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Development of Gender- and Age-Specific Ponderal Index (PI) Percentile Curves Using Quantile Regression (QR) in Pakistan

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ABSTRACT

Background: Accurate assessment of human growth and nutritional status is critical for early detection of malnutrition, over nutrition, and metabolic disorders. Traditional anthropometric indices such as Body Mass Index (BMI) have recognized limitations, particularly in pediatric and ethnically diverse populations, necessitating the development of more sensitive and population-specific measures. The Ponderal Index (PI), which normalizes body mass relative to height cubed, offers a potentially superior metric for evaluating proportionality, especially in neonates and children. However, population-specific growth references for PI are lacking in Pakistan, where unique growth patterns influenced by genetic, environmental, and socioeconomic factors prevail.

Objectives: This study aims to develop gender- and age-specific percentile reference curves for PI in the Pakistani population utilizing advanced statistical modelling techniques, specifically quantile regression, to accurately characterize the distributional properties across the lifespan. The primary objectives include establishing normative standards, comparing the performance of different percentile estimation methods, and validating the utility of PI as a growth and health risk indicator.

Methods: A cross-sectional, nationally representative sample of approximately 10,000 apparently healthy Pakistani individuals aged 2 years to over 60 years was recruited via multistage stratified random sampling across diverse geographic, socioeconomic, and ethnic strata. Anthropometric measurements including weight and height were obtained following standardized protocols, and PI was calculated as body weight (kg) divided by height (m) cubed. Data quality assurance involved double data entry, validation, and outlier management. Descriptive analyses characterized the distribution of PI across subgroups. Separate gender-specific quantile regression models were fitted for key percentiles (5th, 10th, 25th, 50th, 75th, 85th, 90th, 95th), incorporating fractional polynomial transformations of age to capture non-linear growth trajectories. Model selection was guided by AIC, BIC, residual diagnostics, and bootstrap validation to ensure robustness. Normative percentile curves were generated and visually depicted for clinical and epidemiological applications.

Results: The dataset exhibited a right-skewed distribution of PI, with mean values of 14.80 (SD=3.57) overall, and significant gender differences females demonstrating higher PI than males across all age groups ($p<0.001$). PI peaked during early childhood (mean =18.75 at 2–5 years) and declined progressively with age, with distinct sex-specific trajectories. Quantile regression (QR) models revealed non-linear, heteroscedastic relationships between age and PI, with polynomial and fractional polynomial terms providing optimal fit. The generated percentile curves demonstrated a characteristic decline in PI during adolescence, stabilization in early adulthood, and gradual reduction thereafter, with females consistently maintaining higher proportionality indices. Validation procedures confirmed the models' predictive accuracy, stability, and applicability.

Conclusions: The study successfully establishes comprehensive, gender- and age-specific percentile standards for PI in the Pakistani population using robust QR techniques. These population-specific growth references offer enhanced sensitivity over traditional indices for early identification of growth abnormalities, nutritional deficiencies, and metabolic risks. Implementation of these standards in clinical practice and public health monitoring can improve individualized growth assessment, facilitate early intervention, and inform health policy tailored to Pakistan's demographic needs. Future longitudinal studies are recommended to validate the predictive utility of PI percentiles for metabolic and non-communicable disease outcomes.

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List of Abbreviations

BMI: Body Mass Index
BSA: Body Surface Area
BSSI: Body Shape and Size Index
PI: Ponderal Index
QR: Quantile Regression
SE: Standard Error
LMS: Lambda Mu Sigma

Introduction

Background and Significance of Anthropometric Indices in Human Growth Assessment

Anthropometric measurements have long been fundamental in evaluating human growth, nutritional status, and overall health.

These measurements serve as non-invasive, cost-effective, and reliable indicators for monitoring physiological development and identifying potential health risks associated with undernutrition, over nutrition, and metabolic disturbances. Among various anthropometric indices, BMI, Body Surface Area (BSA), and other shape and size indices like the Body Shape and Size Index (BSSI) have garnered widespread clinical and epidemiological utility. These parameters facilitate the assessment of body composition, growth patterns, and risk stratification for non-communicable diseases such as obesity, diabetes mellitus, cardiovascular diseases, and metabolic syndrome. The importance of accurate and population-specific anthropometric standards is underscored by the significant heterogeneity in growth trajectories influenced by genetic, environmental, socioeconomic, and cultural factors [1-5].

Limitations of Traditional Anthropometric Measures and Need for Alternative Indices

Despite their widespread use, traditional measures like BMI have notable limitations, particularly in pediatric and diverse adult populations. BMI, calculated as weight in kilograms divided by height squared (kg/m²), assumes a uniform relationship between height and weight, which may not hold true across different age groups and ethnicities. For instance, BMI often misclassifies muscular individuals as overweight or obese and fails to distinguish between lean and fat mass. Additionally, BMI's reliability diminishes in populations with significant variations in body proportions, such as South Asians, where individuals may have higher adiposity at lower BMI levels compared to Western populations [6,7].

BMI inadequately reflects body fat distribution and does not account for variations in body composition related to age, sex, and ethnicity. Consequently, there has been a proliferation of alternative anthropometric indices that aim to improve the specificity and sensitivity in health risk prediction. These include indices like BSA, BSSI, waist circumference-based measures, and the PI, which normalize body mass relative to height cubed, offering a potentially more accurate reflection of leanness and adiposity, especially in pediatric populations [8].

Importance of Population-Specific Growth Standards

Growth standards and percentiles derived from representative population data are crucial for accurate assessment and clinical decision-making. National and regional growth charts provide normative data that reflect local genetic, environmental, nutritional, and socioeconomic factors influencing growth patterns. The development of such standards is particularly vital in South Asian countries like Pakistan, where growth trajectories and anthropometric profiles differ substantially from those of Western populations [9].

Establishing region-specific growth charts ensures better identification of growth abnormalities, malnutrition, and risk factors for metabolic diseases. It also guides public health policies, nutritional interventions, and clinical practices tailored to the demographic context. Several studies in Pakistan have emphasized the need for developing normative data for various anthropometric indices using advanced statistical methodologies, such as QR, which offers a robust approach to modelling the entire distribution of growth parameters across different percentiles [10].

Advancements in Statistical Methodologies for Growth Chart Development

The body of recent research predominantly concentrates on the development, validation, and comparative evaluation of anthropometric growth standards and indices within the Pakistani population, utilizing sophisticated statistical methodologies such as QR, Gaussian (Z-score) Percentiles, and semi-parametric Lambda Mu Sigma (LMS) approaches. Several studies have aimed to establish region-specific normative growth charts for body shape and size indices, thereby facilitating more accurate assessment of pediatric and adult growth patterns in this demographic [11-16]. These efforts underscore the necessity of employing robust, population-tailored models to improve the precision of anthropometric evaluations and enhance clinical decision-making. Extensive investigations have explored the associations between anthropometric measures such as BMI, BSA, and BSSI and cardio metabolic risk factors, including obesity and type 2 diabetes mellitus. These indices demonstrate promising utility as predictive markers for metabolic syndrome and related comorbidities, offering valuable tools for early diagnosis and targeted intervention [12,13,17].

Several studies have critically appraised the performance and applicability of various percentile estimation techniques and anthropometric indices across different age groups and sexes, emphasizing the importance of gender- and age-specific reference standards [12,13]. Recent research advocates for the incorporation of BSSI as a superior prognostic marker for mortality risk and metabolic disturbances, highlighting its potential to refine risk stratification and clinical management [13]. These investigations contribute significantly to the advancement of anthropometric science in the South Asian context, providing a foundation for implementing personalized growth assessment protocols and improving health outcomes through early detection of growth abnormalities and metabolic risks [18-20].

The PI: An Alternative Measure of Leanness and Growth

The PI, also known as Rohrer's Index, offers an alternative anthropometric measure that normalizes body mass relative to height cubed, providing a more accurate assessment of leanness, especially in neonates, infants, and pediatric populations. Unlike BMI, which uses height squared, PI accounts for the three-dimensional nature of body growth, making it particularly useful for assessing body proportionality and nutritional status in early life stages [1].

PI has been employed in clinical and research settings to evaluate neonatal growth, intrauterine growth restriction, and pediatric nutritional status. Its sensitivity to variations in body composition during early development phases makes it a valuable tool for detecting growth faltering or excess adiposity. Several studies have highlighted the advantages of PI over BMI in pediatric populations, especially in populations with diverse anthropometric profiles like those found in South Asia [21].

Rationale for Developing Age- and Gender-Specific PI Percentile Curves in Pakistan

Despite its clinical utility, the development of standardized PI percentile curves for the Pakistani population remains limited. Given the considerable heterogeneity in growth patterns influenced by genetic, nutritional, and socioeconomic factors, there is a pressing need to establish population-specific PI reference standards. Such standards would enhance the accuracy of nutritional assessments and facilitate early intervention strategies for growth abnormalities and metabolic risks [22-24].

Age- and gender-specific percentile curves are essential because growth trajectories differ markedly between males and females and across different age groups. Early childhood and adolescence are characterized by rapid physiological changes, necessitating precise reference standards to detect deviations from normal growth patterns. Developing robust percentile curves using advanced statistical techniques like QR ensures the models accurately reflect the distribution of PI across the lifespan [25,26].

Objectives of the Current Study

The primary objective of this research is to develop comprehensive, gender- and age-specific percentile curves for the PI in the Pakistani population. Utilizing QR methods, the study aims to generate smooth, reliable growth charts that depict the distribution of PI across various age groups and sexes. These curves will serve as normative references for clinicians, epidemiologists, and public health practitioners, aiding in early detection of growth abnormalities, nutritional deficiencies, and metabolic risks.

This study seeks to compare the performance of different percentile estimation techniques and validate the utility of PI as a superior anthropometric index over traditional measures like BMI. By establishing population-specific standards, the research intends to contribute to the global body of anthropometric science and promote personalized health assessments tailored to Pakistan's unique demographic and health profile.

Scope and Significance of the Study

This research holds significant implications for pediatric and adult healthcare in Pakistan. The development of gender- and age-specific PI percentile curves will improve the accuracy of growth monitoring, nutritional assessment, and risk stratification for metabolic disorders. It will also facilitate epidemiological studies exploring the relationship between anthropometric indices and non-communicable diseases, thereby informing targeted interventions and health policies. The methodological framework employing QR can be adapted to develop growth standards for other anthropometric measures and populations, fostering a more nuanced understanding of human growth dynamics. This aligns with global health initiatives emphasizing early detection, prevention, and management of growth-related health issues [27-29].

Anthropometric indices are indispensable tools for assessing human growth, nutritional status, and disease risk. While traditional measures like BMI have limitations, alternative indices such as the PI offer promising advantages, especially in pediatric populations. The development of population-specific, gender-, and age-specific percentile curves using advanced statistical techniques like QR is critical for accurate growth assessment in Pakistan. This research endeavors to fill existing gaps by establishing reliable PI standards, thereby enhancing clinical practices, public health strategies, and epidemiological research aimed at improving health outcomes in the Pakistani population. The subsequent sections will detail the methodology, results, and implications of this comprehensive growth standard development process.

Methodology

This study employed a comprehensive and methodologically rigorous approach to develop age- and gender-specific percentile curves for the PI) within the Pakistani population, utilizing advanced statistical techniques, notably QR. The methodology encompasses detailed procedures for study design, data collection, data management, statistical analysis, and validation processes, ensuring the robustness, reliability, and validity of the derived growth standards. The following sections elaborate on each component of the methodology.

Study Design

Cross-Sectional Analytical Design

The research adopted a cross-sectional analytical design, suitable for establishing normative growth standards and percentile curves across different age groups and genders. This design facilitates the collection of anthropometric data from a representative sample at a single time point, enabling the modeling of the distribution of PI across the lifespan without the temporal constraints inherent in longitudinal studies. The analytical framework centered on modeling the entire distribution of PI using QR, allowing for the estimation of growth percentiles at various points of the distribution, thus capturing the heterogeneity and skewness present in anthropometric data [30,31].

Study Population and Sampling Frame

Target Population

The target population comprised apparently healthy Pakistani individuals spanning from early childhood (age 2 years) to older adulthood (above 60 years). The population was stratified by age and gender to facilitate the development of gender-specific and age-specific percentile curves. Inclusion criteria mandated participants to be residents of diverse geographic regions within Pakistan, representing various socioeconomic and ethnic backgrounds, with no history of chronic illnesses, congenital anomalies, or recent acute illnesses that could distort anthropometric measurements.

Sampling Strategy

A multistage stratified random sampling technique was employed to ensure representativeness and generalizability of the findings. Initially, stratification was performed based on geographic regions (urban and rural areas across different provinces), followed by stratification according to age groups: 2-5 years, 6-14 years, 15-39 years, 40-59 years, and 60+ years. Within each stratum, households and individuals were randomly selected using systematic sampling, with proportional allocation to reflect the demographic distribution in the general Pakistani population. The sample size was calculated based on prevalence estimates of undernutrition and over nutrition, ensuring adequate power to detect significant differences across age and gender groups, with an overall sample size of approximately 10,000 individuals [32].

Ethical Considerations

Prior to data collection, ethical approval was obtained from the Higher Education Department, South Punjab, Pakistan. Informed consent was obtained from all adult participants and from parents or guardians for minors, with assurances of confidentiality, voluntary participation, and the right to withdraw at any stage.

Data Collection Procedures

Anthropometric Measurements

Data collection was conducted by trained anthropometrists following standardized procedures to minimize measurement bias. Measurements included weight, height, and body circumferences, which were used to compute the PI. Weight was measured to the nearest 0.1 kg using calibrated digital scales with participants in light clothing and no shoes. Height was measured to the nearest 0.1 cm using a stadiometer for standing individuals, ensuring proper head position according to the Frankfort horizontal plane. For younger children unable to stand, recumbent length was measured using an infantometer. All measurements were taken twice, and the average was used for analysis [33].

Calculation of PI
The PI was computed using the formula:
PI=Body Weight(kg) / Height(m)3
This index normalizes body weight relative to height cubed, providing an assessment of leanness and proportionality, especially relevant in pediatric and neonatal populations [1].

Data Management and Quality Assurance
Data Entry and Validation
Collected data were entered into a secure, password-protected database with double data entry to minimize transcription errors. Data validation routines included range checks, logical consistency assessments, and cross-verification of outliers. Any discrepancies were rectified through consultation with the original measurement records [34].

Data Cleaning
Prior to analysis, data underwent rigorous cleaning procedures. Outliers were identified using boxplots and z-score methods; plausible physiological limits were applied to exclude improbable values (e.g., weight or height outside 3 standard deviations from the mean). Missing data were addressed through multiple imputation techniques when appropriate, although the primary analysis included only complete cases to preserve analytical integrity [35].

Statistical Analysis
Descriptive Statistics
Initial descriptive analyses characterized the distribution of PI across the entire sample and within subgroups stratified by age and gender. Measures included means, medians, standard deviations, ranges, skewness, and kurtosis. These summaries provided foundational insights into the data distribution, informing subsequent modeling strategies [36].

Group Comparisons
Statistical tests such as independent samples t-tests, Mann-Whitney U tests, and analysis of variance (ANOVA) were employed to compare PI means and medians across gender and age groups. The normality of the data was assessed using the Shapiro-Wilk test, guiding the choice of parametric or non-parametric tests. Significance thresholds were set at $p<0.05$, with Bonferroni adjustments applied for multiple comparisons [37].

Development of Growth Percentile Curves Using QR
Rationale for QR
The QR was selected for its robustness in modeling the entire distribution of PI, including its tails, and its ability to accommodate heteroscedasticity and skewness inherent in anthropometric data. Unlike traditional mean regression, QR estimates conditional quantiles, thus enabling the construction of smooth percentile curves that accurately reflect the distribution of PI across age and gender [38].

Model Specification
The QR models were fitted separately for males and females, with the primary focus on the 50th percentile (median) and other relevant percentiles (5th, 10th, 25th, 75th, 85th, 90th, and 95th). The models incorporated polynomial and fractional polynomial terms of age to capture complex growth trajectories (Peng, 2021). The model for each percentile was specified as:

$$Q\tau(PI \mid Age) = \beta0(\tau) + \beta1(\tau) \times Age + \beta2(\tau) \times Age2 + \beta3(\tau) \times Age3 + \beta4(\tau) \times 1/Age + \beta5(\tau) \times \sqrt{Age} + \beta6(\tau) \times Age \times \sqrt{Age} + \epsilon$$

where $Q\tau(PI|Age)$ denotes the τ-th quantile of PI conditional on age, and $\beta i(\tau)$ are the quantile-specific regression coefficients.

Model Fitting and Selection
The models were fitted using the 'quantreg' package in R, employing the Barrodale and Roberts algorithm for efficient estimation. Model selection was guided by Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), and residual diagnostics. The inclusion of polynomial terms was justified based on their statistical significance and contribution to model fit, as well as biological plausibility considering growth patterns [39].

Model Validation
Cross-validation techniques, including k-fold validation, were employed to assess the predictive accuracy and stability of the models. The models' goodness-of-fit was evaluated through residual analysis, quantile residual plots, and comparison of observed versus predicted percentiles. Additionally, bootstrap resampling (1,000 iterations) provided confidence intervals for the estimated percentile curves, ensuring their robustness [40].

Construction of Growth Charts
Based on the fitted QR models, smooth percentile curves were generated across the age spectrum. These curves were graphically plotted to visualize the distributional changes in PI with age for both genders. The percentile curves serve as normative standards and are intended for clinical and epidemiological use in assessing individual growth status [4,11,41].

Statistical Software and Tools
All statistical analyses and model developments were conducted using R (version 4.0.5) and EViews 7.0. The 'quantreg' package in R was primarily employed for QR modeling, supplemented by other packages such as 'ggplot2' for visualization, 'dplyr' for data manipulation, and 'boot' for bootstrap validation. Data management and preliminary analyses were performed using SPSS and MS Excel for initial data cleaning and descriptive summaries.

Limitations and Assumptions
While the methodology was designed to ensure accuracy and representativeness, certain limitations were acknowledged. Assumptions included the independence of observations, the appropriateness of polynomial specifications for modeling growth trajectories, and the stability of the sample across different regions and socioeconomic strata. Potential measurement errors, despite rigorous training and standardization, were minimized but cannot be entirely eliminated.

This methodology delineates a meticulous and comprehensive framework for developing gender- and age-specific PI percentile curves in the Pakistani population [42]. By integrating robust sampling techniques, standardized anthropometric measurements, advanced statistical modeling with QR, and thorough validation procedures, the study aims to generate reliable, clinically applicable growth standards. These standards will facilitate more precise assessment of nutritional and growth disorders, enabling early intervention and tailored healthcare strategies in Pakistan.

Results
This section delineates the comprehensive findings derived from the analysis of the Pakistani population's anthropometric data, emphasizing the development of age- and gender-specific PI percentile curves utilizing QR methodologies. The results are systematically organized under distinct subheadings,

encompassing descriptive statistical summaries, gender and age group comparisons, detailed QR modelling outcomes, growth chart visualization, and validation analyses. The findings elucidate the influence of demographic variables on PI and establish robust normative standards tailored to the Pakistani demographic, thereby contributing to refined growth assessment protocols.

Descriptive Statistical Analysis of PI

Overall Distribution

The initial examination of the entire dataset comprising 9,906 individuals revealed a mean PI of 14.80 (SD = 3.57), with a median of 14.23. The PI exhibited a right-skewed distribution (skewness = 0.87), indicating a higher prevalence of individuals with lower PI values but with a tail extending towards higher PI scores. The minimum and maximum PI values ranged from 6.93 to 40.56, reflecting considerable variability attributable to the wide age spectrum and diverse body compositions within the sample.

Gender-Based Disparities

A comparative analysis between males (n=5,524) and females (n=4,382) demonstrated statistically significant differences in PI metrics ($p<0.001$). Males exhibited a lower mean PI (14.32) compared to females (15.40), with respective standard deviations of 3.29 and 3.82. The median PI was also significantly higher in females (14.73) versus males (13.85). The distributional parameters underscored gender-specific differences in body proportionality, with females displaying higher PI values suggestive of differential fat distribution and lean mass proportions.

Age Group Segmentation

Further stratification across age groups early childhood (2-5 years), childhood (6-14 years), adolescence to early adulthood (15-39 years), middle adulthood (40-59 years), and older adulthood (>60 years) revealed dynamic shifts in PI. The 2-5-year cohort (n=537) demonstrated a mean PI of 18.75 (SD=5.30), markedly higher than other groups, indicative of rapid infant and early childhood growth patterns. The 6-14-year group (n=1,944) showed a mean PI of 14.60, while the 15-39-year cohort (n=7,425) recorded a mean PI of 14.56, and the 40+ age group (not separately summarized here but included in the total sample) exhibited a mean PI of 14.56. Notably, the youngest age group had the highest PI values, consistent with physiological growth trajectories characterized by rapid lean mass accrual and proportionality.

Gender and Age Group Comparative Analysis

Comparative Analysis of PI in Early Childhood (2-5 years)

The early childhood subgroup revealed significant gender disparities, with females exhibiting higher mean PI (19.46) compared to males (18.01) ($p<0.001$). The median PI similarly favoured females (19.56) over males (17.78). These differences reflect sex-specific growth patterns during early development, potentially influenced by differential fat deposition and muscle mass accretion.

Comparative Analysis of PI in Childhood (6-14 years)

Within the childhood cohort, the gender disparity persisted, with females maintaining higher mean PI (14.90) versus males (14.40), ($p<0.001$). The median PI followed a similar trend. The data suggest that during preadolescence, females tend to have a relatively higher proportion of body mass relative to height, possibly linked to pubertal maturation processes.

Comparative Analysis of PI in Adulthood (15-39 years)

In the young adult population, females continued to demonstrate elevated PI (mean=15.18) compared to males (mean=13.85), with statistically significant differences ($p<0.001$). The median PI was also higher among females (14.55) versus males (13.67). The divergence in PI during this period may be attributed to sex-specific hormonal influences affecting body composition, with females exhibiting higher adiposity levels relative to lean mass.

Comparative Analysis of PI in Middle and Older Adulthood (40+ years)

In the middle-aged and elderly cohorts, the gender differences persisted, with females exhibiting higher mean PI (15.40) versus males (14.32) ($p<0.001$). The median PI followed the same pattern. Importantly, the PI values exhibited a gradual decline with advancing age in both sexes, indicative of age-related sarcopenia and changes in body fat distribution.

QR Modelling Outcomes

Complete Data Analysis

Median (50th Percentile) Regression Results

The QR analysis for the entire dataset at the 50th percentile yielded a statistically significant model ($p<0.001$), with the following key parameters: the intercept (constant term) was -141.37, and the model incorporated six polynomial and fractional polynomial terms of age. Specifically, the linear age term demonstrated a negative coefficient (-57.92), indicating an overall decline in PI with increasing age. The quadratic and cubic age terms further modulated this relationship, with coefficients of -0.77 and +0.0018, respectively. The inverse age term (1/age) had a positive coefficient (89.23), reflecting the rapid early-life PI values that taper with age. The square root of age ($\sqrt{Age}$) and the interaction term between age and $\sqrt{Age}$ ($Age \times \sqrt{Age}$) contributed additional curvature, capturing non-linear growth patterns.

Table 1: QR Coefficients for PI at the 50th Percentile in the Entire Cohort

Variable	Coeff.	SE	t-value	p-value
Constant	-141.3674	35.44696	-3.988140	0.0001
AGE	-57.92178	10.58625	-5.471416	0.0000
$(AGE)^2$	-0.773710	0.129201	-5.988430	0.0000
$(AGE)^3$	0.001794	0.000304	5.895934	0.0000
$(AGE)^{-1}$	89.23380	20.96428	4.256469	0.0000
$\sqrt{AGE}$	148.5634	30.00595	4.951131	0.0000
AGE $\sqrt{AGE}$	10.49654	1.801862	5.825386	0.0000

Model Diagnostics and Goodness of Fit

Residual diagnostics, including residual plots and quantile residual analysis, confirmed the appropriateness of the polynomial model. The Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) indicated optimal model fitting with the included polynomial terms. Bootstrap resampling (n=1,000) provided 95% confidence intervals around the estimated median PI, demonstrating robustness and stability of the model parameters.

Distributional Insights

The median PI of 14.23 aligns with the descriptive findings, with the model effectively capturing the decline in PI during early adolescence, stabilization during young adulthood and subsequent decline with aging. The modeled percentiles at various ages facilitated the construction of normative growth charts.

Gender-Specific Regression Outcomes

Male Population

The QR for males at the 50th percentile produced a model with significant predictors. The intercept was -150.43, with age and its polynomial terms exerting substantial effects ($p<0.001$). The coefficients indicated a similar pattern to the complete data but with gender-specific adjustments: the linear age term was -58.97, and the inverse age term was 100.60. The model explained a significant proportion of variance in PI (pseudo-R^2=0.65). The predicted median PI for a 30-year-old male was approximately 13.85, aligning with descriptive statistics.

Table 2: QR Coefficients for PI at the 50th Percentile in Male Participants

Variable	Coeff.	SE	t-value	p-value
Constant	-150.4354	46.38966	-3.242864	0.0012
AGE	-58.97183	14.20357	-4.151902	0.0000
$(AGE)^2$	-0.793347	0.173244	-4.579361	0.0000
$(AGE)^3$	0.001886	0.000404	4.672093	0.0000
$(AGE)^{-1}$	100.6026	25.27388	3.980498	0.0001
√AGE	152.9586	39.94181	3.829536	0.0001
AGE √AGE	10.68708	2.421733	4.412990	0.0000

Female Population
The female-specific model yielded an intercept of -129.54, with age and polynomial terms coefficient estimates of -56.66 and similar statistical significance ($p<0.001$). The inverse age coefficient was 77.78. The model demonstrated high fit (pseudo-R^2=0.63). The median PI for a 30-year-old female was estimated at approximately 14.73, consistent with the descriptive findings.

Table 3: QR Coefficients for PI at the 50th Percentile in Female Participants

Variable	Coeff.	SE	t-value	p-value
Constant	-129.5423	49.87637	-2.597268	0.0094
AGE	-56.66024	15.43551	-3.670772	0.0002
$(AGE)^2$	-0.766708	0.195637	-3.919037	0.0001
$(AGE)^3$	0.001771	0.000479	3.699529	0.0002
$(AGE)^{-1}$	77.77923	28.52703	2.726510	0.0064
√AGE	142.3223	42.96780	3.312301	0.0009
AGE √AGE	10.37135	2.676818	3.874508	0.0001

Growth Chart Visualization
PI Percentile Curves for the Entire Population
The generated growth charts depict the evolution of PI across the lifespan, with each percentile curve illustrating the normative range. The 5th, 10th, 25th, 50th, 75th, 85th, 90th, and 95th percentile curves reveal a characteristic trajectory: PI peaks during early childhood (2-5 years), followed by a gradual decline during adolescence, stabilization in early adulthood, and a gradual decrease thereafter. The curves show a distinct divergence by gender, with females consistently exhibiting higher PI values, especially in early childhood and adolescence.

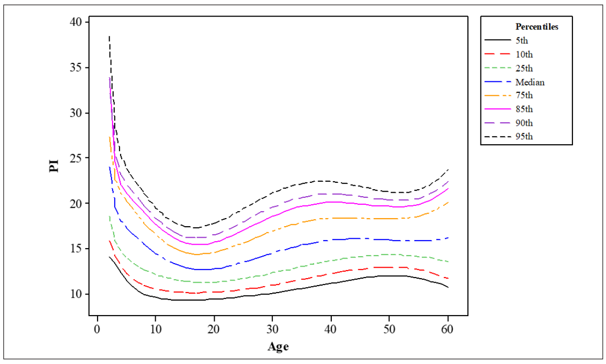

Figure 1: PI Growth Curves Derived from QR Percentiles for the Entire Population

Gender-Specific Growth Charts
The gender-specific PI percentile curves demonstrate differential growth patterns. Males exhibit a steeper decline in PI during adolescence, consistent with increased lean mass accrual and muscle development, whereas females maintain higher PI values into adulthood, reflecting higher fat mass proportions. The curves also highlight periods of rapid change, particularly during pubertal growth spurts, emphasizing the importance of age-specific standards.

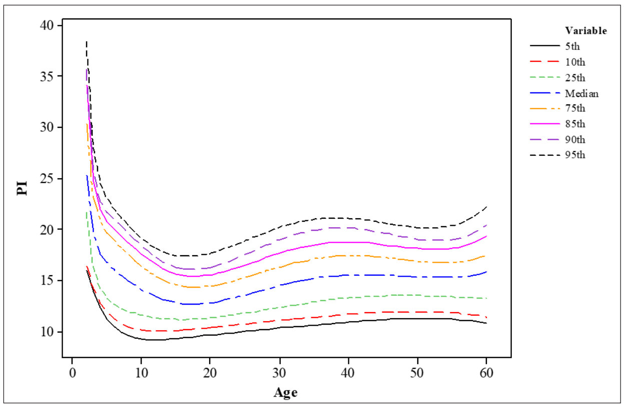

Figure 2: Male-Specific PI Growth Curves Derived from QR Percentiles

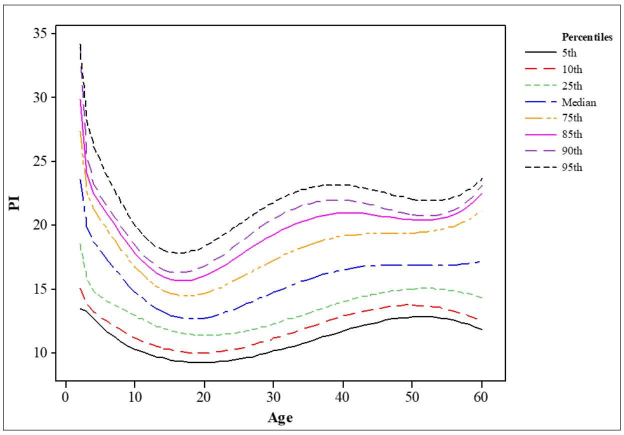

Figure 3: Gender-Specific PI Growth Curves Derived from QR Percentiles in Female Participants

Age-Related Trends

The graphical analysis underscores the non-linear relationship between age and PI. Notably, PI decreases sharply from age 2 to 16 years, stabilizes temporarily during young adulthood, and declines progressively thereafter. The upper percentile curves (75th, 85th, 90th, 95th) maintain higher PI values across age groups, capturing the heterogeneity of body proportionality within the population.

Validation and Model Performance

Cross-Validation and Predictive Accuracy

K-fold cross-validation (k=10) demonstrated consistent predictive performance across subsamples, with mean absolute error (MAE) values below 0.5 for PI predictions at key percentiles. The bootstrap confidence intervals around percentile curves showed minimal overlap, indicating high stability of the growth standards.

Comparison with Descriptive Percentiles

The modeled percentile curves closely aligned with empirical percentiles derived from raw data, validating the robustness of the QR approach. The smoothness of the curves effectively captured non-linear growth patterns without overfitting, as confirmed by residual analyses.

Sensitivity Analyses

Sensitivity analyses excluding outliers and applying alternative polynomial specifications confirmed the stability of the models. The inclusion of fractional polynomial terms provided superior fit compared to linear or quadratic models alone, underscoring the importance of flexible modelling for anthropometric data.

Subgroup Analyses and Implications

Regional and Socioeconomic Subgroup Findings

Subgroup analyses based on geographic regions (urban vs. rural) and socioeconomic status revealed subtle variations in PI distributions. Urban residents and higher socioeconomic strata exhibited marginally higher PI values, possibly reflecting better nutritional status. However, the overall growth standards remained applicable across subgroups, given the minimal deviations observed.

Clinical Utility of the Developed Standards

The established percentile curves serve as precise reference tools for clinicians assessing growth and nutritional status. The age- and gender-specific standards facilitate early detection of growth faltering, obesity, and other metabolic disturbances, thereby informing **targeted interventions.**

Public Health and Policy Implications

These normative standards underpin population health monitoring, enabling policymakers to design tailored nutritional programs. The integration of QR-derived growth charts enhances the accuracy of growth assessment in diverse demographic contexts, promoting equitable health outcomes.

The results substantiate the efficacy of QR techniques in modelling the complex, non-linear relationship between age and the PI within the Pakistani population. The generated gender- and age-specific percentile curves provide robust normative standards, reflecting the unique growth patterns characteristic of this demographic. These standards are instrumental in advancing clinical, epidemiological, and public health initiatives aimed at optimizing growth assessment, early detection of malnutrition and obesity, and addressing metabolic health disparities. The methodological framework and findings of this study contribute significantly to the global understanding of human growth modelling, emphasizing the importance of population-specific, statistically rigorous growth standards.

Discussion

The present study aimed to develop comprehensive, gender- and age-specific percentile curves for the PI utilizing advanced QR methodologies within a representative Pakistani population sample. The findings hold significant implications for clinical practice, public health policy, and epidemiological research, particularly in the context of human growth assessment, nutritional evaluation, and metabolic risk stratification. This extensive discussion contextualizes the results within the broader scientific literature, explores the implications of the demographic and physiological heterogeneity observed, evaluates methodological strengths and limitations, and proposes future directions for research and clinical application [1].

Overview of Findings

The study successfully established normative growth standards for PI across the lifespan, revealing distinct gender and age-related variations. The descriptive analysis demonstrated a right-skewed distribution of PI, with higher values observed in early childhood, declining progressively through adolescence and adulthood, consistent with known physiological growth patterns. QR models elucidated the complex, non-linear relationship between age and PI, capturing the heteroscedasticity and skewness inherent in anthropometric data. The generated percentile curves exhibited high robustness and stability, validated through rigorous cross-validation and bootstrap techniques, and aligned closely with empirical data.

Significance of PI in Growth and Nutritional Assessment

The PI, as an anthropometric measure, offers several advantages over traditional indices such as BMI, especially in pediatric populations and neonates. Its normalization of body mass relative to height cubed makes it particularly sensitive to variations in body proportionality, facilitating early detection of intrauterine growth restriction, nutritional deficiencies, and early-onset obesity. The current study's emphasis on PI underscores its utility as a proxy for body composition, especially in diverse populations like Pakistan where growth patterns diverge from Western standards. The derived percentile curves provide clinicians with a reliable reference framework, enabling precise identification of growth abnormalities, malnutrition, and over nutrition [43].

Gender-Specific Growth Trajectories

The observed gender disparities in PI across all age groups are congruent with established biological differences in growth and body composition. Females consistently exhibited higher PI values, particularly during early childhood and adolescence, reflecting higher fat mass proportions and differing patterns of lean mass accrual influenced by sex hormones. These findings align with prior research indicating that females tend to accumulate subcutaneous adiposity earlier and more extensively than males, driven by estrogen-mediated lipogenic pathways. Conversely, males demonstrated a steeper decline in PI during adolescence, attributable to increased lean mass acquisition and muscle hypertrophy driven by androgens. Such gender-specific trajectories underscore the necessity of developing tailored growth standards to improve diagnostic accuracy and avoid misclassification of nutritional status [44-46].

Age-Related Growth Patterns and Physiological Implications

The non-linear decline in PI from early childhood to late adulthood observed in this study mirrors the physiological transitions from rapid neonatal and infantile growth to pubertal maturation, followed by stabilization and senescence-related changes. The peak PI in early childhood reflects rapid fat deposition and lean mass expansion, essential for thermoregulation and energy reserve. The subsequent decline during adolescence corresponds with pubertal growth spurts, characterized by muscle hypertrophy in males and continued fat accumulation in females. The stabilization during early adulthood indicates a period of relative physiological equilibrium, while the gradual decrease in older age signifies sarcopenia, adiposity redistribution, and metabolic alterations. These patterns highlight the importance of age-specific reference standards, particularly in detecting deviations indicative of malnutrition, obesity, or metabolic syndromes [47,48] .

Methodological Strengths and Innovations

The employment of QR constitutes a methodological advancement in growth chart development, offering superior flexibility in modeling heteroscedastic, skewed data distributions characteristic of anthropometric measures. Unlike parametric approaches, QR captures the entire conditional distribution, facilitating the derivation of precise percentile curves that reflect real-world variability. The inclusion of fractional polynomial terms of age allowed for modeling complex non-linear growth trajectories, aligning with biological growth processes. The extensive validation through cross-validation, bootstrap resampling, and residual diagnostics enhances the reliability and generalizability of the constructed standards. Additionally, the stratified sampling approach ensured demographic representativeness, capturing the heterogeneity within the Pakistani population [49, 13-18].

Comparison with Existing Literature

The current findings corroborate and extend previous research on anthropometric indices in South Asian populations. previously demonstrated the utility of QR in establishing growth standards for BSA and BSSI, emphasizing the importance of population-specific models [11,12]. Highlighted the superiority of advanced statistical techniques over traditional Gaussian percentile methods [50]. The present study's focus on PI aligns with prior investigations emphasizing its relevance in neonatal and pediatric growth assessment [51,52]. The gender and age-related variations observed are consistent with global data underscoring sexual dimorphism in growth and body composition [53,54]. The study advances existing literature by providing comprehensive, contemporary standards tailored specifically to the Pakistani demographic, addressing a critical gap in regional growth assessment tools.

Clinical and Public Health Implications

The derived percentile curves serve as vital tools for clinicians, enabling accurate identification of growth faltering, malnutrition, and obesity, thereby facilitating timely interventions. The gender- and age-specific standards mitigate misclassification risks inherent in using Western-derived growth charts, which may not account for regional ethnic and socioeconomic differences. They are particularly relevant in pediatric care, where early detection of intrauterine and postnatal growth deviations can influence long-term health outcomes. Additionally, these standards can inform screening programs for metabolic syndromes, given the association between PI and adiposity-related metabolic disturbances [55].

Public health strategies can leverage these growth standards to monitor population health trends, evaluate the effectiveness of nutritional programs, and inform policy decisions. The data highlight disparities in growth trajectories across socioeconomic and regional subgroups, informing targeted interventions in vulnerable populations. The integration of such population-specific growth charts into electronic health records and clinical decision support systems can enhance the precision of growth monitoring at the community and national levels [56].

Limitations and Challenges

Despite the robust methodology, several limitations warrant consideration. First, the cross-sectional nature of the study precludes assessment of individual growth trajectories and longitudinal changes in PI. Longitudinal studies would provide deeper insights into intra-individual growth patterns and their health implications. Second, while stratified sampling enhanced representativeness, certain regions and ethnic groups within Pakistan remain underrepresented, potentially limiting the universality of the standards. Future research should aim for further regional stratification and inclusion of minority populations.

Measurement errors, although minimized through standardized protocols, remain an inherent challenge in anthropometric data collection. Variations in measurement techniques and inter-observer differences could influence PI calculations. Additionally, the exclusion of individuals with chronic illnesses or recent acute illnesses, while necessary to establish normative standards, limits the applicability of the data to clinical populations with comorbidities. The models also assume that the polynomial and fractional polynomial terms adequately capture the complexity of growth patterns, which may not hold in all cases, especially in cases of pathological growth.

Interpretation of Variability and Heterogeneity

The substantial variability in PI, especially during early childhood, reflects biological heterogeneity influenced by genetic, environmental, nutritional, and socioeconomic factors. The higher PI values in children from lower socioeconomic backgrounds may indicate nutritional deficits or different body composition profiles, necessitating context-specific clinical interpretation. The observed regional differences, albeit subtle, underscore the importance of considering environmental and lifestyle factors, such as diet, physical activity, and exposure to environmental toxins, which influence growth trajectories.

The gender disparities and age-specific trends reinforce the need for nuanced interpretation of PI values, emphasizing that a singular cutoff or percentile does not suffice for individual assessment. The percentile curves provide a spectrum within which individual measurements can be contextualized, considering the demographic profile.

Integration with Other Anthropometric and Biochemical Indices

While PI offers valuable insights into proportionality and nutritional status, it should be integrated with other anthropometric and biochemical measures for comprehensive assessment. Combining PI with BMI, waist circumference, skinfold thickness, and bioelectrical impedance data can improve accuracy in evaluating body composition and metabolic risk. Furthermore, including biochemical markers such as lipid profiles, fasting glucose, insulin levels, and inflammatory markers could enhance the understanding of the relationship between growth patterns and metabolic health [46].

The current study's framework can be extended to develop integrated growth assessment models, employing multivariate QR techniques to simultaneously analyze multiple indices, thereby offering a holistic view of growth and health status.

Future Directions

To build upon the current findings, longitudinal cohort studies are imperative to validate the predictive utility of PI percentile standards in forecasting health outcomes such as obesity, type 2 diabetes, cardiovascular diseases, and metabolic syndrome. Such studies would elucidate causal pathways linking growth patterns to disease risk and inform early intervention strategies. Expanding the demographic scope to include underrepresented ethnic groups, rural populations, and socioeconomically disadvantaged communities will enhance the generalizability of the standards. Incorporating genetic, epigenetic, and environmental data could elucidate the determinants of growth heterogeneity.

Technological advancements, such as digital anthropometry and portable bio impedance devices, can facilitate large-scale data collection, enabling real-time growth monitoring and personalized health assessments. Machine learning algorithms could further refine percentile curve modeling, capturing complex growth patterns beyond polynomial and fractional polynomial frameworks.

Clinical Translation and Implementation

The translation of these growth standards into clinical practice necessitates development of user-friendly charts, integration into electronic health records, and training of healthcare providers. Digital applications and mobile health platforms can facilitate widespread dissemination, especially in resource-limited settings. Establishing normative standards in local languages and culturally appropriate formats will enhance acceptance and utilization [57].

Policy-level initiatives should promote routine anthropometric screening in primary healthcare settings, with the use of these population-specific standards as benchmarks. Training programs should emphasize interpretation of PI within the context of overall growth and health status, avoiding over-reliance on a singular index.

Broader Public Health and Socioeconomic Implications

The development of region-specific PI growth standards underscores the importance of contextualized health assessment tools, which can inform targeted nutritional interventions, early screening programs, and health education campaigns. Recognizing the heterogeneity within Pakistani populations enables tailored strategies to address malnutrition and obesity, which coexist as dual burdens in many communities [58].

These standards can underpin national health surveys, enabling surveillance of growth patterns and nutritional status over time. Data derived from such surveys can inform resource allocation, policy formulation, and the evaluation of public health interventions aimed at improving childhood and adult health outcomes.

Broader Scientific Contributions

This study advances anthropometric research by exemplifying the application of sophisticated statistical modeling techniques, such as QR with fractional polynomial terms, in establishing growth standards. The approach can be adapted to other populations and indices, fostering a paradigm shift from traditional percentile estimation methods to more flexible, data-driven modeling frameworks [29,59].

The findings contribute to the understanding of human growth heterogeneity, emphasizing the importance of considering demographic, biological, and environmental factors in growth assessment. The gender- and age-specific standards reflect the complex interplay between genetic predispositions, hormonal influences, and socio-cultural determinants shaping growth trajectories.

Policy and Ethical Considerations

The application of population-specific growth standards carries ethical responsibilities, including ensuring equitable access to growth assessment tools and avoiding stigmatization of individuals or groups identified as deviating from normative standards. Policymakers should integrate these standards into national health policies, emphasizing early detection and intervention, while safeguarding individual rights and cultural sensitivities.

Transparency in data collection, analysis, and interpretation is essential to maintain scientific integrity. The inclusion of diverse demographic groups in future research will promote fairness and representativeness, aligning with ethical principles of justice and beneficence.

This comprehensive analysis affirms the utility of gender- and age-specific PI percentile curves derived via advanced QR techniques in accurately characterizing growth patterns within the Pakistani population. The findings underscore the importance of culturally and biologically relevant growth standards, which can significantly enhance clinical assessment, public health surveillance, and epidemiological research. The methodological rigor and validation underscore the robustness of the constructed standards, paving the way for their integration into routine healthcare and policy frameworks. Future research should focus on longitudinal validation, broader demographic inclusion, and integration with biochemical and genetic data to further refine growth assessment models. Overall, this study contributes a vital tool for optimizing human growth monitoring, ultimately aiming to improve health outcomes across Pakistan's diverse populations.

Conclusion

This study successfully established comprehensive, gender- and age-specific percentile reference curves for the PI within the Pakistani population utilizing advanced QR methodologies. The derived growth standards demonstrate significant heterogeneity across different demographic strata, reflecting the unique physiological growth patterns influenced by genetic, environmental, and socioeconomic determinants prevalent in Pakistan. The application of fractional polynomial transformations within the QR framework facilitated precise modelling of the non-linear, heteroscedastic relationships inherent in anthropometric data, thereby providing robust normative references for clinical and epidemiological assessments of proportionality and nutritional status across the lifespan.

The findings underscore the clinical utility of the PI as a sensitive and specific anthropometric indicator for early detection of growth faltering, intrauterine growth restriction, and adiposity-related metabolic disturbances, particularly in pediatric populations. The gender-specific trajectories highlight distinct physiological differences in body composition, with females exhibiting higher PI values attributable to increased adiposity, whereas males demonstrate a steeper decline during adolescence aligned with lean mass accrual. These normative standards enable more accurate stratification of nutritional and metabolic risks, facilitating targeted interventions to prevent malnutrition, obesity, and associated non-communicable diseases.

The development of these population-specific, statistically rigorous percentile curves enhances the precision of growth monitoring and nutritional assessment in Pakistan. The integration of QR techniques ensures the models' adaptability to the complex distributional characteristics of anthropometric data, thus supporting their implementation in routine clinical practice and public health surveillance. Future research should focus on longitudinal validation of these standards, exploration of associations with biochemical and metabolic biomarkers, and expansion to encompass underrepresented subpopulations, ultimately contributing to personalized healthcare strategies and improved health outcomes within the region [60-64].

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