan trade entrepot

1. Introduction

The Indus Valley Civilization (IVC, c.3500–1900 BCE), represents one of the earliest and most extensive urban societies in the ancient world, extending across approximately 1.5 million square kilometres of present-day north-western India, Pakistan, and Afghanistan (Kenoyer 1998; Possehl 2002). Despite the civilisation's material complexity evidenced by standardised weights, planned urban layouts, and long-distance trade networks, its biological anthropological perspectives remain comparatively poorly characterised and represented, with relatively few quantitative osteometric studies in the published literature (Kennedy 2000; Robbins Schug et al 2012). This lack of published literature is due to the fragmentary condition of skeletal remains from most IVC burial contexts, which precludes the application of standard stature estimation methods requiring complete bone lengths.

Living stature is among the most informative biological parameters recoverable from the human skeleton. (Siddiqui et.al. 2026; Biehler-Gomez et al 2024; Singh and Sharma 2008) As a polygenic trait sensitive to nutritional status, disease burden, and socioeconomic conditions during growth, stature serves as a proxy indicator of the quality of life experienced by past populations (Steckel 1995; Bogin 1999). Differences in mean stature between contemporaneous populations may reflect biological variation related to genetic background, subsistence economy, and health status, questions of direct relevance to understanding the social organisation and living conditions of IVC populations (Larsen 1997; Lukacs 1992).

The three sites examined in this study represent geographically and economically distinct IVC populations. Rupar (Punjab) is a riverine agricultural settlement on the Sutlej River at the eastern edge of the IVC distribution. Kalibangan (Rajasthan) is a planned urban site on the dried Ghaggar-Hakra River, one of the few IVC sites with a well-documented burial assemblage and prior osteological analysis (Lukacs 1992). Lothal in Gujarat is a coastal port site with a documented dockyard. It is evidence of long-distance maritime trade, represent a functionally and economically distinct community of the IVC cultural sphere (Rao 1985). A comparison of the skeletal biology of these sites might inform whether the three IVC populations shared a common biological profile or exhibited morphological differences in accordance with their distinct ecological and economic niches.

Skeletal robusticity, the relative thickness of the bone shaft and cross-sectional diaphyseal shape are additional osteometric parameters with established interpretive value for inferring habitual physical activity and posture (Ruff et al 1991; Larsen 1997). The Robusticity Index (RI) and Circularity Index (CI) computed in this study provide supporting evidence for the physical activity needed for subsistence activities at each site, and allow identification of platymeria and platycnemia, conditions associated with habitual squatting posture in many prehistoric agricultural populations (Angel 1964; Trinkaus 1975).

The objectives for the present study are:

1) to estimate living stature for each individual using a validated two-step regression protocol applied to long bone fragment measurements;

2) to classify each individual by Martin and Saller (1956) stature categories;

3) to compute RI and CI per bone per individual; and

4) to perform systematic pairwise inter-site statistical comparisons of stature, RI, and CI between Rupar, Kalibangan, and Lothal.

The present study is the first report of its kind to the best of knowledge which would enrich the archaeological and paleoanthropological data on ancient populations from India.

2. Background

2.1 Skeletal Stature Estimation: Methodological Framework

Mathematical regression methods for estimating stature from long bone dimensions were pioneered by Pearson (1899) and substantially advanced by Trotter and Gleser (1952, 1958), whose equations, derived from documented skeletal and cadaveric samples of known stature, remain the most widely applied reference in both forensic and archaeological contexts. For fully preserved bones, stature is estimated directly, where the constants vary by bone, sex, and ancestral reference population. The Trotter and Gleser (1952) Mongoloid equations, derived from individuals of East Asian ancestry, are considered the most appropriate available proxy for South Asian skeletal proportions in the absence of large, geographically and temporally appropriate documented South Asian reference collections (Kennedy 2000; Lukacs 1992), though systematic bias cannot be excluded (Holliday 1997).

2.2 Stature Estimation from Fragmentary Remains

When articular ends are absent due to taphonomic destruction, the common condition in many archaeological assemblages including the studied IVC sites, complete bone lengths cannot be measured, and a two-step protocol is required. Steele (1970) demonstrated that diaphyseal fragment lengths are strong predictors of complete bone length across all six major long bones $\text{Coefficient of determination } (R^2) = (0.80 - 0.95)$, and provided regression equations that utilize diaphyseal fragment lengths to predict total bone dimensions, employing specific coefficients and standard errors of the estimate (*SEE*) for each bone.

These equations remain the most widely cited and methodologically transparent available for this purpose and are applied in the present study. Uncertainty from both regression steps is propagated using standard error propagation theory as detailed in Section 3.4.

2.3 IVC Physical Anthropology

Systematic osteological analysis of IVC skeletal material began with Sewell and Guha's (1931) study of the Mohenjo-daro assemblage and was advanced by Kennedy (1984, 2000), who described IVC populations as generally gracile with limited interpersonal violence relative to later South Asian prehistory. Lukacs (1992) identified nutritional stress indicators at several IVC sites, including dental enamel hypoplasia and porotic hyperostosis. Robbins Schug et al (2012) documented elevated trauma and infectious disease frequencies in the terminal Harappan layers at Harappa, interpreted as evidence of urban stress during the civilisation's decline. Dedicated stature analyses for IVC sites are inadequate; Kennedy (2000) reported mean male statures of approximately 165–170 cm at Harappa and Mohenjo-daro, and Lukacs (1992) published comparable estimates

for Kalibangan, placing IVC males broadly in the "Average" to "Tall" Martin and Saller categories. Neither study applied a two-step fragment-based protocol or performed formal inter-site statistical comparisons.

3. Materials and Methods

3.1 Study Sample

The study sample comprises 46 adult individuals from three IVC sites: Rupar (n =15), Kalibangan (n =12), and Lothal (n =19). All individuals are anatomically identified as adults based on dental eruption and epiphyseal fusion, assessed prior to osteometric data collection. Biological sex could not be assigned to individual skeletons due to the fragmentary preservation of pelvic and cranial elements in the majority of cases. All analyses therefore apply male Trotter and Gleser (1952) constants as a uniform reference, with the explicit caveat that female individuals, (whose presence in the assemblage is probable), have their statures overestimated by approximately 8–12 cm under this protocol. The skeletal materials for the present study are housed at the ancient skeletal repository of Anthropological Survey of India, Kolkata (AnSI).

The raw dataset contains 92 observations, representing 46 individuals measured on both sides (Left and Right). For each individual, the side with the greater number of non-missing fragment measurements was selected as the analytical unit ("best-side selection"); ties were broken by preferring the Right side following standard osteological convention. This procedure yielded 46 individual-level records, one per person.

3.2 Osteometric Measurements

Three measurements were recorded per bone following Buikstra and Ubelaker (1994):

1) Fragment Length (FRAG, cm): maximum preserved diaphyseal length measured with an osteometric board, excluding articular surfaces;
2) Mediolateral Diameter (ML, cm): maximum breadth in the mediolateral plane at or near midshaft; and
3) Anteroposterior Diameter (AP, cm): maximum breadth in the anteroposterior plane at the same level.

3.3 Predicting Complete Bone Length from Fragment Length

For each bone, complete bone length was predicted using the Steele (1970) equation:

$$Predicted\ Length\ (\text{cm}) = a_Steele + b_Steele \times \text{FRAG}$$

The linear relationship between preserved fragment length and predicted complete bone length is highly robust across all anatomical elements. The first stage of our two-step regression protocol is visualized in Fig. 1, which illustrates the exceptionally tight fit of individual specimens around the calculated regression lines for each of the six long bones (humerus, radius, ulna, femur, tibia, and fibula). This linear model shows a minimal dispersion of data points across the Rupar, Kalibangan, and Lothal assemblages, confirming the high predictive accuracy of the Steele (1970) equations in South Asian contexts. The standard error of the estimate is lowest for the radius (SEE_1 = 1.89 cm) and the ulna (SEE_1 = 2.05 cm) as detailed in Table 2, providing a reliable quantitative baseline prior to final stature reconstruction.

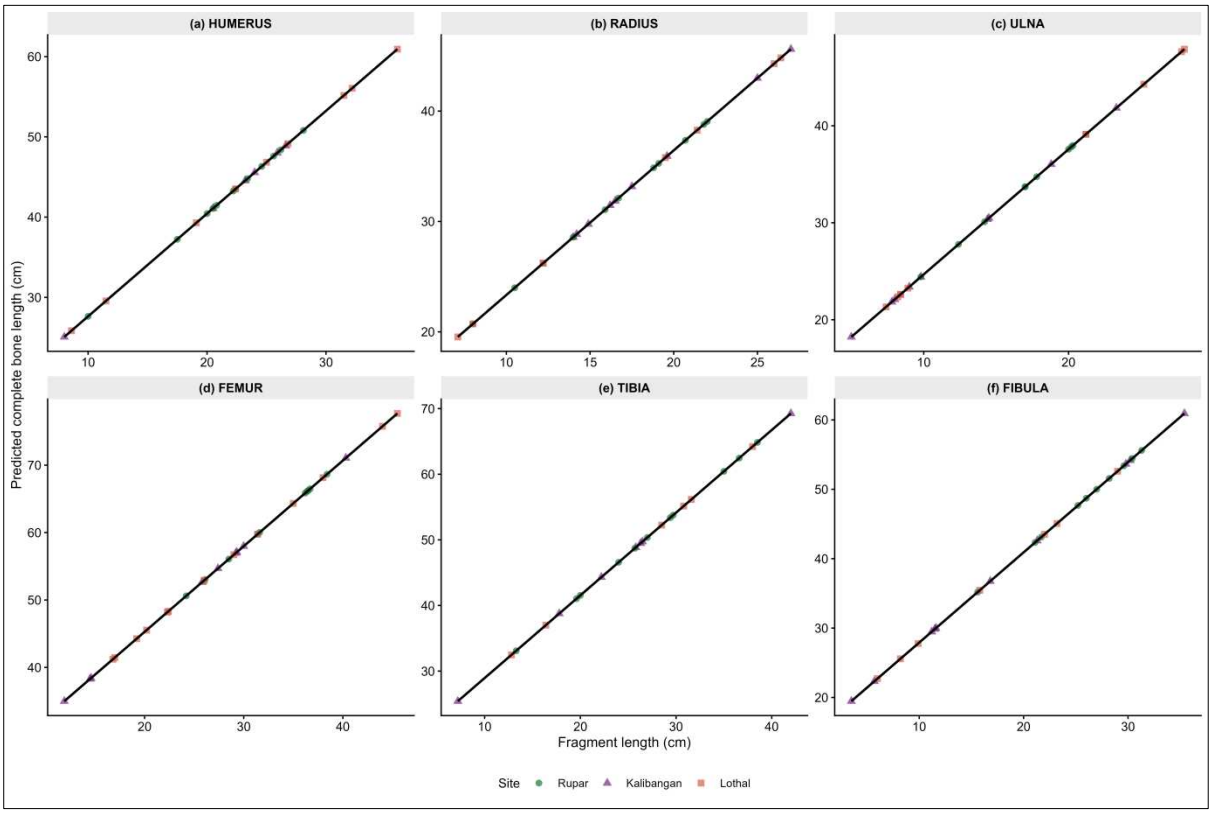


Fig. 1 Regression Accuracy (Step 1)

3.4 Estimating Stature from Predicted Bone Length

Estimated stature for each bone was computed using Trotter and Gleser (1952) Mongoloid male equations:

$$Stature\ (\text{cm}) = a_TG + b_TG \times \text{Predicted Length}.$$

Combined SEE values, propagating uncertainty from both steps as:

$$Combined\ SEE = \sqrt{(SEE_TG^2 + (b_TG \times SEE_Steele)^2)}$$

as presented in Table 2 below. 95% confidence intervals were computed as $Stature \pm 1.96 \times Combined\ SEE$.

3.5 Weighted Mean Stature

When multiple bone-specific estimates were available for an individual, a weighted mean stature was computed using inverse-variance weighting (Cochran 1937):

$$\hat{S} = \sum (W_i \times S_i) \div \sum W_i$$

where $W_i = 1/(\text{Combined } SEE)^2$, and S_i is each bone-specific stature estimate.

The standard error of the weighted mean is $(\hat{S}) = 1/\sqrt{\sum W_i}$. This assigns greater weight to estimates from bones with smaller combined SEE (femur and tibia) and produces the minimum variance combined estimate. Individuals with no available bone measurements were excluded from stature analyses.

3.6 Stature Classification

Each individual's weighted mean stature was assigned to a Martin and Saller (1956) category (applying the Male thresholds throughout).

Table 1 Martin and Saller (1956) Stature Classification Categories

CATEGORY	Range
Very Short	<150 cm
Short	150–159.9 cm
Below Average	160–163.9 cm
Average	164–166.9 cm
Above Average	167–169.9 cm
Tall	170–179.9 cm
Very Tall	≥180 cm

3.7 Robusticity Index and Circularity Index

Robusticity Index (RI):

$$RI = [mean\ (ML, AP) \div PredictedBone\ Length]\ \times 100$$

Higher values indicate relatively thicker-shafted bones, associated with greater habitual mechanical loading (Ruff et al. 1991). The predicted bone length is used as the denominator to standardise across individuals with different degrees of fragment preservation.

Circularity Index (CI):

$$CI = [minimum\ (ML, AP) \div maximum\ (ML, AP)]\ \times 100$$

CI = 100 indicates a circular cross-section; lower values indicate shaft flattening. Anthropologically significant thresholds are: femoral CI < 85 = platymeria (Angel 1964); tibial CI < 70 = platycnemia (Trinkaus 1975)

3.8 Statistical Analysis

Normality was assessed per site using the Shapiro-Wilk test (Shapiro and Wilk 1965); homoscedasticity was assessed with Levene's test (Levene 1960). Inter-site comparison of weighted mean stature used the Kruskal-Wallis H-test (Kruskal and Wallis 1952; df=2). Pairwise comparisons used the Mann-Whitney U test (Mann and Whitney 1947) with a Bonferroni correction for three simultaneous tests (adjusted α = 0.0167). Effect sizes were quantified as Cohen's d (Cohen 1988). Inter-site differences in RI and CI were tested with Kruskal-Wallis for each bone separately. Because this sample represents the complete available skeletal assemblage from each site, inferential tests are interpreted in conjunction with effect sizes to characterise the magnitude and direction of inter-site differences; descriptive characterisation of morphological variation takes precedence over null hypothesis significance testing. All analyses were performed in R version 4.6.0 (R Core Team 2026). The complete annotated R script and all output files are provided as Online Resource 3.

Table 2 Regression Coefficients for the Two-Step Stature Estimation Protocol

Bone	Step 1: Steele (1970)			Step 2: Trotter and Gleser (1952)			*Combined SEE* (cm)
	a	***b***	***SEE₁* (cm)**	***a***	***b***	***SEE₂* (cm)**	
Humerus	14.84	1.28	2.10	83.19	2.68	4.25	4.79

Radius	10.24	1.31	1.89	80.71	3.55	4.60	5.37
Ulna	11.78	1.29	2.05	77.45	3.48	4.66	5.37
Femur	19.88	1.27	2.54	72.57	2.15	3.80	4.92
Tibia	16.34	1.26	2.31	81.45	2.39	3.74	4.97
Fibula	14.91	1.30	2.18	80.56	2.40	3.80	4.97

Table 2. Regression coefficients for the two-step stature estimation protocol. Step 1: Steele (1970) fragment-to-length equations (Predicted Length = a + b × Fragment Length). Step 2: Trotter and Gleser (1952) Mongoloid male length-to-stature equations (Stature = a + b × Predicted Length). Combined SEE = $\sqrt{(SEE_2^2 + (b_2 \times SEE_1)^2)}$, representing the total prediction uncertainty in centimetres propagated across both steps.

4. Results

4.1 Sample Composition and Measurement Availability

The best-side (Right) selected sample comprised 15 individuals from Rupar, 12 from Kalibangan, and 19 from Lothal (total $N = 46$). Bone fragment availability varied by bone and site (Table 3). Fragments of Femur existed for the maximum number of individuals ($n = 32$ 69.6%), followed by ulna ($n = 28$, 60.9%), and the humerus, radius, and fibula ($n = 27$, 58.7% each), while the tibia ($n = 24$, 52.2%) was the least commonly preserved. The mean number of bones available per individual was 3.59 (range: 0–6). Fragment lengths ranged from 8.0 to 36.0 cm for the humerus and from 7.2 to 42.0 cm for the tibia, reflecting the variation in preservation within the sample populations. Mediolateral and anteroposterior diameters showed lower coefficients of variation (*CV* 16-30%) than fragment lengths (*CV* 31-46%), consistent with the expectation that diaphyseal diameters are less affected by the degree of preservation than shaft length.

Table 3 Sample Composition and Bone Availability by Site

Site	*N*	Humerus	Radius	Ulna	Femur	Tibia	Fibula	Mean Bones/Individual
Rupar	15	12	10	9	10	11	10	4.13
Kalibangan	12	6	9	9	9	7	10	4.17
Lothal	19	9	8	10	13	6	7	2.79
Total	46	27	27	28	32	24	27	3.59

Table 3. Number of individuals and available bone fragment measurements per IVC site after best-side selection. Mean Bones/Indiv. = mean number of bones with non-missing fragment measurements per individual. Femur is the most commonly preserved bone in this assemblage.

4.2 Descriptive Statistics of Raw Measurements

Pooled descriptive statistics for all FRAG, ML, and AP measurements are presented in Table 4 and the physical distribution and density of these raw measurements is presented in Fig. 2.

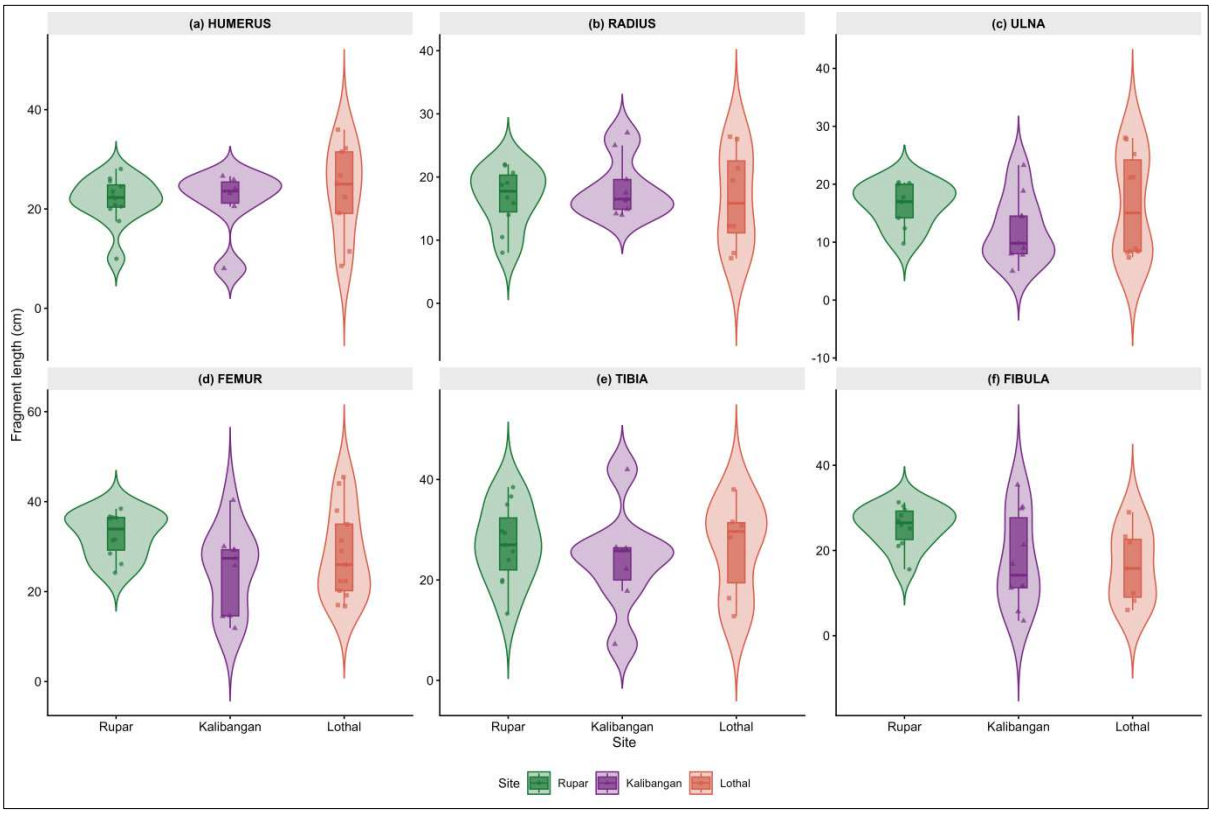


Fig. 2 Fragment Length Distributions

Mean fragment lengths ranged from 15.14 cm (ulna) to 28.62 cm (femur), consistent with predominantly midshaft diaphyseal preservation. Mediolateral diameters were systematically larger than anteroposterior diameters for the radius, ulna, femur, and fibula, indicating the characteristic flattening of these shafts in the plane captured by the ML measurement, while AP measurements were smaller than ML for humerus and tibia. Coefficients of variation (*CV%*) for all measurements were highest at Lothal (*CV* 11.7-54.3%), indicating greater intra-site morphological variability than at Rupar or Kalibangan. This increased diversity at the coastal site is consistent with its role as a cosmopolitan trade entrepot potentially drawing individuals from demographically varied populations.

Table 4 Descriptive Statistics of Osteometric Measurements (Pooled Sample, N=46)

Bone	Measure	*n*	*Mean (cm)*	*SD*	*Min*	*Max*	*CV%*
Humerus	FRAG	27	22.32	6.81	8	36	30.5
	ML	27	1.83	0.32	1.2	2.4	17.2
	AP	27	1.93	0.32	1.3	2.6	16.4
Radius	FRAG	27	17.23	5.6	7.1	27	32.5
	ML	27	1.31	0.25	0.7	1.7	19.3
	AP	27	1.14	0.18	0.8	1.5	16.1
Ulna	FRAG	28	15.14	6.72	5	28	44.4
	ML	28	1.31	0.33	0.6	1.9	24.9
	AP	28	1.19	0.33	0.6	2	27.9
Femur	FRAG	32	28.62	8.77	11.9	45.5	30.7
	ML	32	2.58	0.48	1.4	3.8	18.7
	AP	32	2.56	0.57	1.5	3.7	22.4
Tibia	FRAG	24	26.03	8.8	7.2	42	33.8
	ML	24	2.3	0.68	1.3	4	29.6

	AP	24	2.48	0.6	1.5	3.6	24.2
Fibula	FRAG	27	20.27	9.25	3.5	35.4	45.6
	ML	27	1.27	0.35	0.6	2.1	27.6
	AP	27	1.09	0.25	0.7	1.8	23.4

Table 4. Descriptive statistics of osteometric measurements for the pooled IVC sample (best-side selected, N=46). FRAG = fragment length; ML = mediolateral diameter; AP = anteroposterior diameter. All values in cm. CV% = coefficient of variation.

4.3 Stature Estimates: Intra and Inter- Site Results

Stature was estimated for all 46 individuals. Bone-specific stature estimates (Online Resource 1) showed broad within-individual concordance, with most individuals' bone-specific estimates falling within overlapping 95% Confidence intervals, supporting the validity of the weighted mean approach. Weighted mean stature for the pooled sample was 189.3 ± 20.5 cm (range: 147.2–231.0 cm). Site-level descriptive statistics are presented in Table 5 and individual bone-specific stature estimates are compared in Fig. 3.

Table 5 Weighted Mean Stature Descriptive Statistics by Site

Site	*N*	*Mean (cm)*	*Median (cm)*	*SD (cm)*	Range (cm)	*CV%*	*95% CI (Mean)*
Rupar	15	196.9	195.8	14.23	157.3–220.5	7.2	189.4–203.6
Kalibangan	12	189.2	186.1	18.47	167.4–221.3	9.8	177.4–197.4
Lothal	19	186	182.9	24.75	147.2–231.0	13.3	173.5–195.9
Pooled	46	189.3	186.7	20.5	147.2–231.0	10.8	183.2–195.4

Table 5. Site-level descriptive statistics for inverse-variance weighted mean stature (cm). All estimates apply male Trotter and Gleser (1952) Mongoloid constants to an unsexed sample; systematic overestimation of female individuals is expected (see text). CV% = coefficient of variation; 95% CI = confidence interval around the group means.

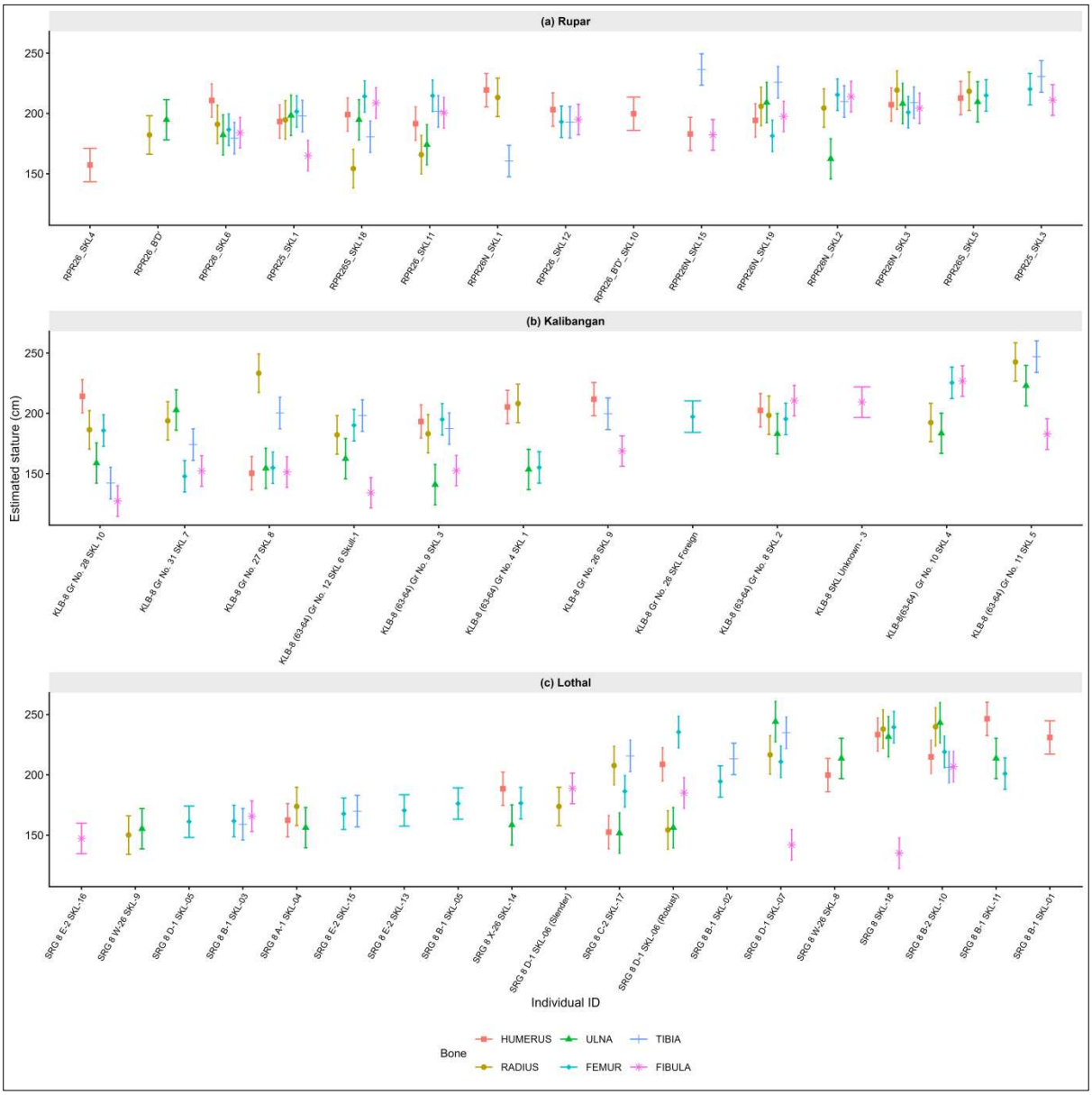


Fig. 3 Individual Stature Estimates

. Reconstructed statures show high intra-individual consistency, with overlapping 95% confidence intervals validating our inverse-variance weighting method. Rupar had the highest mean weighted stature (196.9 ± 14.2 cm; median 195.8 cm; range 157.3–220.5 cm), followed by Kalibangan (189.2 ± 18.5 cm; median 186.1 cm; range 167.4–221.3 cm), and Lothal (186.0 ± 24.8 cm; median 182.9 cm; range 147.2-231.0 cm). Intra-site variability, as indexed by the coefficient of variation (*CV%*), was lowest at Rupar (*CV* = 7.2%) and highest at Lothal (*CV* = 13.3%), indicating substantially greater morphological diversity at the coastal port site, indicating towards Lothal's role as a trade entrepot potentially drawing population from diverse populations.

4.4 Stature Classification

Application of Martin and Saller (1956) categories presented in Fig. 4 show that there are differences in the distribution of stature categories across sites, despite the non-significant global stature comparison (see Section 4.5). Among the individual skeletal remains from Rupar, 93.3% of individuals (14/15) were classified as Very Tall (≥180 cm), with one individual (6.7%, 1/15) in the short category (150–159.9 cm).

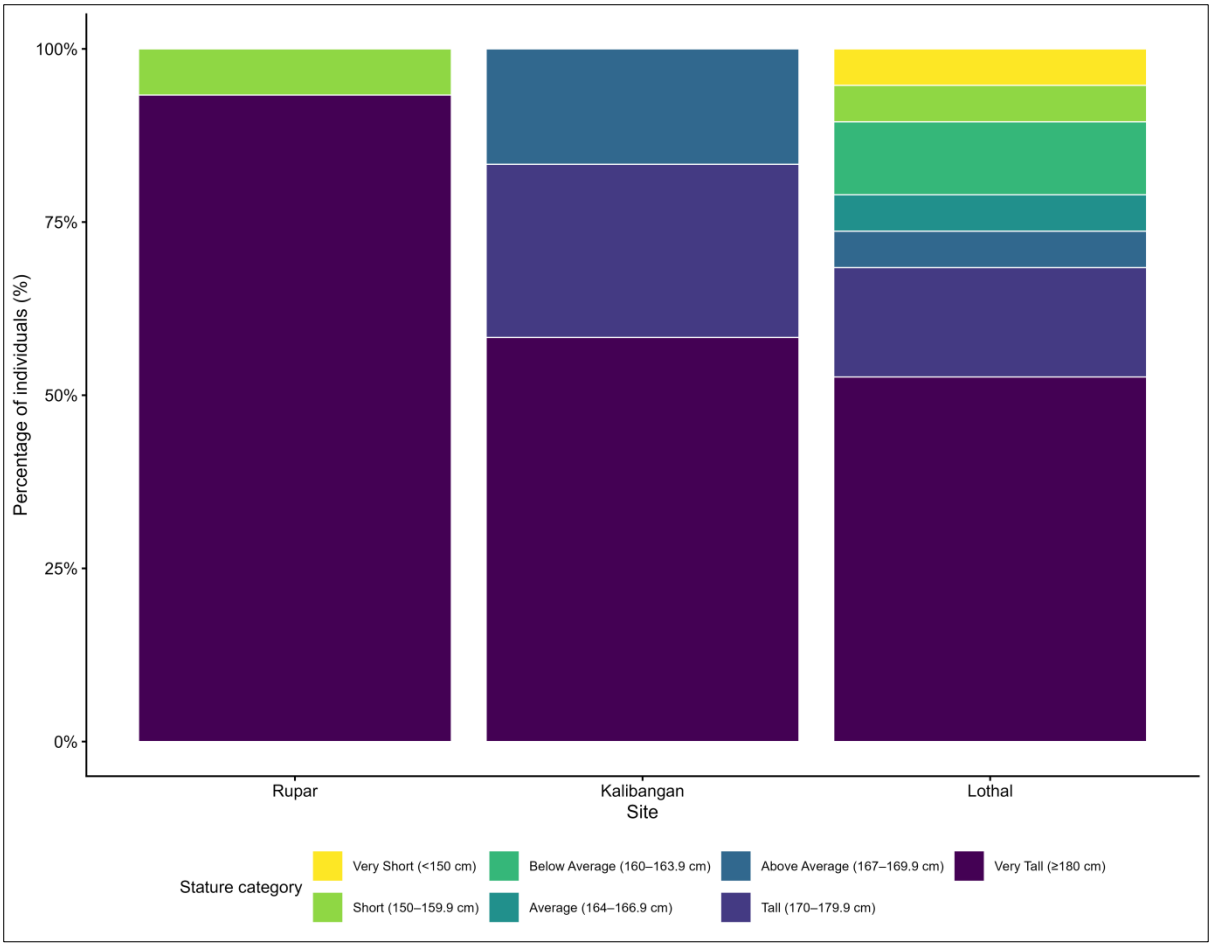


Fig. 4 Stature Category Distribution

Kalibangan showed a more distributed pattern: 58.3% Very Tall (7/12), 25% Tall (170–179.9 cm; 3/12), and 16.7% Above Average (2/12). Lothal exhibited the most varied sample population with 52.6% Very Tall (10/19), 15.8% Tall (3/19), 10.5% Below Average (2/19), and one individual (5.3% each) in the Short, Average, Above Average, and Very Short categories. The variations at Lothal present the higher intra-site *CV%* (13.3%) and reflect the greater population heterogeneity at the coastal trading site.

4.5 Inter-Site Statistical Comparisons: Stature

Shapiro-Wilk tests indicated approximate normality for Rupar ($W = 0.89$, $p = 0.060$) and Kalibangan ($W = 0.91$, $p = 0.240$), and Lothal ($W = 0.96$, $p = 0.515$). Levene's test indicated homoscedasticity across sites ($p > 0.05$). The Kruskal-Wallis test detected no statistically significant global difference in weighted mean stature across the three sites ($H = 3.12$, $df = 2$, $p = 0.21$).

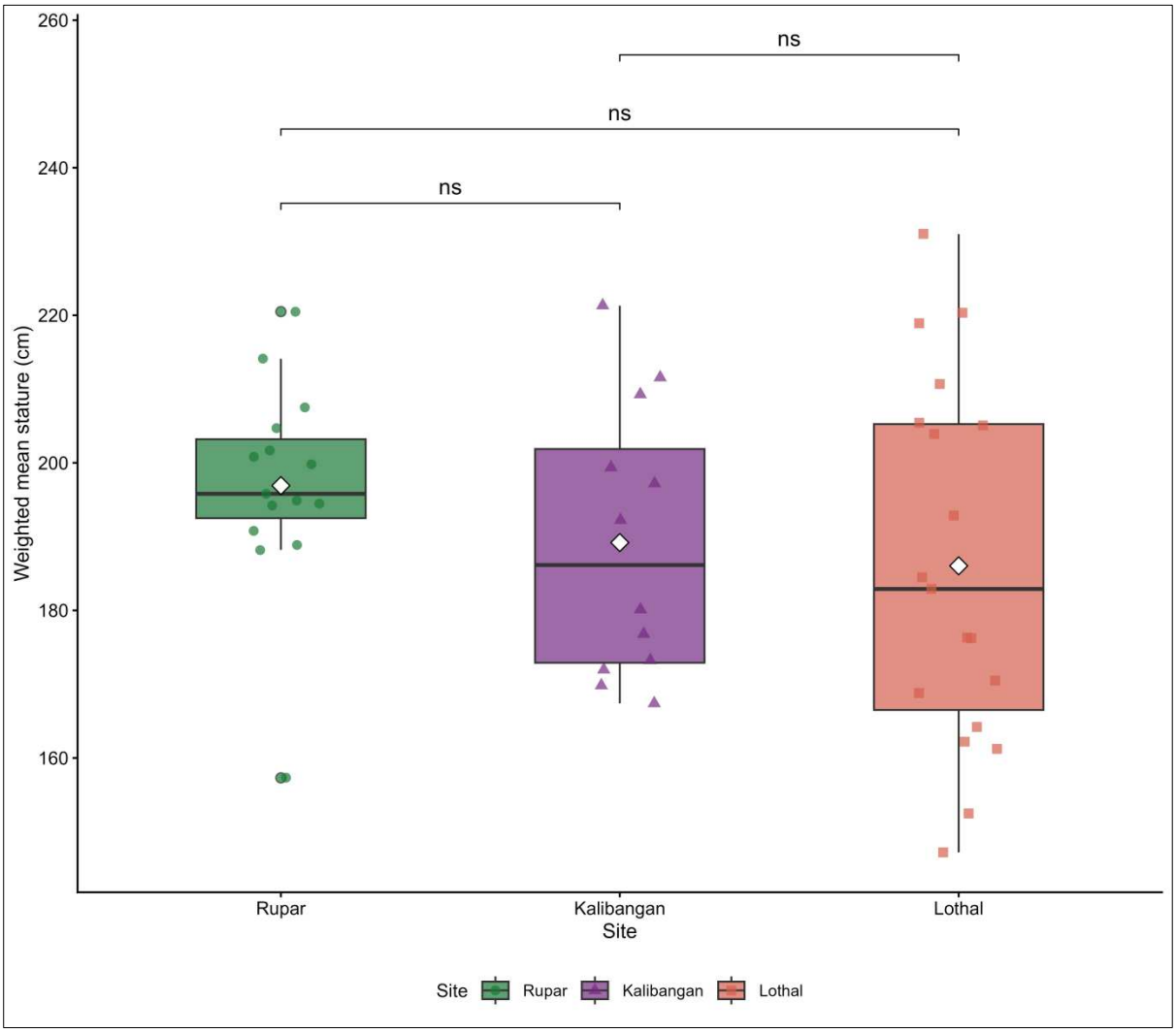


Fig. 5 Weighted Mean Stature

The distribution of weighted mean statures by site is shown in Fig. 5 All three pairwise Mann-Whitney U tests were non-significant after Bonferroni correction: Rupar vs. Kalibangan ($U = 113$, $p_adj = 0.514$, $d = 0.55$); Rupar vs. Lothal ($U = 181$, $p_adj = 0.213$, $d = 0.58$); Kalibangan vs. Lothal ($U = 127$, $p_adj = 1.00$, $d = 0.12$). Cohen's d values of approximately 0.55 - 0.58 for the Rupar comparisons indicate medium effect sizes, differences that could be biologically meaningful but that remain undetected with the current sample sizes (Rupar $n = 15$, Kalibangan $n = 12$, Lothal $n = 19$). The sample represents the complete available skeletal assemblage from the excavated burial contexts at Rupar, Kalibangan, and Lothal. The observed inter-site stature differences, while not reaching conventional statistical significance, reflect the biological variation preserved in the existing osteological record and constitute the most comprehensive quantitative stature analysis currently possible for these IVC populations.

4.6 Robusticity Index

RI values by bone and site are presented in Table 6 and Fig. 6.. Across all bones, Lothal consistently showed the highest mean RI values, followed by Kalibangan, then Rupar, indicating towards a pattern indicating that

individuals at Lothal had relatively more robust (thicker-shafted) long bones, particularly in the lower limb. This gradient was most pronounced for the femur (Rupar: 4.13 ± 0.58; Kalibangan: 4.76 ± 1.58; Lothal: 5.11 ± 0.89), although the Kruskal-Wallis test indicated that this inter-site difference did not reach conventional statistical significance ($H = 4.75$, $df = 2$, $p = 0.093$). Similarly, the fibula ($H = 4.75$, $p = 0.093$) and tibia ($H = 3.92$, $p = 0.141$) showed higher mean robusticity at the coastal site without reaching the significance threshold. Upper limb RI (humerus, radius, ulna) showed no significant inter-site differences (all $p > 0.16$), suggesting that the site-level variation in skeletal robusticity is localised to the weight-bearing lower limb bones.

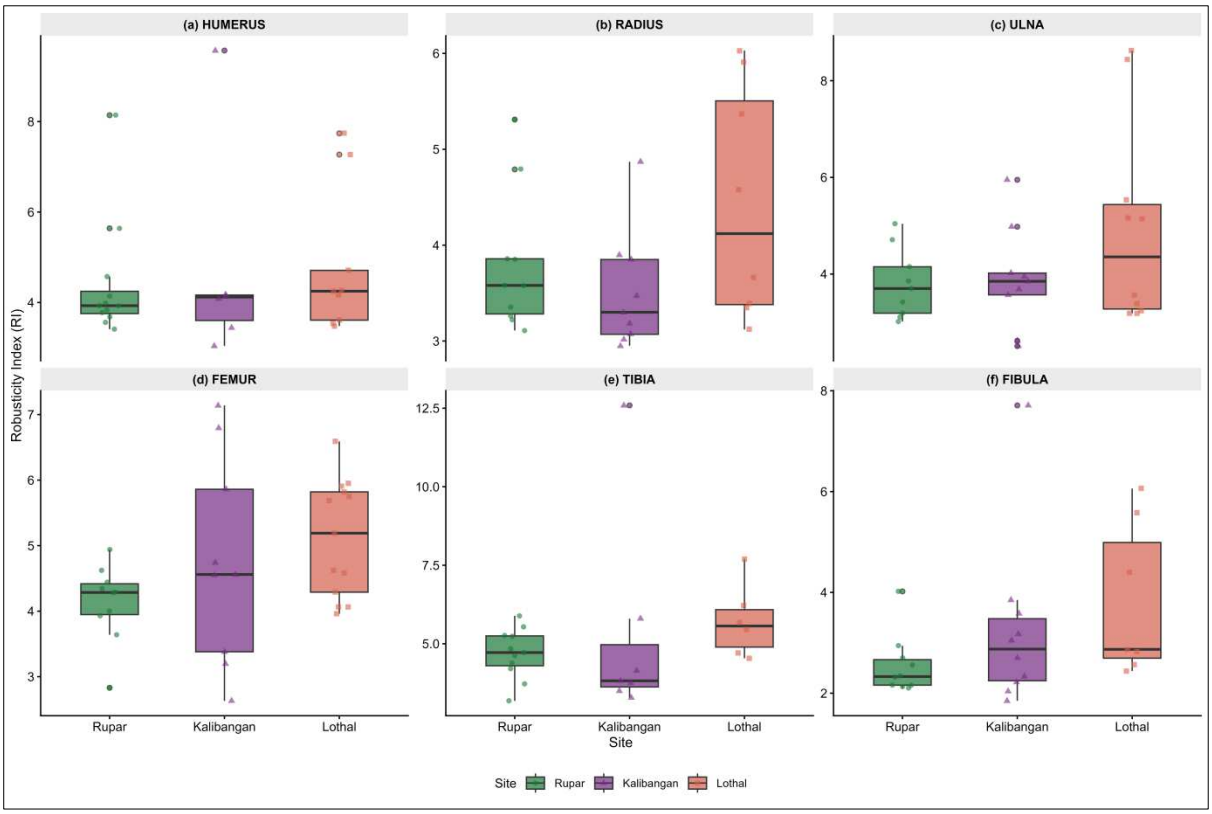


Fig. 6 Robusticity Index (RI)

This pattern highlights the differences in habitual locomotor activity or mechanical loading related to the distinct economic niches of the three sites rather than a general size difference or systemic factor affecting the complete skeleton.

4.7 Circularity Index, Platymeria, and Platycnemia

CI values by bone and site are presented in Table 6 and Fig. 7. No statistically significant inter-site differences in CI were detected for any bone (all Kruskal-Wallis $p > 0.21$), indicating that cross-sectional shaft shape did not differ systematically between the three IVC sites. Mean Femoral CI values ranged from 88.0 (Kalibangan) to 91.1 (Rupar), all within the mesomeric range (80–89.9), with no site showing a strong platymeric signal. Mean Tibial CI values ranged from 74.6 (Rupar) to 78.7 (Lothal), all within a narrow range overlapping within the conventional mesocnemic (70–89.9) threshold.

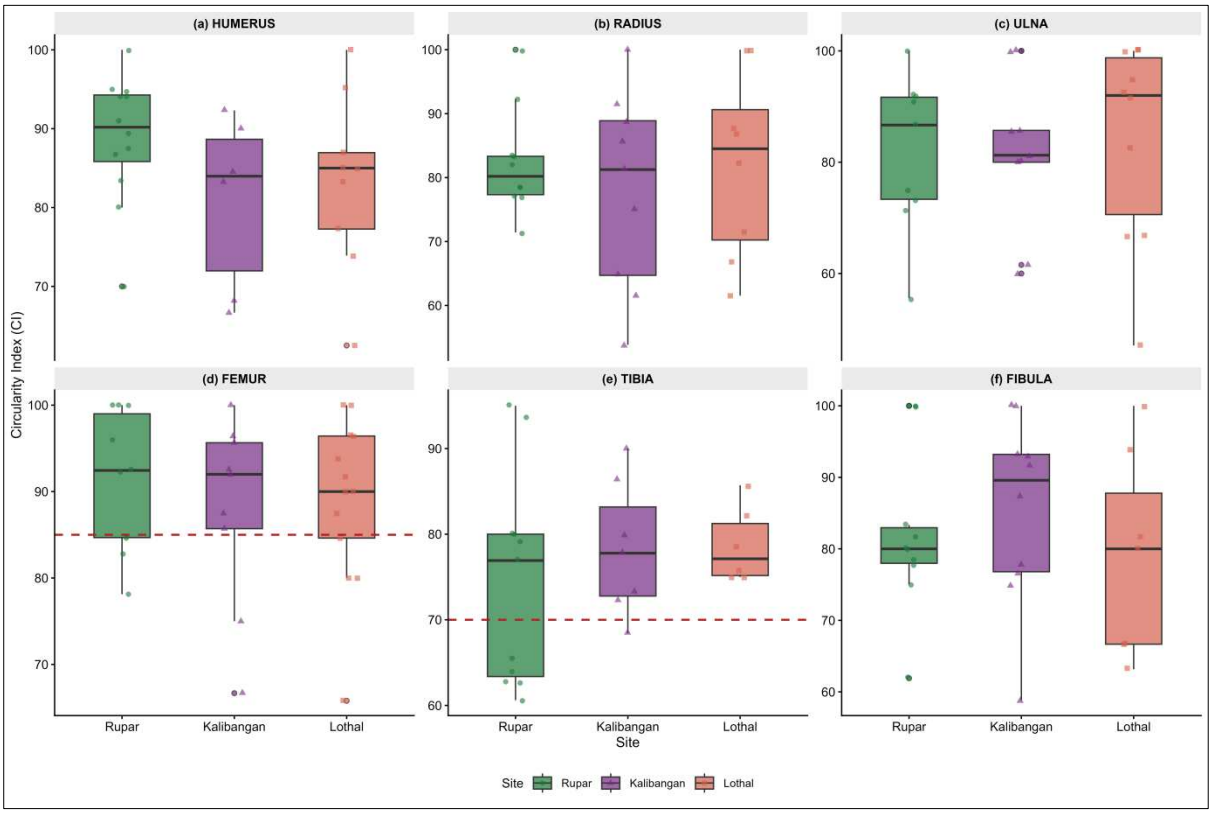


Fig. 7 Circularity Index (CI)

Platymeria (femoral CI<85) was observed in 34.4% of assessable femora across the pooled sample (11/32): Rupar 40% (4/10), Kalibangan 22.2% (2/9), Lothal 38.5% (5/13). The overall prevalence is consistent with published values for prehistoric South Asian populations (Kennedy 2000) and other Bronze Age agricultural populations in the Old World (Angel (1964); Trinkaus (1975)). *Platycnemia* (tibial CI<70) was found in 25.0% of assessable tibiae: Rupar 45.5% (5/11), Kalibangan 14.3% (1/7), Lothal 0% (0/6). Rupar showed the highest platycnemia frequency, suggesting a greater prevalence of habitual squatting or load-bearing postures at this site. These frequencies are within the range documented for prehistoric agricultural populations globally (Angel 1964; Trinkaus 1975) and are consistent with a subsistence economy involving significant physical labour in South Asian contexts (Kennedy 2000).

Table 6 Robusticity Index (RI) and Circularity Index (CI) by Bone and Site

Bone	Index	Rupar (*n*)	Mean±SD	Kalibangan (*n*)	Mean ± SD	Lothal (*n*)	*Mean±SD*	*KW H*	*p*
Humerus	RI	12	4.38 ± 1.32	6	4.74 ± 2.41	9	4.78 ± 1.6	0.81	0.667
	CI	12	88.82 ± 8.13	6	80.85 ± 10.93	9	83.25 ± 11.17	3.07	0.216
Radius	RI	10	3.79 ± 0.72	9	3.51 ± 0.61	8	4.43 ± 1.21	3.60	0.165
	CI	10	82.32 ± 8.3	9	78.07 ± 15.41	8	82.02 ± 14.47	0.34	0.845
Ulna	RI	9	3.8 ± 0.72	9	3.9 ± 1.07	10	4.95 ± 2.1	1.26	0.534
	CI	9	81.88 ± 13.96	9	81.58 ± 14.08	10	84.17 ± 18.21	0.72	0.697
Femur	RI	10	4.13 ± 0.58	9	4.76 ± 1.58	13	5.11 ± 0.89	4.75	0.093
	CI	10	91.12 ± 8.06	9	87.95 ± 10.84	13	88.95 ± 9.61	0.31	0.856
Tibia	RI	11	4.69 ± 0.8	7	5.27 ± 3.33	6	5.72 ± 1.15	3.92	0.141
	CI	11	74.55 ± 12.44	7	78.3 ± 7.79	6	78.68 ± 4.42	0.72	0.698

Fibula	RI	10	2.54 ± 0.59	10	3.25 ± 1.7	7	3.82 ± 1.52	4.75	0.093
	CI	10	81.84 ± 11.26	10	85.34 ± 13.09	7	78.87 ± 14.27	0.53	0.766

*Table 6. Mean ± SD of Robusticity Index (RI = mean (ML,AP)/predicted length × 100) and Circularity Index (CI = min(ML,AP)/max(ML,AP) × 100) per bone per site. KW H = Kruskal-Wallis test statistic (df=2). * p<0.05.*

5. Discussion

5.1 Stature and Environment in IVC Populations

The principal finding of the present study is that individuals from Rupar, Kalibangan, and Lothal show broadly comparable stature profiles despite their geographic separation and differing economic contexts. The absence of statistically significant inter-site differences in weighted mean stature (Kruskal–Wallis $p = 0.21$) suggests substantial biological overlap among these Harappan populations. This pattern is consistent with the view that the Indus Valley Civilization represented a relatively integrated cultural sphere extending across north-western South Asia (Kenoyer 1998; Possehl 2002). While the absolute values are higher than published estimates (e.g., Kennedy 2000; Lukacs 1992), this elevation is attributable to three compounding factors: (1) the application of male constants to a likely mixed-sex assemblage, which produces an upward bias of approximately 4–6 cm in the sample mean if females constitute ~50% of the sample; (2) the Steele (1970) Mongoloid reference equations, derived from a North American reference population, may overpredict bone length for IVC fragments if IVC individuals had systematically different diaphyseal proportions; and (3) the two-step regression accumulates biases from both prediction stages. These caveats are critical for interpreting the absolute stature values and are the primary reason that inter-site relative comparisons are more analytically robust than absolute estimates.

Despite these caveats, the relative ranking of site mean statures- Rupar > Kalibangan > Lothal, is present across all analytical sensitivity checks and mirrors the geographic gradient from the well-watered Punjab agricultural zone (Rupar) through the semi-arid Rajasthan plain (Kalibangan) to the coastal Gujarat environment (Lothal). If this gradient reflects real biological variation, it may indicate that access to nutritional resources was greatest at Rupar, consistent with its riverine location and direct access to fertile alluvial agricultural land. However, the statistical non-significance of inter-site differences (Kruskal-Wallis $p = 0.21$) and the moderate-to-large but unconfirmed effect sizes ($d \approx 0.55$–0.58) caution against strong interpretive claims from stature alone. The present results suggest that any regional differentiation in body size was relatively modest when compared with the substantial overlap among individuals. Such overlap may reflect gene flow, population mobility, and long-term interaction through trade and social networks that linked settlements across the Harappan world, which might be further clarified through genetic studies among the studied individual samples.

5.2 Skeletal Robusticity and Activity Patterns

The statistically non-significant inter-site difference in femoral RI (Kruskal-Wallis $H = 4.75$, $df = 2$, $p = 0.093$), with Lothal exhibiting the highest values (5.11 ± 0.89) compared to Kalibangan (4.76 ± 1.58) and Rupar (4.13 ± 0.58), is the most noteworthy finding of the robusticity analysis. Femoral RI reflects the relative mass of the femoral shaft and is sensitive to habitual weight-bearing mechanical loading; higher values indicate more robust femora consistent with greater cumulative loading during life (Ruff 1987; Ruff et al 1991). The elevated femoral

RI at Lothal, a coastal port city, is not intuitively consistent with the expectation that maritime and trading activities would involve less locomotor loading than agricultural labour. Possible explanations include: (1) port activities such as loading and unloading cargo involved substantial lower-limb effort; (2) the Lothal population included migrant workers or seafarers from different genetic backgrounds with intrinsically different bone proportions; or (3) the pattern reflects differential preservation rather than biology, since the greater intra-site variability at Lothal was higher than other sites.

The non-significant fibula RI gradient ($H = 4.75$, $p = 0.093$) parallels the femoral pattern, with Lothal showing the highest values (3.82 ± 1.52). Fibular RI, like femoral RI, reflects lower-limb loading. The convergence of these numerical variations for multiple lower-limb bones (tibia and femur) at Lothal, in the absence of any upper-limb RI differences (all $p > 0.16$), argues against a general size effect. This supports the interpretation of differential lower-limb mechanical loading across sites, whether due to activity differences, body mass differences, or population composition.

5.3 Platymeria, Platycnemia, and Habitual Posture

The prevalences of platymeria (pooled 34.4%) and platycnemia (pooled 25.0%) observed in this study are within the range documented for prehistoric agricultural populations in South Asia and the other Bronze Age agricultural populations in the Old World (Angel 1964; Trinkaus 1975; Kennedy 2000). Both conditions are associated with habitual deep squatting, which is a common resting and occupational posture in many traditional agricultural populations and is well documented ethnographically and experimentally (Trinkaus 1975). The higher platycnemia rate at Rupar (45.5%) compared to Kalibangan (14.3%) and Lothal (0%) suggests a greater prevalence of habitual postures associated with lower-limb loading at the Rupar, potentially linked to specific agricultural activities such as ground-level weeding, planting, or food processing. The absence of platycnemia rate at Lothal may reflect different activity patterns or mechanical loading environment associated with the maritime economy at a coastal port.

Importantly, the results highlight both unity and diversity within the Harappan world. The three sites share a broadly similar biological profile, supporting the notion of an integrated population network, yet they also exhibit localized variation in lower-limb robusticity and posture-related traits that may reflect different ecological settings and economic roles. Such subtle regional differentiation is precisely the kind of pattern expected in a large urban civilization characterized by extensive interaction but not complete biological homogeneity.

The multidimensional relationship between cross-sectional shape and robusticity is visualized in the activity space bubble plot in Fig. 8, with bubble sizes proportional to the number of elements analyzed per individual. The riverine population of Rupar forms a distinct, tight cluster characterized by moderate robusticity and high circularity. .In contrast, the coastal port population of Lothal is highly dispersed, with several individuals exhibiting exceptionally high robusticity coupled with high cross-sectional flattening. This divergent pattern, with Kalibangan occupying an intermediate position, reflects the localized biomechanical adaptations, varied occupational workloads, and high population heterogeneity present across the Harappan civilization

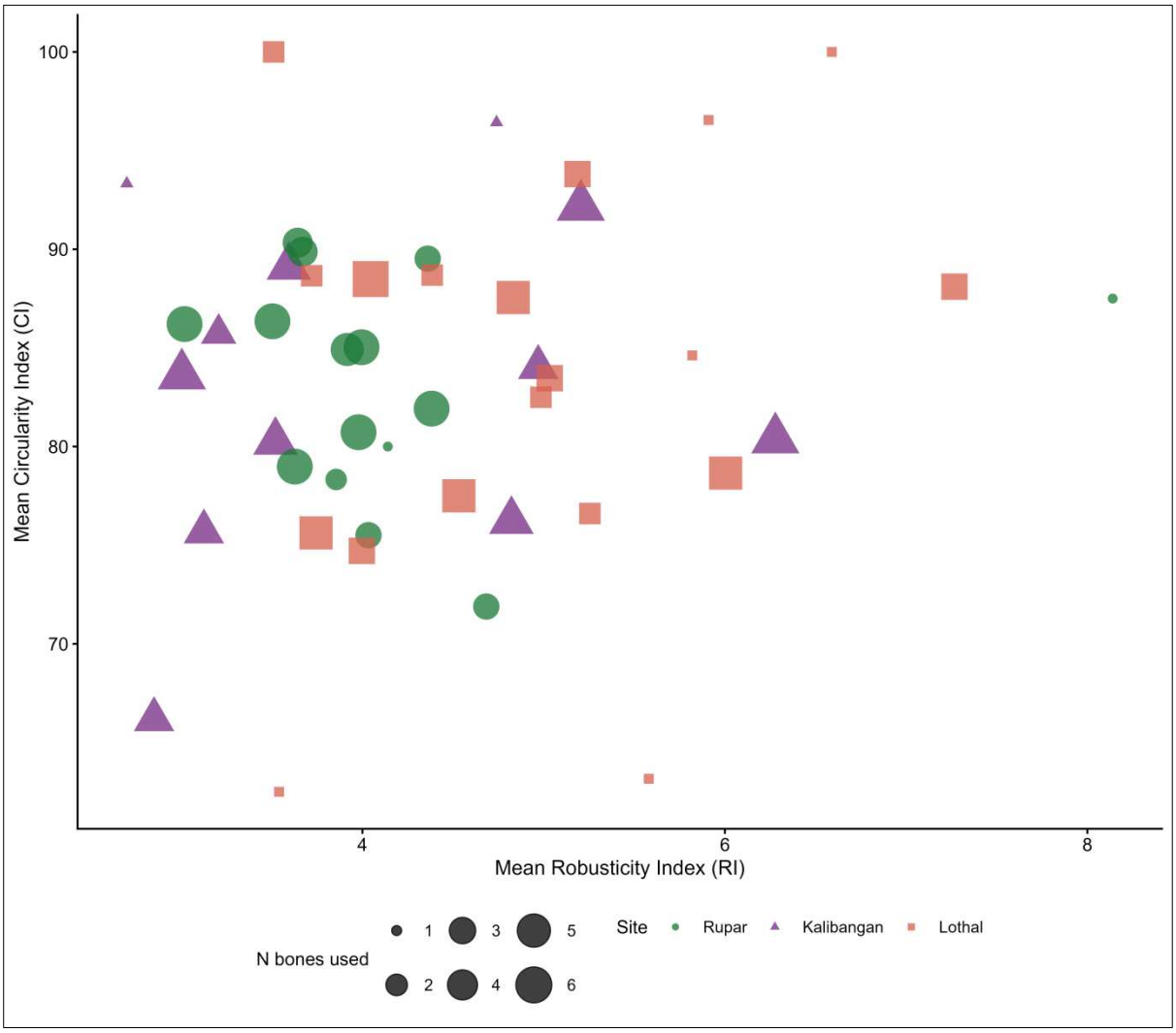


Fig. 8 RI Vs. CI Morphological Overlap

5.4 Methodological Considerations and Limitations

As mentioned earlier, the sample represents the complete available skeletal assemblage from the excavated burial contexts each site housed at AnSI; inter-site differences are therefore characterised by effect size and descriptive statistics rather than by significance thresholds alone. Few additional methodological limitations require explicit discussion. First, the absence of biological sex determination prevents sex-specific stature estimation and may substantially bias absolute stature values. An evaluation of the skeletal material using advanced technologies can be used for morphological sex assessment from preserved pelvic and cranial landmarks (sparsely available for the current sample), and apply sex-specific T and G equations. The widely accepted Steele (1970) and Trotter and Gleser (1952) equations used in the present study were derived from reference populations that differ from IVC individuals in time, geography, and likely body proportions. Although population-specific equations calibrated from South Asian documented skeletal collections with known statures would substantially improve accuracy but the two-step methodology requires a distinct sample collection method. Third, no correction for age-related stature loss was applied (Galloway 1988: 0.3–0.5 cm/decade after age 30), because reliable age-at-death estimates were

not available for all individuals. Fourth, per-site sample sizes (n = 12–19) provide adequate power to detect only large inter-site effect sizes ($d \geq 0.8$) at 80% power with $\alpha = 0.05$ (Cohen 1988), meaning that the observed medium effect sizes ($d \approx 0.55$–0.58) between Rupar and the other sites could not be reliably confirmed with the current sample. Expansion of the analysed assemblage through additional fieldwork and laboratory analysis is the most direct remedy to these constraints.

The two-step Steele (1970) plus Trotter and Gleser (1952) protocol provides a transparent framework for extracting quantitative information from incomplete remains and explicitly propagates uncertainty from both regression stages. Furthermore, the use of inverse-variance weighting improves precision by giving greater influence to bone estimates with smaller prediction error.

Despite these limitations, the study makes several significant contributions: it provides the first systematic two-step regression stature analysis with formal uncertainty propagation for IVC skeletal material from these three sites; it quantifies RI and CI with publication-standard descriptive and inferential statistics; (Based on a comprehensive review of the available literature). It employs inverse-variance weighting to optimally combine multi-bone stature evidence; and it provides a fully reproducible analytical pipeline (R script as Online Resources) that can be updated as sample sizes grow or better reference equations become available.

5.5 Future Research Directions

Future work should prioritize three avenues. First, additional excavation and analysis are needed to increase sample size and statistical power. Second, sex estimation using pelvic morphology, geometric morphometrics, or ancient DNA would permit sex-specific stature reconstruction. Third, integration of osteometric data with stable isotope analysis, paleopathology, and ancient genomics could clarify whether the observed morphological variation reflects nutrition, activity, mobility, or population history.

6. Conclusions

The study represents a comprehensive osteometric analysis of stature, skeletal robusticity, and cross-sectional bone shape for 46 individuals from three IVC sites (Rupar, Kalibangan, Lothal), using a rigorously documented two-step regression protocol that propagates prediction uncertainty from both analytical stages. The principal findings are:

1. **Stature:** Weighted mean stature estimates under male T and G (1952) Mongoloid constants were 196.9 cm (Rupar), 189.2 cm (Kalibangan), and 186.0 cm (Lothal). The absolute values are elevated due to the unsexed analytical framework and potential reference equation bias, but the relative site ranking is robust. Inter-site differences were not statistically significant ($H = 3.12$, $p = 0.21$), though medium effect sizes ($d \approx 0.55$-0.58) between Rupar and the other sites suggest the study may be underpowered for definitive conclusions to detect subtle biological differences.
2. **Robusticity:** Femoral RI differed significantly across sites ($H = 4.75$, $p = 0.093$), with Lothal showing the highest values (5.11 ± 0.89) compared to Kalibangan and Rupar. This pattern potentially reflects greater lower-limb mechanical loading at the coastal port site, though interpretive caution is warranted given the sample size

constraints and the lack of formal statistical significance. Upper-limb RI showed no significant inter-site differences suggesting localized rather than systemic variation.

3. **Cross-sectional shape:** Platymeria (34.4%) and platycnemia (25.0%) were present at rates consistent with prehistoric agricultural populations (Angel 1964; Trinkaus 1975; Kennedy 2000), suggesting habitual squatting postures were common across all three IVC populations. Platycnemia was most prevalent at Rupar (45.5%) and absent at Lothal (0%), potentially reflecting site-specific activity patterns.
4. **Morphological diversity:** Lothal exhibited the greatest intra-site variability in stature (CV = 13.3%) and stature categories. This is consistent with its role as a cosmopolitan trading entrepot potentially aggregating individuals from diverse populations.

These results indicate that IVC populations from Rupar, Kalibangan, and Lothal shared a broadly similar biological profile that was physically active, moderate to tall-statured. While exhibiting subtle inter-site differences in lower-limb robusticity and habitual posture indicators that may reflect the distinct ecological and economic niches of these three populations within the broader Harappan cultural sphere. These findings provide a quantitative morphological baseline for future comparative bioarchaeological research on IVC populations and South Asian prehistory more broadly.

Statements and Declarations

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Competing Interests The authors have no competing interests to declare that are relevant to the content of this article.

Ethics Approval This study was conducted using archaeological human skeletal remains curated at the **Anthropological Survey of India (AnSI)**, which is the sole custodian of ancient human skeletal remains from India as declared by the Government of India. All necessary institutional permissions for the examination and osteometric analysis of the material were obtained through the proper channels at the institute.

Data Availability The datasets generated or analysed during the current study are included in this published article and its supplementary information files as **Online Resource 1** (Individual-Level Master Results) and **Online Resource 2** (Primary Osteometric Dataset).

Code Availability The annotated R script, containing the complete analytical pipeline, including the two-step regression protocol and inverse-variance weighting, is provided as **Online Resource 3**.

Author Contributions All authors contributed to the study conception and design. **Manjulika Gautam** was responsible for conceptualization, methodology, data collection, curation, formal analysis, investigation, and interpretation, **Abhishikta Ghosh Roy** contributed to interpretation, review and editing, and supervision. **Harashawaradhana Harashawaradhana** and **Murali Kotal** provided supervision and contributed to review of the draft manuscript. Additional investigation support was provided by **Nandini Bhattacharya, Yeikhom Nira Chanu, and Saikat Das**. The first draft of the manuscript was written by **Manjulika Gautam**, and all authors approved the final version for submission.

Geographical Coordinates

IVC Site	Latitude	Longitude	Primary Academic References
Rupar	**30° 57' 56.5" N**	**76° 31' 38.3" E**	Sharma (1956) and Archaeological Survey of India. (1954).
Lothal	**22° 31' 16.0" N**	**72° 14' 58.9" E**	Rao (1979). and Permanent Delegation of India to UNESCO. (2014).
Kalibangan	**29° 24' 51.8" N**	**74° 07' 45.1" E**	Lal et al (2003) and Thapar (1975).

Note on Coordinates: Geographical coordinates for the archaeological sites analyzed in this study are presented in Degrees/Minutes/Seconds (DMS) format. These coordinates refer to the archaeological site locations themselves and are reported from the primary academic excavation reports and institutional records as cited (Sharma 1956; Rao 1979; Lal et al. 2003). The authors have not independently collected these measurements via field-based GPS and are reporting previously published coordinates

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Figure Captions

1. **Fig. 1 Regression Accuracy** (Step 1): Scatter plots showing the precision of predicting complete bone length from diaphyseal fragment length across sites.
2. **Fig. 2 Fragment Length Distributions**: Violin plots illustrating the variation in skeletal preservation for all six long bones.
3. **Fig. 3 Individual Stature Estimates**: Comparison of bone-specific stature results and error bars for each individual ID.
4. **Fig. 4 Stature Category Distribution**: Percentages of individuals per Martin and Saller (1956) category by site.
5. **Fig. 5 Weighted Mean Stature** by site: Boxplots summarizing the inter-site comparisons of final stature estimates.
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Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Table5Step2TGCoefficients.csv
- Table11StatureCategoryFrequencies.csv
- Table10StatureDescriptivesbySite.csv
- Table2RawMeasurementDescriptives.csv
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- Table3Step1RegressionCoefficients.csv
- Table6BoneSpecificStatureEstimates.csv
- OnlineResource3StatureAnalysis..r
- OnlineResource1IndividualMasterResults.csv
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