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Anthropometric Determination of Gestational Age in Cadaveric Fetuses From the Konkan Region, Maharashtra

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Abstract

Background: Estimation of gestational age (GA) is important in fetal anatomy, pathology, and forensic medicine, particularly when reliable obstetric records or imaging are unavailable. Although limb measurements are commonly used to assess fetal growth, craniofacial measurements have received relatively less attention in studies involving Indian cadaveric fetuses. The present study examined craniofacial and limb anthropometric parameters and their relationship with GA in cadaveric fetuses from the Konkan region of Maharashtra, India.

Methods: This cross-sectional observational study included 100 human cadaveric fetuses with documented GAs ranging from 12.4 to 42.0 weeks. Facial height (FH), bizygomatic width (BZW), foot length (FL), and femur diaphyseal length (FDL) were measured using a manual Vernier caliper. Each parameter was measured three times by the same observer, and the mean value was considered for analysis. Pearson's correlation, simple and multiple linear regression, and one-way analysis of variance (ANOVA) were performed using IBM SPSS Statistics for Windows, Version 26.0 (Released 2019; IBM Corp., Armonk, New York).

Results: The mean GA of the study specimens was 31.16 ± 7.68 weeks. All four anthropometric parameters showed significant positive correlations with GA ($p < 0.001$). FL had the highest numerical correlation ($r = 0.930$), followed closely by FDL ($r = 0.924$), FH ($r = 0.877$), and BZW ($r = 0.862$). The FL-only regression model had an R^2 of 0.864 and a root mean square error (RMSE) of 2.82 weeks. The addition of FH resulted in a modest improvement in model fit, with an R^2 of 0.872, an adjusted R^2 of 0.869, and an RMSE of 2.69 weeks. Anthropometric measurements also differed significantly across the GA groups ($p < 0.001$).

Conclusion: FL showed the highest numerical correlation with GA among the parameters examined, although its association was comparable to that of FDL. Adding FH to the FL model produced a modest improvement in the regression model. The findings provide preliminary data on the relationship between fetal anthropometric measurements and GA in a single-center cohort from the Konkan region. The proposed equations require further evaluation through independent validation in larger, multicenter studies before their use in clinical or forensic practice can be considered.

Categories: Obstetrics/Gynecology, Forensic Medicine, Anatomy
Keywords: bizygomatic width, craniofacial measurements, facial height, femur length, fetal anthropometry, foot length, forensic anatomy, gestational age estimation, regression model

Introduction

Accurate estimation of gestational age (GA) is important in obstetrics, fetal anatomy, and forensic medicine. Knowledge of GA helps in assessing preterm birth, identifying small-for-gestational-age (SGA) fetuses, and understanding abnormalities of fetal growth and development. In clinical practice, ultrasonography (USG) is widely used for GA assessment through measurements such as crown-rump length, biparietal diameter, and femur diaphyseal length (FDL). However, these imaging methods may not be available in postmortem examinations or situations where reliable obstetric records are lacking. In such circumstances, direct anthropometric measurements may provide useful supplementary information. Ravisankar et al. reported that foot length (FL) could serve as an alternative parameter for estimating GA when USG is not feasible [1]. This highlights the potential value of simple anatomical measurements in fetal age assessment.

Several studies have examined the relationship between fetal anthropometric measurements and GA, particularly those involving the limbs. Alkhafaje et al. studied 144 aborted fetuses between 12 and 40 weeks of gestation and reported positive correlations between GA and the measured fetal parameters, with FDL showing the highest correlation ($r \approx 0.991$) [2]. Similarly, a Turkish study involving 83 cadaveric fetuses between 13 and 40 weeks reported progressive increases in foot measurements, including FL, with advancing gestation. These measurements accounted for 72-90% of the variation in GA [3]. An Indian

postmortem study involving 60 fetuses also reported a strong correlation between FL and GA, with FL showing a higher correlation than crown-rump length and crown-heel length ($r \approx 0.922$) [4]. Together, these findings suggest that limb measurements, particularly FL and FDL, are useful parameters for studying fetal growth in relation to GA.

Although several studies have examined fetal anthropometry, the findings may vary across study populations because fetal growth is influenced by genetic, nutritional, maternal, and environmental factors. Population-specific data may therefore provide additional information when interpreting fetal measurements. The Konkan region of Maharashtra has its own demographic and geographical characteristics; however, region-specific information on fetal anthropometric measurements obtained from cadaveric specimens remains limited.

Craniofacial measurements have also been investigated as potential indicators of fetal growth, although they have received comparatively less attention than limb measurements. Facial height (FH) and bizygomatic width (BZW) increase with advancing gestation and may provide additional information about fetal development. In a three-dimensional ultrasonographic study involving 207 normal pregnancies between 16 and 36 weeks, FH increased from approximately 1.5 cm at 16 weeks to 5.1 cm near term, with a strong relationship with GA ($R^2 = 0.93$). BZW also showed an increase from approximately 2.2 to 6.4 cm, with an R^2 of 0.85 [5]. Previous anatomical and forensic studies have likewise examined facial and cranial measurements for estimating fetal age [6,7]. These findings suggest that craniofacial dimensions may complement conventional limb measurements when assessing fetal growth.

Most available studies have examined either limb or craniofacial parameters, while relatively few have evaluated both groups of measurements together in cadaveric fetal specimens. Direct measurements on cadavers allow several anatomical dimensions to be assessed on the same specimen without relying on ultrasound image acquisition. However, such measurements have their own limitations. Preservation-related tissue changes, dehydration, specimen positioning, and differences in the identification of anatomical landmarks may influence measurement accuracy. Thus, cadaveric anthropometry and ultrasonographic biometry should be considered complementary approaches, each with specific methodological advantages and limitations.

Differences in fetal growth patterns across populations have also been discussed in the literature. Studies have reported variations in parameters such as FDL and abdominal circumference between South Asian and other populations [8]. International reference standards, including INTERGROWTH-21st, provide important information on fetal growth; however, their applicability to individual regional populations should be considered in the context of differences in study populations and methodology. Indian studies have contributed to this area, but further regional data are needed to understand variations in fetal anthropometric characteristics.

In the Konkan region of Maharashtra, information on the anthropometry of cadaveric fetuses remains limited. Although previous studies have examined fetal growth using ultrasonographic and other anthropometric approaches [9], data based on direct measurements of preserved fetal specimens are relatively scarce. Such information may be useful in anatomical and forensic settings, particularly when conventional imaging or reliable obstetric records are unavailable [10]. However, the applicability of measurements derived from one regional cohort to other populations requires further evaluation.

Aim and objectives

The present study aimed to examine the relationship between craniofacial and limb anthropometric measurements and GA in cadaveric fetuses received at a tertiary care referral center in the Konkan region of Maharashtra. The study included fetuses with documented GAs ranging from 12.4 to 42.0 weeks. FH, BZW, FL, and FDL were measured to assess their individual associations with GA. Simple and multiple linear regression analyses were performed to develop preliminary regression models for GA estimation within the study cohort. The findings and derived equations were also compared with those reported in previously published fetal anthropometric studies.

Materials And Methods

Study design and population

This cross-sectional observational study was conducted in the Department of Anatomy, B.K.L. Walawalkar Rural Medical College, Sawarde, Maharashtra, a tertiary care referral center serving the Konkan region. The institution maintains a fetal specimen repository containing specimens received through institutional body donation and obstetric referral protocols. The hospital receives fetal specimens from several districts of the Konkan region, including Ratnagiri, Sindhudurg, and Raigad, as well as surrounding referral areas. Accordingly, the study cohort comprised specimens received through the institution's regional referral network rather than representing a single local population.

A total of 100 human cadaveric fetuses with documented GAs ranging from 12.4 to 42.0 weeks were included.

The study population consisted of 57 male fetuses, 40 female fetuses, and three fetuses with ambiguous sex. All eligible specimens were included in the overall analysis, as the primary objective was to examine the relationship between anthropometric measurements and GA in the entire cohort rather than to develop sex-specific models.

The specimens were selected from the Department of Anatomy fetal repository, which has been maintained since the establishment of the institution. The repository contains preserved fetal specimens received over several years through institutional protocols and routine academic preservation practices. All specimens meeting the predefined inclusion and exclusion criteria and having documented GA were considered for the study. Anthropometric measurements and data collection were carried out over a period of two months. The final sample comprised 100 eligible specimens. The study was exploratory in nature and aimed to develop regression models within the available cohort rather than validate their predictive performance in an independent population.

The exact duration of preservation and the interval between fetal death and anthropometric measurement were not uniformly documented in the repository records. Similarly, detailed clinical information regarding the circumstances of specimen collection, including spontaneous abortion, medical termination, stillbirth, or intrauterine fetal death, and the underlying causes, was not consistently available. Consequently, the specimens could not be classified according to these clinical circumstances.

Ethical considerations

The study was approved by the Institutional Ethics Committee of B.K.L. Walawalkar Rural Medical College and Hospital, Sawarde, Maharashtra (Approval No. IEC/08/2025). A waiver of informed consent was granted by the committee, as the study involved anonymized fetal cadaveric specimens obtained from institutional records and did not involve personally identifiable information. All procedures were carried out in accordance with institutional ethical guidelines and applicable national regulations governing research involving human cadaveric specimens.

Inclusion and exclusion criteria

Cadaveric fetuses with documented GA based on institutional obstetric records, including maternal last menstrual period (LMP) and USG findings, were considered for inclusion. Only specimens with sufficiently preserved and intact craniofacial and limb structures suitable for anthropometric assessment were included.

Specimens with congenital malformations, skeletal dysplasias, trauma involving the measurement sites, postmortem decomposition, or distortion of the anatomical landmarks required for measurement were excluded. Fetuses with missing or unreliable GA records were also excluded.

Data collection and measurement protocol

Anthropometric measurements were obtained manually using a Vernier caliper with a reported least count of 0.02 mm. The same instrument was used throughout the study to maintain consistency. Each parameter was measured three times by the same observer, and the mean of the three readings was used for analysis. Formal intraobserver reliability statistics were not calculated. The measurements were initially recorded on a structured data collection sheet and subsequently entered into Microsoft Excel (Microsoft Corporation, Redmond, Washington). The dataset was checked for completeness and consistency before statistical analysis.

FH was measured as the linear distance between the nasion (n), located at the junction of the frontonasal and internasal sutures, and the gnathion (gn), the most anteroinferior point on the chin (Figure *1A*). BZW was measured as the maximum transverse distance between the most prominent points of the right and left zygomatic arches (Figure *1B*). FDL was measured as the distance between the proximal and distal palpable ends of the ossified femoral diaphysis (Figure *1C*). FL was measured on the plantar aspect of the foot, from the skin overlying the calcaneal tuberosity to the distal tip of the longest toe (Figure *1D*). The longest toe was identified for each specimen rather than assuming that it was invariably the first or second toe. Identification of these endpoints was more difficult in early gestation, when the ossified diaphysis was relatively short and less readily distinguishable by palpation. This could have introduced some uncertainty in landmark identification, particularly in younger specimens. The FDL/FL ratio was calculated for each fetus using the mean values of the respective measurements.



FIGURE 1: Visual demonstration of key anthropometric parameters used for analysis

Representative photographs showing the standardized measurements of (A) facial height (FH), (B) bizygomatic width (BZW), (C) femur diaphyseal length (FDL), and (D) foot length (FL) in cadaveric fetuses. Measurements were obtained using a manual Vernier caliper following a standardized protocol.

GA was obtained from the institutional obstetric records accompanying each fetal specimen. When a USG report was available, the GA documented in that report was used as the reference value. In cases where an ultrasound report was unavailable, the GA recorded on the basis of maternal LMP was used. Since the specimens had accumulated in the departmental repository over several years, the timing of USG and the biometric parameters used for obstetric dating were not uniform across all cases. The analysis was therefore based on the GA information available in the institutional records.

Crown-heel length, crown-rump length, head circumference, and abdominal circumference were also recorded as supplementary descriptors of fetal size and growth. These measurements were used to describe the available specimens and provide additional anatomical information. They were not considered independent reference standards for GA or included as predictors in the final regression models.

Statistical analysis

Data were entered into Microsoft Excel (Microsoft Corporation, Redmond, Washington) and analyzed using IBM SPSS Statistics for Windows, Version 26.0 (Released 2019; IBM Corp., Armonk, New York). Continuous variables were summarized using descriptive statistics and expressed as mean ± standard deviation (SD). Median values were also calculated where appropriate.

Pearson's correlation coefficient was used to examine the strength and direction of the relationship between GA and each anthropometric parameter. Normality of the data distribution was assessed before performing the correlation analysis.

Simple linear regression was performed to examine the relationship between individual anthropometric measurements and GA. Multiple linear regression was subsequently used to assess the combined contribution of the anthropometric parameters. FH, BZW, FL, FDL, and the FDL/FL ratio were initially entered into a full multivariable model to examine their conditional associations with GA.

A reduced model incorporating FL and FH was also examined because it provided comparable in-sample performance with fewer predictors. No automated variable selection procedure or penalized regression method was used. Similarly, bootstrap resampling, cross-validation, and independent external validation were not performed. The regression models were therefore considered exploratory models developed within the available study cohort.

Linearity was examined by visual inspection of scatterplots and residual-versus-fitted plots. Model performance was assessed using the coefficient of determination (R^2), adjusted R^2, and root mean square error (RMSE). These values represent the performance of the models in the same cohort used for their development and should not be interpreted as independently validated estimates of predictive accuracy.

Multicollinearity among the predictors in the full multiple regression model was assessed using variance inflation factors (VIFs) and tolerance values. Regression coefficients, standard errors, standardized coefficients, and 95% confidence intervals were used to describe the associations between individual predictors and GA, where available from the statistical analysis.

Differences in anthropometric measurements across GA groups were examined using one-way analysis of variance (ANOVA). The corresponding F statistics and p-values were reported. Post hoc pairwise comparisons were not performed; therefore, the ANOVA results were interpreted as indicating overall differences among the groups rather than differences between specific pairs of groups.

Scatterplots, regression plots, and bar graphs with error bars were prepared to illustrate the relationships and distribution of the anthropometric measurements. A p-value of less than 0.05 was considered statistically significant.

Results

Sample characteristics

A total of 100 cadaveric fetal specimens, with GAs ranging from 12.4 to 42.0 weeks, were included in the analysis. The mean GA was 31.16 ± 7.68 weeks. The mean values of FH, BZW, FL, and FDL were 3.50 ± 0.87 cm, 4.63 ± 1.52 cm, 5.10 ± 1.59 cm, and 6.60 ± 1.93 cm, respectively. The mean FDL/FL ratio was 1.31 ± 0.10. The descriptive characteristics of the study population and anthropometric measurements are presented in Table *1*.

Variable	Mean ± SD
GA (weeks)	31.16 ± 7.68
FH (cm)	3.50 ± 0.87
BZW (cm)	4.63 ± 1.52
FL (cm)	5.10 ± 1.59
FDL (cm)	6.60 ± 1.93
FDL/FL ratio	1.31 ± 0.10

TABLE 1: Descriptive statistics

GA: gestational age; FH: facial height; BZW: bizygomatic width; FL: foot length; FDL: femur diaphyseal length.

Correlation analysis

Pearson's correlation analysis showed significant positive correlations between GA and all four anthropometric measurements. FL had the highest numerical correlation with GA ($r = 0.930$, $p < 0.001$), followed closely by FDL ($r = 0.924$, $p < 0.001$). FH and BZW also demonstrated strong positive correlations, with coefficients of 0.877 and 0.862, respectively (both $p < 0.001$). In contrast, the FDL/FL ratio showed a moderate negative correlation with GA ($r = -0.479$, $p < 0.001$). The correlation coefficients for all parameters are presented in Table *2* and illustrated in Figure *2*.

Variable	Pearson's r	p-value
FH	0.877	<0.001
BZW	0.862	<0.001
FL	0.930	<0.001
FDL	0.924	<0.001
FDL/FL ratio	−0.479	<0.001

TABLE 2: Correlation coefficients

FH: facial height; BZW: bizygomatic width; FL: foot length; FDL: femur diaphyseal length.

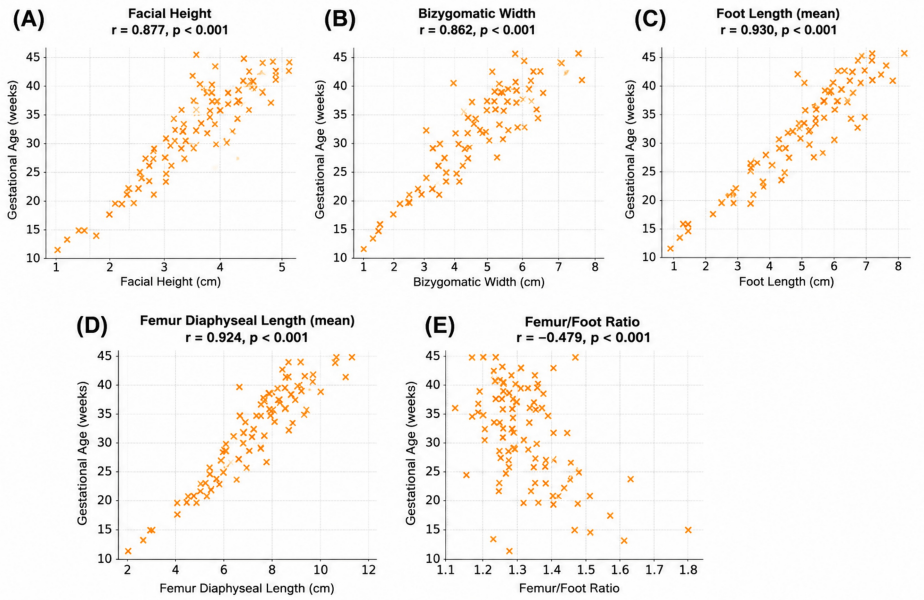


FIGURE 2: Correlation analysis between gestational age (GA, weeks) and fetal anthropometric parameters

Scatterplots show the relationships between GA and (A) FH, (B) BZW, (C) FL, (D) FDL, and (E) FDL/FL ratio. Each cross represents an individual fetal observation. Pearson correlation analysis was used to assess the association between GA and each anthropometric parameter. The Pearson correlation coefficients were r = 0.877 for FH, r = 0.862 for BZW, r = 0.930 for FL, r = 0.924 for FDL, and r = −0.479 for the FDL/FL ratio; all correlations were statistically significant ($p < 0.001$). A p-value < 0.05 was considered statistically significant.

GA: gestational age; FH: facial height; BZW: bizygomatic width; FL: foot length; FDL: femur diaphyseal length.

Simple linear regression analysis

Simple linear regression analysis showed significant associations between each anthropometric parameter and GA (all $p < 0.001$). Among the individual models, FL demonstrated the highest R^2 (0.864) and the lowest RMSE (2.82 weeks), followed closely by FDL, with an R^2 of 0.854 and an RMSE of 2.92 weeks. The regression equation for FL was:

GA (weeks) = 8.297 + 4.484 × FL (cm)

The models based on FH and BZW showed R^2 values of 0.769 and 0.743, with RMSE values of 3.67 and 3.87 weeks, respectively. The FDL/FL ratio showed comparatively lower explanatory performance, with an R^2 of 0.229 and an RMSE of 6.71 weeks. The regression equations and corresponding statistical parameters are presented in Table *3* and Figure *3*.

Predictor	Regression equation	R^2	RMSE	F	p
FH	GA = 4.009 + 7.768 (FH)	0.769	3.67	326.89	<0.001
BZW	GA = 10.951 + 4.362 (BZW)	0.743	3.87	283.78	<0.001
FL	GA = 8.297 + 4.484 (FL)	0.864	2.82	622.79	<0.001
FDL	GA = 6.818 + 3.688 (FDL)	0.854	2.92	574.27	<0.001
FDL/FL	GA = 80.080 − 37.303 (FDL/FL)	0.229	6.71	29.15	<0.001

TABLE 3: Simple regression models

R^2 indicates the proportion of GA variability explained by the predictor, root mean square error (RMSE) reflects prediction error in weeks, and the F statistic assesses the overall significance of the regression model. A p-value < 0.05 was considered statistically significant. The reported regression coefficients, R^2 values, and RMSE values represent the performance of the models in the development dataset and should not be interpreted as externally validated predictive performance.

GA: gestational age; FH: facial height; BZW: bizygomatic width; FL: foot length; FDL: femur diaphyseal length; RMSE: root mean square error.

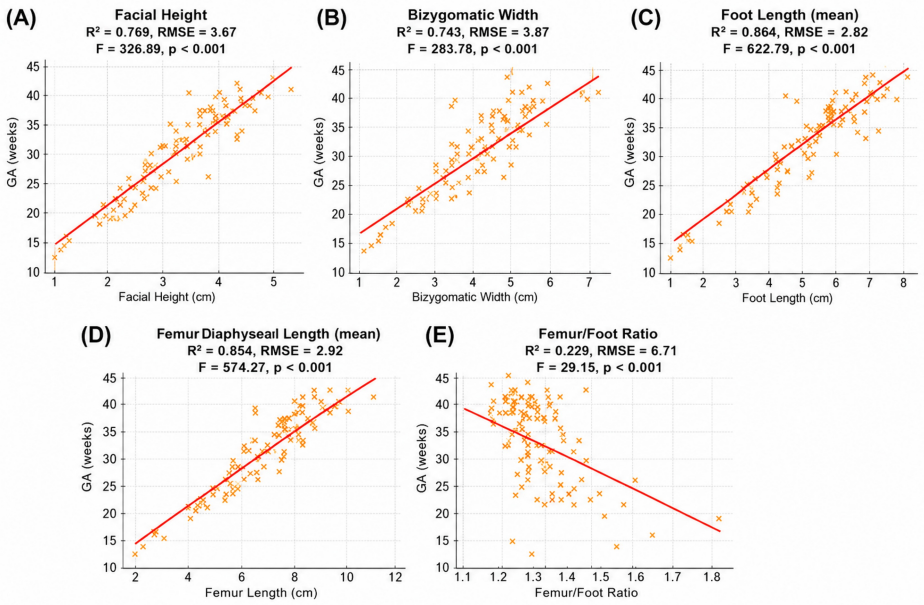


FIGURE 3: Simple linear regression models of GA (weeks) against fetal anthropometric parameters.

The scatterplots demonstrate the relationship between GA and (A) FH, (B) BZW, (C) FL, (D) FDL, and (E) FDL/FL ratio. Each cross represents an individual fetal observation, and the solid line represents the fitted linear regression line. Data are presented as individual observations. The coefficient of determination (R^2), root mean square error (RMSE), and overall regression F statistic are shown for each model. Simple linear regression analysis was used to assess the predictive relationship between each anthropometric parameter and GA. The corresponding model statistics were: FH, R^2 = 0.769, RMSE = 3.67 weeks, F = 326.89; BZW, R^2 = 0.743, RMSE = 3.87 weeks, F = 283.78; FL, R^2 = 0.864, RMSE = 2.82 weeks, F = 622.79; FDL, R^2 = 0.854, RMSE = 2.92 weeks, F = 574.27; and FDL/FL ratio, R^2 = 0.229, RMSE = 6.71 weeks, F = 29.15. All regression models were statistically significant (p < 0.001). A p-value < 0.05 was considered statistically significant.

GA: gestational age; FH: facial height; BZW: bizygomatic width; FL: foot length; FDL: femur diaphyseal length; RMSE: root mean square error.

Multiple linear regression analysis

In the full multiple linear regression model, which included FH, BZW, FL, FDL, and the FDL/FL ratio, FH was the only predictor that remained statistically significant after adjustment for the other variables (B = 1.918, SE = 0.801, β = 0.231, 95% CI: 0.327-3.509, p = 0.019). FL showed a positive regression coefficient but did not reach statistical significance (B = 3.798, SE = 2.059, β = 0.423, 95% CI: −0.290-7.886, p = 0.068). BZW, FDL,

and the FDL/FL ratio were also not statistically significant in the adjusted model ($p > 0.05$).

Assessment of multicollinearity showed high VIF values for FL (138.50) and FDL (113.44), indicating substantial overlap between these predictors. The VIF values for FH, BZW, and the FDL/FL ratio were 6.22, 9.18, and 5.34, respectively. These findings suggest that the regression coefficients in the full model should be interpreted cautiously, as the shared variance among the anthropometric parameters may affect the stability of their individual estimates. The regression coefficients, confidence intervals, VIF, and tolerance values are presented in Table 4.

Predictor	B coefficient	Standard error (SE)	Standardized β	t-value	95% CI	p-value	VIF	Tolerance
Intercept	3.629	9.237	-	0.393	−14.712-21.970	0.695	-	-
FH	1.918	0.801	0.231	2.393	0.327-3.509	0.019	6.22	0.161
BZW	−0.827	0.556	−0.183	−1.487	−1.931-0.277	0.140	9.18	0.109
FL	3.798	2.059	0.423	1.845	−0.290-7.886	0.068	138.50	0.007
FDL	0.458	1.541	0.067	0.297	−2.602-3.519	0.767	113.44	0.009
FDL/FL ratio	1.731	6.531	0.024	0.265	−11.237-14.699	0.792	5.34	0.187

TABLE 4: Multiple regression coefficients of each anthropometric measurement

The coefficients represent conditional estimates after adjustment for all predictors included in the multivariable model. A p-value less than 0.05 was considered statistically significant.

B: unstandardized regression coefficient; SE: standard error; β: standardized regression coefficient; CI: confidence interval; VIF: variance inflation factor; FH: facial height; BZW: bizygomatic width; FL: foot length; FDL: femur diaphyseal length.

A reduced multivariable model incorporating FL and FH was also examined. The resulting equation was:

GA (weeks) = 6.486 + 3.584 × FL (cm) + 1.831 × FH (cm)

This model had an R^2 of 0.872, an adjusted R^2 of 0.869, and an RMSE of 2.69 weeks. The full multivariable model had an R^2 of 0.876 and an RMSE of 2.69 weeks. Thus, the reduced model showed comparable in-sample performance while requiring fewer predictor variables. Both models were statistically significant ($p < 0.001$). Their regression equations and overall performance statistics are presented in Table 5.

Predictor	Regression equation	R^2	RMSE (weeks)	F value	p-value
Full multivariable regression model	GA (weeks) = 3.629 + 1.918 (FH) − 0.827 (BZW) + 3.798 (FL) + 0.458 (FDL) + 1.731 (FDL/FL ratio)	0.876	2.69	133.20	<0.001
Reduced multivariable regression model (FL + FH)	GA (weeks) = 6.486 + 3.584 (FL) + 1.831 (FH)	0.872	2.69	330.30	<0.001

TABLE 5: Multiple regression models

The full multivariable regression model included all anthropometric variables measured in this study (FH, BZW, FL, FDL, and FDL/FL ratio). The reduced multivariable regression model included only FL and FH. R^2 represents the proportion of variance in GA explained by each model, RMSE represents the average prediction error within the study cohort, and the F-statistic indicates the overall significance of the regression model. Both models were developed using the same cohort of 100 cadaveric fetuses; therefore, the reported performance statistics represent in-sample model performance and should not be interpreted as independent model validation.

GA: gestational age; FH: facial height; BZW: bizygomatic width; FL: foot length; FDL: femur diaphyseal length; RMSE: root mean square error.

The relationship between observed and predicted GA for the FL-only and combined FL + FH models is illustrated in Figure 4. The combined model showed a slightly higher R^2 and a lower RMSE than the FL-only model. However, the difference in performance was modest. As both models were developed and assessed using the same 100 specimens, these findings represent in-sample performance and do not establish their

accuracy in independent fetal specimens.

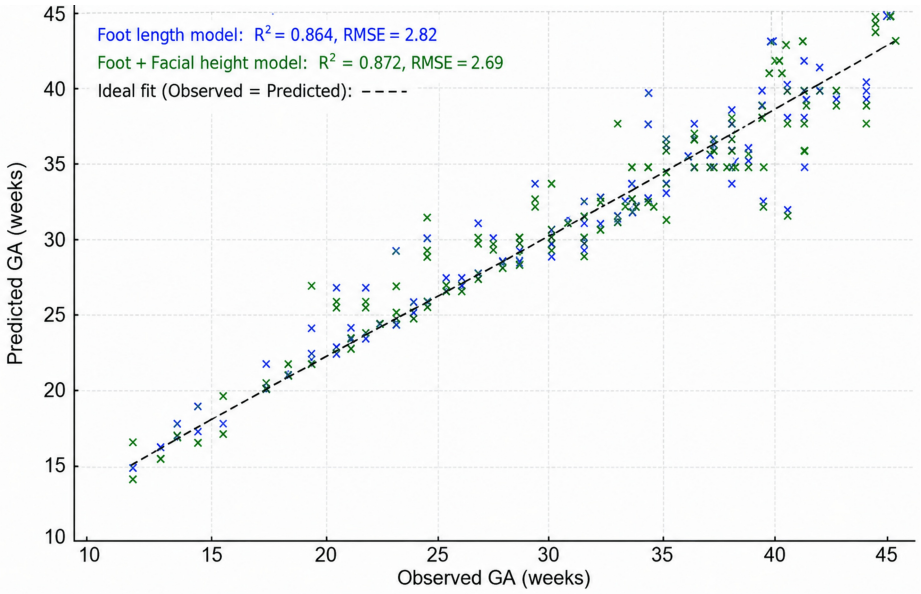


FIGURE 4: Observed versus predicted GA using regression models

The scatterplot compares observed GA with GA predicted using two regression models: the FL model (blue) and the combined FL and FH model (green). Each cross represents an individual fetal observation. The dashed diagonal line represents the ideal agreement between observed and predicted GA (observed = predicted). The FL model demonstrated R^2 = 0.864 and RMSE = 2.82 weeks, whereas the combined FL and FH model demonstrated R^2 = 0.872, adjusted R^2 = 0.869, and RMSE = 2.69 weeks. Model performance was assessed using the coefficient of determination (R^2) and RMSE, with lower RMSE indicating greater predictive accuracy.

GA: gestational age; FL: foot length; FH: facial height; RMSE: root mean square error.

Assessment of regression linearity

The linearity of the regression relationships was examined through visual inspection of scatterplots and residual-versus-fitted plots. The residuals appeared to be distributed approximately symmetrically around the zero line, without an obvious systematic pattern or marked curvature across the fitted GA values. These observations supported the use of linear regression for exploring the relationships within the GA range represented in the study cohort. The residual-versus-fitted plot for the FL + FH regression model is provided in the Appendices as supplementary supporting material.

Comparison across GA groups

One-way ANOVA demonstrated statistically significant differences in anthropometric measurements across the GA groups. The differences were significant for FH ($F = 56.09$), BZW ($F = 41.12$), FL ($F = 91.54$), FDL ($F = 81.85$), and the FDL/FL ratio ($F = 6.88$), with $p < 0.001$ for all parameters.

Among the measurements examined, FL and FDL showed higher F statistics than the craniofacial parameters, whereas the FDL/FL ratio showed a comparatively lower F statistic. These findings indicate overall variation in the measured anthropometric parameters across the GA groups. However, as post hoc pairwise comparisons were not performed, the results do not identify which specific groups differed significantly from one another. The ANOVA results are presented in Table *6*, and the distribution of anthropometric measurements across the seven GA intervals is illustrated in Figure *5*.

Parameter	F	p-value
FH	56.09	<0.001
BZW	41.12	<0.001
FL	91.54	<0.001
FDL	81.85	<0.001
FDL/FL ratio	6.88	<0.001

TABLE 6: One-way ANOVA comparing fetal anthropometric parameters across GA groups

Data are presented as F-statistics and p-values. One-way analysis of variance (ANOVA) was used to compare mean anthropometric measurements across GA groups. A p-value <0.05 was considered statistically significant.

GA: gestational age; FH: facial height; BZW: bizygomatic width; FL: foot length; FDL: femur diaphyseal length.

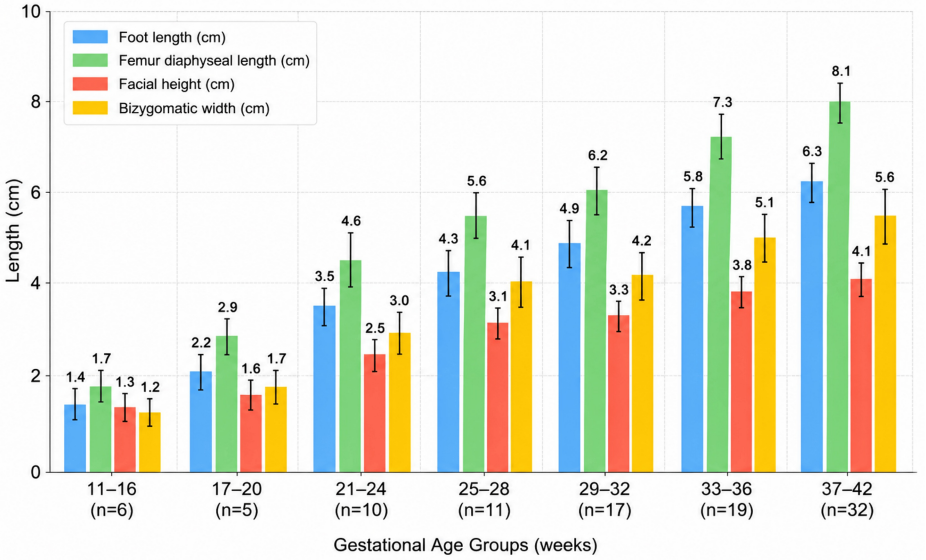


FIGURE 5: Comparison of fetal anthropometric parameters across GA groups (ANOVA)

The figure presents the mean values of FL, FDL, FH, and BZW across seven GA groups: 11-16, 17-20, 21-24, 25-28, 29-32, 33-36, and 37-42 weeks. Data are presented as mean ± SD, and the sample size for each GA group is indicated as n below the corresponding group. One-way ANOVA was used to compare the mean anthropometric measurements across GA groups. The corresponding ANOVA statistics were FH: F = 56.09; BZW: F = 41.12; FL: F = 91.54; FDL: F = 81.85; and FDL/FL ratio: F = 6.88; all p < 0.001. A p-value < 0.05 was considered statistically significant.

GA: gestational age; FH: facial height; BZW: bizygomatic width; FL: foot length; FDL: femur diaphyseal length.

Discussion

The present study examined the relationship between fetal craniofacial and limb anthropometric measurements and GA in 100 cadaveric fetuses. All four measurements showed significant positive correlations with GA. Among them, FL had the highest numerical correlation (r = 0.930), followed closely by FDL (r = 0.924). The difference between these correlation coefficients was small (0.006) and therefore does not establish a clear statistical advantage of FL over FDL. Both measurements showed a strong relationship with GA in the present cohort. The combined FL and FH model showed a modest improvement in model fit compared with the FL-only model.

The present findings are in close agreement with the cadaveric study by Bulandra et al., which also demonstrated strong correlations of both FL and FDL with GA, supporting the relevance of fetal limb anthropometry for age estimation [11]. The association between FL and GA observed in this study is

consistent with previous reports describing the progressive growth of the fetal foot during gestation [1]. FL can be measured directly using identifiable anatomical landmarks and is relatively convenient to assess in cadaveric specimens. Ravisankar et al. studied 150 fetuses between 17 and 25 weeks of gestation and reported a very strong correlation between FL and GA ($r = 0.996$; $p < 0.0001$) [1]. Mercer et al., in a larger study involving postpartum and ultrasonographic measurements across 11-43 weeks of gestation, reported a curvilinear relationship between FL and GA, with an R^2 of 0.981 [12]. These findings support the usefulness of FL in fetal anthropometric assessment (Table 7). However, the relationship may vary with GA, study population, measurement technique, and preservation conditions. The present study used a linear regression model across a relatively wide GA range, and the possibility of a nonlinear relationship was not formally evaluated.

Study (year)	Sample and GA range	Region	Predictor(s)	Reported model	Fit (R^2 / r)	Notes
Mercer et al. (1987) [12]	Postpartum n = 223; US n = 224	New York, USA	FL	Curvilinear regression	$R^2 = 0.981$	Classic demonstration: FL closely follows GA
Mhaskar et al. (1989) [13]	n = 105; GA 13-42 weeks	New Delhi	FL	Linear regression	$R^2 \approx 0.84$ ($p < 0.001$)	Sonographic series confirming strong linear fit
Hadlock et al. (1984) [19]	Large sonographic cohorts	Texas, USA	FDL (composite models)	Standard regression charts	High correlations	Widely used obstetric biometry reference
Pandey et al. (2015) [14]	n ≈ 100; GA 15-36 weeks	North India (Meerut)	FL	Linear regression; nomogram	r up to 0.96	Regional Indian series
Ravisankar et al. (2025) [1]	n = 150; GA 17-25 weeks	Tamil Nadu	FL, FDL, FDL/FL ratio	FL (mm) = 2.6133 (GA) − 18.491; FDL (mm) = 0.9898 (GA) + 1.0886	r = 0.996 (foot vs GA)	Recent Indian data; explicit equations reported
Present study (2025)	n = 100; GA = 12.4-42 weeks	Konkan, Maharashtra	FH + FL	Multiple regression	$R^2 = 0.872$	Cadaveric fetuses

TABLE 7: Comparison of selected prior studies of fetal anthropometry for GA estimation with our study

GA: gestational age; FL: foot length; FDL: femur diaphyseal length; FH: facial height.

In the present study, the FL-only regression model had an R^2 of 0.864 and an RMSE of 2.82 weeks. Although these findings indicate a strong association within the study cohort, the model performance was lower than that reported in some previous ultrasonographic studies. Mhaskar et al. reported an R^2 of approximately 0.84 in a series of 105 ultrasonographic measurements, while Pandey et al. observed a strong correlation between FL and GA ($r = 0.960$) in a North Indian study [13,14]. Differences between these findings and the present results may be related to variations in the study populations, GA ranges, measurement techniques, and reference methods. Direct comparison should therefore be made cautiously, particularly when measurements obtained from preserved cadaveric specimens are compared with those obtained through USG.

FDL is another commonly used parameter in fetal anthropometry and obstetric biometry. Suganya et al. reported a strong relationship between FDL and GA ($R^2 = 0.899$; $p < 0.001$), along with a close association between FDL and FL ($R^2 = 0.955$; $p < 0.001$) [15]. In the present study, FDL also showed a strong positive correlation with GA ($r = 0.924$; $R^2 = 0.854$; $p < 0.001$). Its correlation was only marginally lower than that of FL. Thus, the findings support the usefulness of both measurements for studying fetal growth, without establishing that one is consistently superior to the other. Differences in the identification of anatomical landmarks and the assessment of preserved specimens may also influence the measurements obtained.

FH and BZW were also positively correlated with GA, with R^2 values of 0.769 and 0.743, respectively, in the individual regression models. Although their explanatory performance was lower than that of the limb measurements, these findings indicate that craniofacial dimensions also vary with advancing gestation. Satija et al. reported progressive changes in facial dimensions with increasing GA and discussed the usefulness of facial measurements in assessing fetal maturity [16]. Similarly, Boogert et al. demonstrated associations between fetal facial dimensions and GA using USG [5]. The findings of the present study add

observations from direct measurements of cadaveric specimens. Nevertheless, differences in tissue preservation and anatomical landmark identification should be considered when interpreting craniofacial measurements obtained after death.

An important observation in the present study was that FL, despite having the highest individual correlation with GA, did not remain statistically significant in the full multiple regression model. In contrast, FH retained statistical significance after adjustment for the other measurements. This finding needs to be interpreted in the context of the substantial multicollinearity observed among the predictors. The VIF values were particularly high for FL (138.50) and FDL (113.44), indicating considerable overlap in the information provided by these two measurements. In addition, the FDL/FL ratio was derived from the same two variables and introduced further redundancy into the model. Under these circumstances, the regression coefficients represent conditional associations and may be unstable. The statistical significance of FH in the full model should therefore not be interpreted as proof that it is a stronger biological predictor of GA than FL or FDL.

The reduced model incorporating FL and FH was also examined. Its R^2 was 0.872, with an adjusted R^2 of 0.869 and an RMSE of 2.69 weeks. Compared with the FL-only model (R^2 = 0.864; RMSE = 2.82 weeks), the improvement was small. Although the combined model suggests that FH may provide some additional information when considered alongside FL, the difference in model performance does not establish a clinically or forensically meaningful advantage. The reduced model should therefore be regarded as an exploratory model developed within the present cohort rather than a validated prediction equation.

The FDL/FL ratio showed a moderate negative correlation with GA ($r = -0.479$; $p < 0.001$), but its individual regression model had a comparatively low R^2 of 0.229 and a higher RMSE of 6.71 weeks. This indicates that the ratio alone explained a relatively small proportion of the variation in GA compared with the absolute measurements. Its inclusion in the full multivariable model also needs to be considered in light of its mathematical relationship with FL and FDL. On the basis of the present findings, absolute limb measurements appear to have a stronger association with GA than the ratio; however, their relative performance requires further evaluation in independent samples.

One-way ANOVA showed significant overall differences in FH, BZW, FL, FDL, and the FDL/FL ratio across the seven GA groups. The highest F-statistics were observed for FL and FDL, followed by the craniofacial measurements. These results indicate that the measured parameters varied across the GA categories. However, post hoc pairwise comparisons were not performed, and it is therefore not possible to identify which specific groups differed significantly from one another. The ANOVA findings should consequently be interpreted as evidence of overall group variation rather than proof of differences between individual GA intervals.

Previous studies have also highlighted the importance of considering population-related variation in fetal growth (Table 7). Pandey et al. reported a strong correlation between FL and GA in a North Indian cohort [14]. Gadekar et al. developed the Garbhini GA-2 model using ultrasonographic parameters in an Indian population, while Poojari et al. examined the usefulness of abdominal and head circumference measurements for GA estimation [17,18]. Such studies illustrate the contribution of population-based fetal biometric data to GA assessment. However, differences in study design, reference standards, and measurement techniques make direct comparisons between ultrasonographic and cadaveric datasets difficult. The present study adds data based on direct craniofacial and limb measurements from fetal specimens received at a tertiary care referral center in the Konkan region of Maharashtra.

The study cohort was drawn from an institutional fetal repository that receives specimens through a regional referral network covering several districts of the Konkan region. Although this provides a wider referral base than a single local community, the findings cannot be considered representative of the entire Konkan population. Maternal demographic, nutritional, socioeconomic, and geographic characteristics were not uniformly available for analysis. In addition, the clinical circumstances surrounding the collection of individual specimens were not consistently documented. These factors may have influenced fetal growth and could not be accounted for in the present analysis. The regression equations should therefore be regarded as institution-derived models based on the available cohort rather than established regional reference standards.

A major strength of this study is the assessment of both craniofacial (FH and BZW) and limb (FL and FDL) measurements in the same group of cadaveric fetuses. This allowed the relationships of different anatomical parameters with GA to be examined within a single cohort. The study also included 100 specimens covering a GA range of 12.4-42.0 weeks, providing observations across different stages of fetal development. To our knowledge, this is the first study from the Konkan region to examine these craniofacial and limb parameters together in cadaveric fetal specimens. The findings provide preliminary regional data that may be useful for further anatomical and anthropometric research.

The study also has several limitations. It was conducted at a single tertiary care referral center, and the findings may not be generalizable to other populations. The specimens had been accumulated in the departmental repository over several years, and the exact duration of preservation and the interval between

fetal death and measurement were not uniformly documented. Preservation-related tissue changes may therefore have influenced some measurements. Although each parameter was measured three times by the same observer and the mean was used for analysis, formal intraobserver reliability was not assessed. Sex-specific regression models were not developed, and the potential influence of fetal sex could not be evaluated. Furthermore, the reference GA was obtained from available institutional obstetric records, but the timing and biometric basis of ultrasonographic dating were not uniform across all specimens.

Another important limitation is that the regression models were developed and assessed using the same dataset. Neither internal validation through bootstrap resampling or cross-validation nor independent external validation was performed. Consequently, the reported R^2 and RMSE values represent apparent in-sample performance and may overestimate the accuracy of the equations in new specimens. The full multivariable model was also affected by substantial multicollinearity, while the reduced FL + FH model was explored within the same dataset. The latter should therefore be considered hypothesis-generating rather than a validated prediction model.

The findings of the present study should be interpreted as preliminary evidence of the relationship between fetal anthropometric measurements and documented GA in preserved cadaveric specimens. The proposed regression equations may provide a basis for further investigation, but their use in cases where GA is unknown has not been established by this study. Their applicability to clinical or forensic settings, particularly in specimens with different preservation conditions or postmortem changes, remains uncertain.

Further studies involving multiple centers and larger, more diverse populations are needed to assess the consistency of these relationships. Standardized measurement protocols, formal intraobserver and interobserver reliability assessment, and more complete documentation of specimen and maternal characteristics would strengthen future research. Internal and independent external validation should also be undertaken before the proposed equations are considered for wider use. Comparative studies involving cadaveric measurements and ultrasonographic fetal biometry may help clarify the extent to which these approaches provide comparable information on fetal growth.

Conclusions

The present study demonstrated significant associations between craniofacial and limb anthropometric measurements and GA in cadaveric fetuses received at a tertiary care referral center in the Konkan region of Maharashtra. Among the parameters examined, FL showed the highest numerical correlation with GA, although its association was comparable to that of FDL. The addition of FH to the FL model resulted in a modest improvement in model performance. These findings provide preliminary evidence of the usefulness of fetal anthropometric measurements in studying GA relationships in preserved fetal specimens. However, the proposed regression equations have not been independently validated, and their predictive performance in other populations remains uncertain. Further multicenter studies involving larger and more diverse cohorts, standardized measurement protocols, and independent model validation are necessary before these equations can be considered for broader clinical or forensic applications.

Appendices

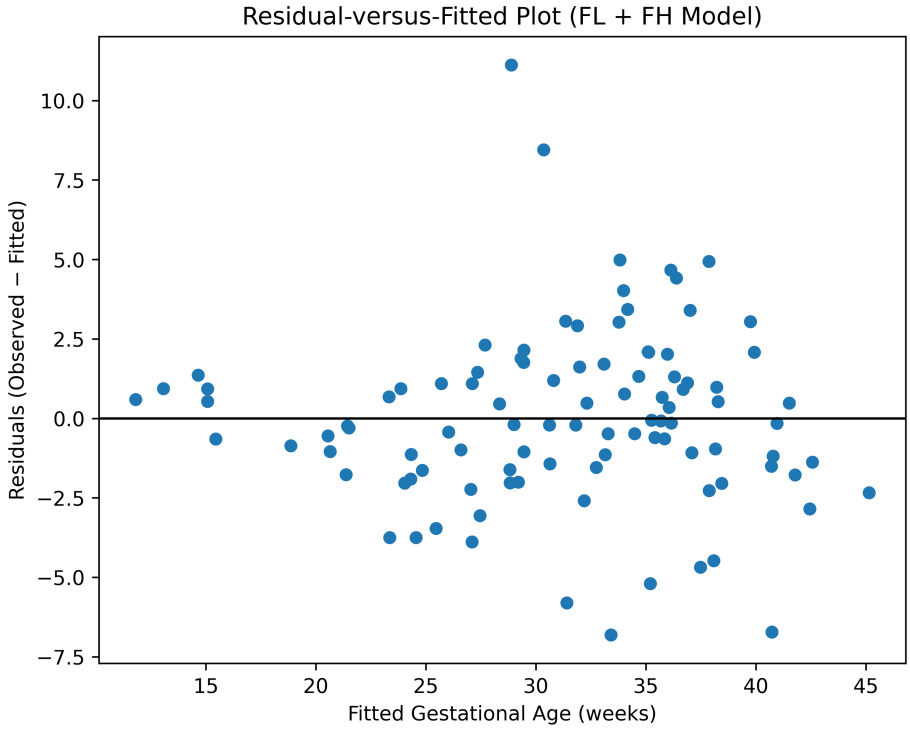


FIGURE 6: Residual-versus-fitted plot for the reduced multivariable regression model (FL + FH)

The residuals are randomly distributed around the zero line without an obvious systematic pattern or curvature across the fitted GA values, supporting the use of a linear regression model within the observed GA range of the study cohort.

GA: gestational age; FL: foot length; FH: facial height.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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References

1. Ravisankar G, Sivalingam SJ, Keerthi BP, Srinivasan S: Estimation of fetal foot length and femur-to-foot length ratio in Indian population for estimating gestational age on sonography during second trimester (17-25 weeks). Cureus. 2025, 17:e84515. 10.7759/cureus.84515
2. Alkhafaje Z, Kmkm A, Madhloom R, et al.: Correlation of fetal measurements with gestational age in 144 aborted fetuses: a cross-sectional hospital-based observational study. Georgian Med News. 2025, 118-24.
3. Canbaloğlu AE, Dursun A, Öztürk K, Kastamoni Y: Correlation between morphometry of fetal foot and gestational age: a cadaver study. Anatomy. 2024, 18:51-60. 10.2399/ana.24.1506392
4. Chikkannaiah P, Gosavi M: Accuracy of fetal measurements in estimation of gestational age . Indian J Pathol Oncol. 2016, 3:11-13. 10.5958/2394-6792.2016.00003.X
5. den Boogert A, de Jong-Pleij E, Ribbert L, Pistorius L, Tromp E, Bilardo C: Facial shape; height and width in the second and third trimester of pregnancy. J Matern Fetal Neonatal Med. 2019, 32:555-61. 10.1080/14767058.2017.1384807
6. Rajlakshmi CH, Bidhumukhi TH: Fetal age from superior facial height and bizygomatic width . J Forensic Med Toxicol. 2001, 18:28-30.
7. Tuli A, Choudhry R, Agarwal S, Anand C, Gary H: Correlation between craniofacial dimensions and fetal age. J Anat Soc India. 1995, 44:1-12.
8. Sletner L, Jenum AK, Yajnik CS, et al.: Fetal growth trajectories in pregnancies of European and South Asian mothers with and without gestational diabetes, a population-based cohort study. PLoS One. 2017, 12:e0172946. 10.1371/journal.pone.0172946
9. Patil N, Patil S, Modak A, et al.: Fetal biometry at the time of diagnosis of gestational diabetes in undernourished (low BMI) mothers from rural Konkan region of Maharashtra, India (BKLWHANC-4). Indian J Public Health Res Dev. 2025, 16:210-15. 10.37506/6cq85354
10. Muller Brochut AC, Taffe P, Piaget-Rossel R, de Leval L, Rougemont AL: Fetal anthropometric features: a postmortem study of fetuses after the termination of pregnancy for psychosocial reasons between 12 and 20 gestational weeks. Pediatr Dev Pathol. 2019, 22:243-51. 10.1177/1093526618812528
11. Bulandra AM, Kuczera M, Machnik J, Kuczera BM, Gielecki JS: Is manual foot length measurement of comparable value to ultrasound femur and humerus measurement in anatomical studies for the assessment of fetal age?. Folia Morphol (Warsz). 2004, 63:203-7.
12. Mercer BM, Sklar S, Shariatmadar A, Gillieson MS, D'Alton ME: Fetal foot length as a predictor of gestational age. Am J Obstet Gynecol. 1987, 156:350-5. 10.1016/0002-9378(87)90282-1
13. Mhaskar R, Agarwal N, Takkar D, Buckshee K, Anandalakshmi, Deorari A: Fetal foot length- a new parameter for assessment of gestational age. Int J Gynaecol Obstet. 1989, 29:35-8. 10.1016/0020-7292(89)90126-4.
14. Pandey VD, Singh V, Nigam GL, Usmani Y, Yadav Y: Fetal foot length for assessment of gestational age: a comprehensive study in North India. Sch J Appl Med Sci. 2015, 3:139-44. 10.36347/sjams.2015.v03i01.031
15. Suganya L, Sarvesh R, Shriram T: Ultrasonographic measurement of the fetal foot length and the ratio of the fetal femur to foot length to determine the fetal gestational age. J Pharm Bioallied Sci. 2025, 17:S1858-60. 10.4103/jpbs.jpbs_575_25
16. Satija A, Kaushal S, Gopichand PV, Chhabra U: Study of relationship between facial index and gestational age in normal newborns. Nepal Med Coll J. 2010, 12:133-6.
17. Gadekar VP, Damaraju N, Xavier A, et al.: Development and external validation of Indian population-specific Garbhini-GA2 model for estimating gestational age in second and third trimesters. Lancet Reg Health Southeast Asia. 2024, 25:100362. 10.1016/j.lansea.2024.100362
18. Poojari Y, Annapureddy PR, Vijayan S, Kalidoss VK, Mf Y, Pk S: A comparative study on third trimester fetal biometric parameters with maternal age. PeerJ. 2023, 11:e14528. 10.7717/peerj.14528
19. Hadlock FP, Deter RL, Harrist RB, Park SK: Estimating fetal age: computer-assisted analysis of multiple fetal growth parameters. Radiology. 1984, 152:497-501. 10.1148/radiology.152.2.6739822