

Does Body Composition Influence Foot Anthropometry? A Study among the Lodha Population of Paschim Medinipur, West Bengal, India

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Abstract

Healthy human feet are essential for supporting body weight. The present study is among the limited research that attempts to assess the multivariate relationship between body composition measures and foot anthropometric variables of the Lodha population, a particularly vulnerable tribal group of Paschim Medinipur district, West Bengal. The present cross-sectional study was conducted on Lodha males (228) and females (215) aged 18 years and above. All variables were obtained by following standard procedures. Canonical Correlation Analysis (CCA) was performed using SPSS version 26.0. The canonical correlation coefficient between body composition and foot anthropometric variables was .939 and .898 ($p \leq .001$) for males and females, which explained 80.23% and 72.85% of the total variance, respectively. Cross-loading values of Canonical Correlation Analysis revealed that among males, height, weight, body mass index (BMI), body fat percentage, and visceral fat level were the most important predictors of all the breadth and girth measurements of the foot. Among females, all body composition measures were highly important predictors of girth measurements of the foot. The findings of the present study will aid in raising awareness concerning foot health and contribute new knowledge to public health.

Keywords: Foot anthropometry, Body composition, Foot health, Multivariate relationship, Canonical Correlation Analysis (CCA), Lodha population

1 Introduction

Human feet bear the entire weight of the body and stabilize it in contrasting postural and environmental conditions (Murley et al., 2009; Saltzman et al., 1995). To provide its dual functions of weight bearing and ambulation, the human foot is highly evolved and structurally unique (Jahss, 1982). For example, specialized structures, such as the fat pads of the foot, particularly those in the heel, arch, and metatarsal head regions, are designed to provide cushioning to the underlying bones and shock absorption for the whole body (Cavanagh, 1999; Denoth, 1985). These structures protect against the high-ground reaction forces that are generated during walking and other forms of daily activities (Mickle et al., 2006), and the longitudinal arch is the component most responsible for absorbing and dispersing these forces in the feet (Bhatia et al., 2010). Individual weight is an important determinant in the development of distinct foot types since the main purpose of an arched foot is to distribute the load from body weight to different sections of the foot during different stages of the walk cycle (Arthi et al., 2018; Hillstrom et al., 2013). The feet constitute the body's foundation and the final link in the kinetic chain during human locomotion, and a healthy foot structure is crucial for efficient posture and ambulation (Riddiford-Harland et al., 2011;

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Rosenbaum & Becker, 1997). Any alteration from normal or healthy foot structure can influence the gait and lead to different injury patterns (Vangara et al., 2016).

Excessive body mass has been proven to significantly affect foot morphology as it places a greater biomechanical strain on the skeletal and soft tissues (Bhattacharjee & Goswami, 2017, 2019; Chatha & Mohammad, 2020; Domjanić et al., 2013; Morrison et al., 2018). As a result, the shape and function of an obese and overweight adult's foot vary from that of a healthy-weight individual, resulting in alterations in morphology, soft tissue features, and functional capabilities (Dowling et al., 2001; Hills et al., 2001; Price & Nester, 2016; Riddiford-Harland et al., 2011). Furthermore, foot pain was noted as a typical condition in overweight and obese individuals due to increased body weight and stress exerted on the feet.

Obesity is closely linked to flatfoot deformity, pronated dynamic foot function, and higher plantar pressures during walking (Butterworth et al., 2012; Domjanić et al., 2013; Krishnan & Pawar, 2017; Tanamas et al., 2012). Studies have established that being overweight or obese as defined by the body mass index (BMI) probably has detrimental consequences on the foot, most likely due to the increased mechanical loading on the lower limbs (Birtane & Tuna, 2004; Butterworth et al., 2012, 2014; Domjanić et al., 2013; Hills et al., 2001; Morag & Cavanagh, 1999; Tománková et al., 2015; Wearing et al., 2004). A rise in BMI brought on by an increase in body fat mass leads to the collapsing of the arches as it causes a greater force to be applied across the sole (Alcántara et al., 2002; Butterworth et al., 2014; Vijaykumar et al., 2016; Wearing et al., 2004). Chatha and Mohammad (2020) and Zhao et al. (2020) discovered a positive correlation between BMI and forefoot area, forefoot and instep girth, rearfoot width, instep height, and arch height index. Wearing et al. (2004) found that weight, BMI, fat-free mass, fat mass, and percent fat mass significantly correlated with the total area as well as forefoot, midfoot, hindfoot, and toe area, as well as arch index. Adolescents with high body fat and low muscle mass percentages had significantly lower medial longitudinal foot arches (Wyszyńska et al., 2020), and the arch height index was lowest in the lower BMI group (Wearing et al., 2004).

Studies conducted on the influence of being underweight on foot morphology and structure are scanty. Several studies revealed that underweight children and adults have high-arched (*pes cavus*) as well as low-arched feet (*pes planus*) (Alimuiddin et al., 2020; Pathan et al., 2022; Ripka et al., 2017; Vijaykumar et al., 2016; Woźniacka et al., 2013), which have been linked to foot pain, disabilities, and lower extremity injuries (Burns et al., 2005; Tong & Kong, 2013), but the etiology is still unknown. BMI and body fat composition each have been found to have a significant negative relationship with the shape of foot arches (Alimuiddin et al., 2020). Thus, an abnormal lack of body mass (thinness) can cause deviation from normal foot structure and is likely to cause changes in basic motor activities such as gait and postural balance, leading to various injuries (Tojo et al., 2018; Vangara et al., 2016).

The morphology of the human foot also varies significantly due to the combined effects of heredity, ethnicity, geographic locations, lifestyle, climatic factors, physical activities, as well as nutritional factors (Abledu et al., 2015; Addai et al., 2018; Adelakun et al., 2019; Ikpa et al., 2019; Krishan, 2008; Mansur et al., 2020; Oberoi et al., 2006; Rahman et al., 2014; Ukoha et al., 2013; Vangara et al., 2019). Besides, infants, children, and adults have different foot structures (Arthi et al., 2018), and BMI does not give precise information regarding body fat amount and distribution because it is not a direct measure of body fat (Conus et al., 2007; Evans et al., 2006; Güven et al., 2009; Pietrobelli & Tatò, 2005; Romero-Corral et al., 2008; Wyszyńska et al., 2020).

Thus, there is a lack of evidence to support the degree of relationship between body composition measures such as body fat mass and foot morphology parameters, inducing an acute need for data on adults (Butterworth et al., 2014). In terms of the nutritional status of the Indian tribal community, the overall sex-specific prevalence of chronic energy deficiency revealed that both tribal females (52.0%) and males (49.3%) were in critical nutritional stress (extremely low BMI), with females faring worse (Das & Bose, 2015); a situation particularly pronounced among the Lodhas, a particularly vulnerable tribal group (PVTG) mostly found in the forest-covered areas of Paschim Medinipur district of West Bengal, India (Bepari et al., 2015; Bisai et al., 2014). The Lodhas belong to the Austro-Asiatic linguistic group, speaking the Mundari language (Bepari et al., 2015; Bisai et al., 2008; Panda & Guha, 2015). Being Austro-Asiatic language speakers, they belong to the Ancestral Austro-Asiatic (AAA) genetic component (Basu et al.,

2016). Traditionally, they were forest dwellers who lived in the dense forest, exploiting various forest products and hunting wild animals, but now they have started cultivating either as owners or as agricultural labourers and are also engaged in hunting, fishing, and non-agricultural activities. However, their economy is still based mainly on collecting minor forest products (Bisai et al., 2014; Panda & Guha, 2015).

Thus, it is vital to investigate the relationship between foot morphological characteristics and body composition measures among adult tribal populations in India. A complete assessment of such a relationship is indispensable, as changes in body composition govern deviation from normal foot morphology, which affects gait and causes injuries. Therefore, this cross-sectional study aims to assess the multivariate relationship between body composition measures and foot anthropometric variables of the adult Lodha tribal population of Paschim Medinipur district, West Bengal.

2 Materials and methods

2.1 Study area and study participants

The present cross-sectional study was conducted among the adult Lodha population of Paschim Medinipur district, West Bengal, India. Based on numerical dominance and ethnic homogeneity, Tarafbarpanda Mouza of Kashipur Gram Panchayat, under Narayangarh Block of Kharagpur sub-division, has been selected as the study area for the present study. Participants were purposively recruited from three villages, namely Karangabera, Raspata (Taraf Dakshin), and Uttarpara (Taraf Uttar). A total of 443 Lodha participants (228 males and 215 females) aged 18 years and above were identified by a door-to-door survey from the selected villages of Paschim Medinipur district, West Bengal, India. Participants who fulfilled the following criteria were selected: 1) adult males and females (aged 18 years and above, since foot anthropometric parameters does not typically stabilize until adulthood is reached, and by the age of 20 years the foot achieves its adult and fixed measurements), apparently healthy and not reported to be pregnant, not having any foot deformities, genetic disorders, endocrine, or neurological disorders, 2) Participants, their parents and grandparents (both paternal and maternal side) belonging to the above-mentioned ethnic group and residing in the area of study since birth (Alabi et al., 2017; Oria et al., 2017). The purpose of the research was explained, and informed consent was obtained from the participants. Participation in the study was voluntary. The study was approved by the Institutional Ethical Committee for Biomedical and Health Research, University of Calcutta (Ref No. CUIEC/02/31/2022-23, Dated-05.01.2023)

2.2 Methods of data collection and data types

Socio-demographic data

A pre-tested structured schedule was used to collect socio-demographic data using an interview method. It included the age of the participants at the time of the interview, sex, birthplace, and ethnicity. Besides, the ethnicity and birthplace of parents and grandparents were also obtained. The ethnicity of the participants was ascertained by collecting the surnames of their parents and grandparents. They were also asked to recollect and report any history of exogamous (outside community) marriages on both sides of their families. Additionally, they were asked if they, their parents, grandparents, and prior generations had lived in the area of study since birth. Later, these facts were cross-checked with the acquaintances of the participants or elderly individuals residing in the respective villages.

Set 1: Age and body composition measures (Independent variables)

The participants' age was an independent variable in the analysis, as it potentially influences both body composition measures and foot anthropometric variables. The participants' age was initially inquired and those who couldn't recollect their age were questioned further by referring to landmark events such as age at marriage, the gap between marriage and first childbirth, and the age of the first child, which were later

cross-checked by family members of the participants and were requested to present the written records of their date of birth.

Body weight (kg), body mass index (kg/m^2), body fat percentage, skeletal muscle percentage, and visceral fat level were recorded from the Omron Body Composition Monitor (HBF-212) following the standard technique provided in the instruction manual. Height was measured with a stature meter following standardized protocol (Lohman et al., 1988). The participants were made to stand erect and barefoot with light clothing. Each measurement was taken twice to ensure the reliability of the instrument.

Foot anthropometric variables (Dependent variables)

Foot anthropometric variables listed in Table 1 were measured on both feet following the standard protocol (Parham et al., 1992). All measurements were measured nearest to 0.1 cm. To avoid technical errors and increase accuracy, three successive measurements were obtained, and the average value of the measurements was calculated.

Table 1: Table 1: Description of foot anthropometric measurements of the participants

Sl. No.	Variables	Landmarks	Sources	Instruments
Height measurements				
1.	Medial malleolus height	Medial malleolus landmark	Parham et al. (1992)	Martin's sliding caliper
2.	Lateral malleolus height	Lateral malleolus landmark		
3.	1 st Toe height	–		
4.	Ankle height	Ankle landmark		
Breadth measurements				
1.	Bimalleolar breadth	Medial and lateral malleolus landmark	Parham et al. (1992)	Martin's sliding caliper
Circumference/ Girth measurements				
1.	Ankle circumference	Ankle level landmark	Parham et al. (1992)	Steel tape
2.	Heel-ankle circumference	Dorsal junction of foot and leg		
3.	Calf girth	Calf level landmark	Lee et al. (2015)	
4.	Instep girth	Instep girth landmark		
5.	Ball girth	Metatarsale tibiale and metatarsale fibulare		

2.3 Statistical analysis

Descriptive statistics were computed for each variable. Pearson's correlation analysis was performed between age, body composition measures, and foot anthropometric variables to understand the bivariate relationship. Canonical correlation analysis (CCA), a multivariate statistical model, was performed to understand the relationship between two sets of variables. The first set consists of age and body composition measures (independent set), i.e., height, body weight, Body Mass Index, body fat percentage, skeletal muscle percentage, and visceral fat level. The second set consists of foot anthropometric variables (dependent set), i.e., lateral malleolus height, medial malleolus height, 1st Toe height, ankle height, bimalleolar breadth, ankle circumference, heel-ankle circumference, calf girth, ball girth, and instep girth.

The CCA algorithm creates a canonical function based on standardized function coefficients of the observed independent (predictor) and dependent (criterion) variable sets that maximize the correlation

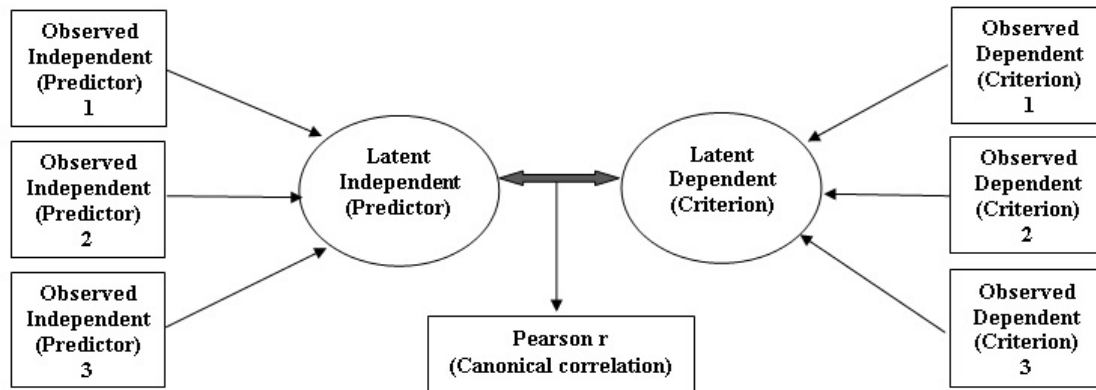


Figure 1: An illustration of a canonical correlation analysis with 3 independent (predictor) and 3 dependent (criterion) variables from the 1st function. Canonical correlation analysis is a simple Pearson's correlation (r) between two latent variables, also known as canonical variates, generated by the linear combination of the observed data.

between the two canonical variates (latent predictor and criterion variate) (Fig. 1). Furthermore, CCA creates as many functions as there are variables in the smaller variable set; each function is independent (orthogonal) from the others, which means that each set of latent variates will be perfectly uncorrelated with all other latent variates from other functions, representing various relationships between the sets of dependent and independent variables. The loadings of the individual variables differ in each canonical function and represent variables' contributions to the specific relationship under investigation (Green, 1978; Hair et al., 2004; Sherry & Henson, 2005; Stewart & Love, 1968).

Hair et al. (1998) proposed three criteria for choosing the important functions: (i) level of significance: The most widely used test for significance is the F statistic of each function (Bartlett, 1941); (ii) magnitude of the canonical correlation; and (iii) redundancy index which provides the amount of variance of one canonical variate (dependent or independent) statistically explained by the other canonical variate. As canonical variates represent the observed independent and dependent variables, the redundancy index measures the ability of a set of independent variables to explain the variation in the set of dependent variables.

To determine the relative importance/contribution of each original/observed variable in the data sets to each function, three methods have been proposed: (i) *Canonical weights (standardized canonical function coefficients)*. These weights are applied to the observed scores in Z-score form to yield the canonical variates, which are correlated to yield the canonical correlation. Weights are derived to maximize this canonical correlation, which is directly analogous to beta weights in regression analysis. (ii) *Structure coefficient (canonical loadings) (r_s)*. This is the bivariate Pearson correlation between the canonical function score (canonical variate) and the observed variable of its own set. The interpretation of canonical loadings is the same as the interpretation of factor loadings in factor analysis. (iii) *Canonical cross-loadings*. This is the bivariate correlation of a canonical variate with the observed variable of the opposite set. As the canonical weights, analogous to regression weights, are unstable and vulnerable to multicollinearity, most of the literature recommends the use of canonical loadings and cross-loadings to evaluate the relationship between original variables and canonical variates. Variables that are highly correlated with a canonical variate should be considered more important when deriving a meaningful interpretation of the related canonical variate (Hair et al., 1998; Shafto et al., 1997; Thompson, 1991). In the present study, variables with loading values (structure coefficient, r_s) $\geq |0.45|$ (Sherry & Henson, 2005) were considered to be most useful in the model. All statistical analyses were performed using Statistical Package for Social Sciences version 26.0 (SPSS Inc., Chicago, IL), with a significance level set at $p \leq 0.05$ (two-tailed).

Table 2 represents the descriptive statistics of body composition measures (Set 1) and foot anthropometric variables (Set 2) across sex. The mean age was slightly higher in males than in females. Males were

taller, heavier, with greater skeletal muscle percentage and visceral fat level than females. Females were found to have a higher body fat percentage than males. Male feet were higher and broader than female feet. Bilateral asymmetry among the foot anthropometric variables was prevalent as mean values of left and right feet differed in both males and females. The left foot had a higher mean lateral malleolus height, ankle circumference (in both males and females), and ankle height (in males) than the right foot. Mean values for left and right calf girth in males and ankle height in females were similar.

Table 2: Descriptive statistics of age, body composition measures (Set 1), and foot anthropometric variables (Set 2) of the adult Lodha population

		Males (n = 228)				Females (n = 215)			
		Mean	SD	95% CI Lower	95% CI Upper	Mean	SD	95% CI Lower	95% CI Upper
Age and Body Composition measures (Set 1)									
Age (years)		42.50	15.24	40.51	44.49	41.57	14.55	39.62	43.53
Height (cm)		158.90	6.29	158.08	159.72	147.95	5.86	147.16	148.73
Body weight (kg)		49.49	7.54	48.50	50.47	42.40	8.09	41.32	43.49
Body Mass Index (kg/m ²)		19.55	2.42	19.24	19.87	19.33	3.19	18.90	19.76
Body fat (%)		18.29	5.19	17.61	18.97	26.11	6.58	25.22	26.99
Skeletal muscle (%)		36.19	3.82	35.69	36.69	28.56	2.65	28.20	28.91
Visceral fat level		4.09	2.92	3.71	4.47	2.97	2.39	2.65	3.29
Foot anthropometric variables (Set 2)									
Lateral malleolus height (cm)	Left	6.50	.57	6.43	6.58	5.91	.50	5.85	5.98
	Right	6.45	.56	6.37	6.52	5.77	.49	5.70	5.83
Medial malleolus height (cm)	Left	7.58	.55	7.51	7.65	6.83	.49	6.76	6.89
	Right	7.76	.60	7.68	7.84	6.95	.48	6.88	7.01
Ankle height (cm)	Left	12.41	.96	12.28	12.53	10.89	.97	10.76	11.02
	Right	12.38	.98	12.25	12.51	10.89	.97	10.76	11.02
1 st Toe height (cm)	Left	2.16	.21	2.13	2.12	1.96	.22	1.93	1.99
	Right	2.30	.27	2.26	2.33	2.03	.29	2.00	2.07
Bimalleolar breadth (cm)	Left	6.77	.35	6.73	6.82	6.04	.46	5.98	6.10
	Right	6.91	.36	6.86	6.96	6.16	.45	6.09	6.22
Ankle circumference (cm)	Left	19.41	1.59	19.21	19.62	18.06	1.54	17.85	18.27
	Right	19.33	1.62	19.12	19.54	18.01	1.55	17.80	18.22
Heel–Ankle circumference (cm)	Left	31.15	1.58	30.94	31.36	28.75	1.49	28.55	28.94
	Right	31.34	1.51	31.15	31.54	28.94	1.48	28.75	29.14
Calf girth (cm)	Left	30.08	2.33	29.78	30.39	28.07	2.74	27.70	28.44
	Right	30.16	2.35	29.85	30.47	28.03	2.73	27.66	28.40
Ball girth (cm)	Left	23.87	1.31	23.70	24.04	21.49	1.22	21.33	21.66
	Right	23.86	1.36	23.69	24.04	21.56	1.22	21.39	21.72
Instep girth (cm)	Left	23.04	1.25	22.88	23.20	20.48	1.22	20.32	20.65
	Right	23.15	1.28	22.98	23.32	20.63	1.18	20.48	20.79

Note. SD = Standard deviation; CI = Confidence interval.

Table 3 shows that there was a significant positive correlation between the variables of Set 1 (body composition) and Set 2 (foot anthropometry) among Lodha males and females, except for age and skeletal

muscle percentage. Among males, the largest correlation was found between height and bimalleolar breadth, between age, body weight, body mass index (BMI), body fat percentage, visceral fat level, and calf girth, between skeletal muscle percentage and 1st toe height. Among females, the largest correlation occurred between age and ankle height, between height and heel-ankle circumference, between body weight, body mass index (BMI), body fat percentage, skeletal muscle percentage, visceral fat level, and calf girth. These results show that the two sets of variables are correlated with each other in both males and females.

Table 3. Pearson's correlation between foot anthropometric variables and body composition measures, including age, among Lodha males and females

		Age (years)	HT (cm)	BW (kg)	BMI (kg/m ²)	BFP (%)	SMP (%)	VF
<i>Males</i>								
LMH (cm)	Left	-.098	.505**	.413**	.186**	.063	.084	.167*
	Right	-.041	.476**	.426**	.221**	.083	.039	.231**
MMH (cm)	Left	-.123	.457**	.369**	.164*	-.008	.143*	.126
	Right	-.042	.493**	.373**	.144*	.005	.056	.126
AH (cm)	Left	.112	.461**	.227**	-.012	-.078	.017	.026
	Right	.122	.457**	.227**	-.010	-.071	.001	.029
1st TH (cm)	Left	.131*	.182**	.376**	.342**	.313*	-.184**	.350**
	Right	.134*	.206**	.392**	.344**	.348**	-.176**	.367**
BM (cm)	Left	-.065	.557**	.486**	.246**	.139*	.104	.238**
	Right	-.066	.541**	.522**	.300**	.150*	.075	.294**
AC (cm)	Left	-.182*	.279**	.464**	.390**	.218**	.123	.369**
	Right	-.201*	.280**	.464**	.389**	.216**	.134*	.363**
HAC (cm)	Left	.021	.540**	.659**	.464**	.299**	-.064	.494**
	Right	-.007	.552**	.663**	.461**	.289**	-.043	.474**
CG (cm)	Left	-.270**	.411**	.875**	.815**	.549**	-.005	.729**
	Right	-.259**	.375**	.859**	.817**	.553**	-.009	.728**
BG (cm)	Left	-.113	.460**	.604**	.450**	.294**	.016	.435**
	Right	-.109	.464**	.580**	.419**	.268**	.020	.409**
IG (cm)	Left	-.163*	.449**	.656**	.523**	.291**	.045	.481**
	Right	-.193**	.466**	.647**	.501**	.278**	.071	.455**
<i>Females</i>								
LMH (cm)	Left	-.060	.439**	.282**	.109	.123	-.069	.061

Table 3 (continued on next page)

		Age	HT (cm)	BW (kg)	BMI (kg/m ²)	BFP (%)	SMP (%)	VF
MMH (cm)	Right	-.074	.359**	.270**	.128	.139*	-.096	.071
	Left	-.098	.408**	.309**	.148*	.115	-.068	.121
AH (cm)	Right	-.100	.396**	.373**	.229**	.167*	-.112	.183**
	Left	.256**	.236**	-.002	-.118	-.031	.057	-.140*
1 st TH (cm)	Right	.241**	.243**	.033	-.080	-.006	.035	-.111
	Left	.111	.095**	.297**	.285**	.288**	-.280**	.269**
BM (cm)	Right	.038	.208**	.331**	.272**	.309**	-.286**	.262**
	Left	.123	.379**	.311**	.174*	.237**	-.205**	.179**
AC (cm)	Right	.144*	.345**	.352**	.236**	.295**	-.256**	.226**
	Left	-.166*	.374**	.644**	.553**	.434**	-.366**	.485**
HAC (cm)	Right	-.180*	.406**	.671**	.568**	.458**	-.388**	.511**
	Left	.080	.598**	.645**	.444**	.487**	-.414**	.406**
CG (cm)	Right	.062	.620**	.658**	.448**	.480**	-.407**	.418**
	Left	-.105	.342**	.861**	.811**	.695**	-.634**	.704**
BG (cm)	Right	-.121	.335**	.859**	.812**	.689**	-.626**	.703**
	Left	-.002	.356**	.455**	.338**	.316**	-.262**	.294**
IG (cm)	Right	-.022	.351**	.477**	.365**	.331**	-.274**	.333**
	Left	-.015	.350**	.537**	.434**	.392**	-.339**	.380**
	Right	-.036	.356**	.534**	.427**	.389**	-.334**	.375**

Table 4 shows the result of canonical correlation analysis (CCA) between two sets, set 1-age and body composition measures, and set 2-foot anthropometric variables, among Lodha males and females. The full canonical correlation analysis process was restricted to extracting seven orthogonal (uncorrelated) functions because the independent set contained a maximum of seven variables.

Table 4: Canonical correlation analysis of foot anthropometric variables and body composition measures, including age, among the Lodha population.

Can. func.	Eigen value	Variance (%)	Cum. variance (%)	Can. corr.	Squared can. corr.	Wilks statistic	F value	p value
<i>Males</i>								
1	7.086	80.23	80.23	.939	.882	.033	6.463	.000
2	1.113	12.60	92.83	.726	.527	.266	2.658	.000
3	.285	3.23	96.06	.471	.222	.561	1.389	.012

Can. func.	Eigen value	Variance (%)	Cum. variance (%)	Can. corr.	Squared can. corr.	Wilks statistic	F value	p value
4	.197	2.23	98.48	.406	.165	.722	1.024	.427
5	.078	0.88	98.29	.269	.072	.864	0.642	.971
6	.051	0.58	98.87	.220	.048	.931	0.500	.988
7	.022	0.25	100	.148	.022	.978	0.331	.989
<i>Females</i>								
1	4.185	72.85	72.85	.898	.806	.058	4.816	.000
2	1.017	17.71	90.56	.710	.504	.301	2.231	.000
3	.246	4.28	94.84	.444	.197	.606	1.118	.221
4	.166	2.89	97.73	.377	.142	.756	0.818	.850
5	.066	1.16	98.89	.248	.061	.881	0.519	.997
6	.046	0.80	99.69	.210	.044	.939	0.414	.998
7	.019	0.30	100	.135	.018	.982	0.259	.997

Note. Can. func. = canonical function; Cum. variance = cumulative variance; Can. corr. = canonical correlation.

Males: In the 1st function, the canonical correlation (R_c) between Set 1 and Set 2 variables was found to be .939. The 2nd and 3rd functions had canonical correlations of .726 and .471. The 4th, 5th, 6th, and 7th functions had even lower canonical correlations. The squared canonical correlation (R_c^2) denotes the proportion of variance (i.e., variance-accounted-for effect size) shared by the two canonical variates. As the canonical variates represent the observed independent and dependent variables, R_c^2 also indicates the amount of shared variance between the two variable sets, which is directly equivalent to the R^2 effect in multiple regression (Sherry & Henson, 2005). The 1st squared canonical correlation coefficient (1st function) (R_c^2) revealed that the two canonical variates derived from Set 1 and Set 2 linearly share 88.2 % of the variance (shared variance). In the 2nd function, the two canonical variates derived from Set 1 and Set 2 linearly share 52.7 % of the variance. The 3rd function revealed that the two canonical variates linearly share 22.2% of the variance. Similarly, the shared variances between Set 1 and Set 2 in functions 4, 5, 6, and 7 were lower, and all of them lacked statistical significance. Interestingly, the 1st canonical function explains 80.23% of the total variance (derived from eigenvalue). The 2nd function deals with the residual variance of the first one, i.e., 12.60%. The 3rd function deals with 3.23% of the total variance. The remaining variance of 3.94% is shared between the other functions. Only the first three canonical functions made a statistically significant contribution to the model ($p < .05$). The first three canonical functions had larger effect sizes (R_c^2) and had larger cumulative contributions of the first three pairs of canonical variables (functions 1, 2, and 3), which accounted for 96.06%.

Females: In the 1st function, the canonical correlation (R_c) between Set 1 and Set 2 variables was found to be .898. The 2nd function had a canonical correlation of .710. The 3rd, 4th, 5th, 6th, and 7th functions had lower canonical correlations that did not reach conventional statistical significance. 1st squared canonical correlation coefficient (1st function) (R_c^2) revealed that the two canonical variates derived from Set 1 and Set 2 linearly share 80.6 % of the variance (shared variance). In the 2nd function, the two canonical variates derived from Set 1 and Set 2 linearly share 50.4 % of the variance (shared variance). The 1st canonical function explains 72.85 % of the total variance (derived from eigenvalue). The 2nd function deals with the residual variance of the first one, i.e., 17.71 %. The remaining variance of 9.4% is shared between the other functions. Only the first two canonical functions made a statistically significant contribution to the model ($p < .001$).

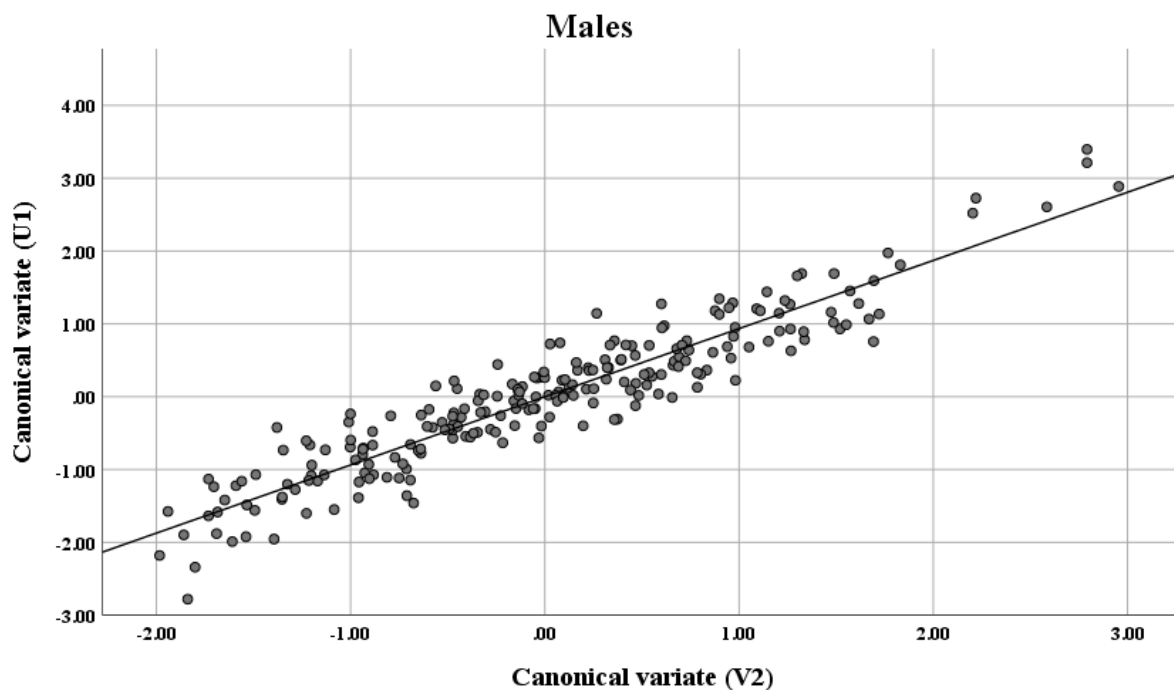
Table 5 shows the redundancy index for independent and dependent canonical variates of the chosen functions (Function 1 and Function 2 in both sexes and Function 3 in males).

Table 5: Redundancy analysis for canonical correlation analysis: proportion of variance explained

Can. var.	Males				Females			
	Set 1 by self	Set 1 by Set 2	Set 2 by self	Set 2 by Set 1	Set 1 by self	Set 1 by Set 2	Set 2 by self	Set 2 by Set 1
1	.416	.365	.341	.299	.532	.429	.316	.255
2	.129	.068	.180	.095	.122	.062	.117	.059
3	.342	.076	.035	.008	–			

Note. Can. var. = canonical variable

In males, the 1st function had higher indexes of redundancy for the independent variables (.365) and the dependent variables (.299) than the 2nd function (.068 and .095, respectively) and the 3rd function (.076 and .008, respectively). In females, the 1st function has higher indexes of redundancy for the independent variables (.429) and the dependent variables (.255) than the 2nd function (.062 and .059, respectively). The 2nd function in both sexes and the 3rd function in males had no practical significance, even though they were found to be statistically significant (Hair et al., 2004). The redundancy analysis reduces the multiple significant functions into a single relevant function, further simplifying the interpretations of the interrelationship between two sets of variables. The loadings and cross-loadings of Function 1 have been investigated in detail. Fig. 2a and Fig. 2b represent scatterplots between the scores of the first pair of canonical variates (Function 1) of males and females, depicting a strong correlation between the two canonical variates.

**Figure 1a:** Scatterplot between the scores of the first pair of canonical variates (Function 1) of males

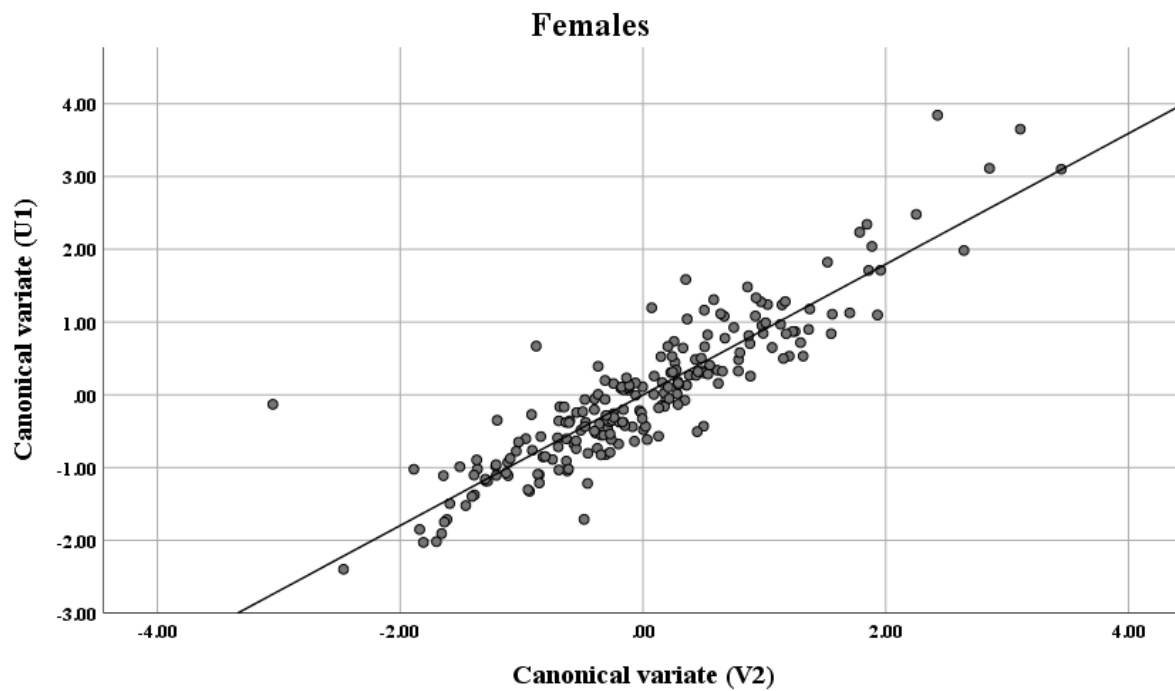


Figure 1b: Scatterplot between the scores of the first pair of canonical variates (Function 1) of females

Table 6: Loadings (structure coefficients) and cross-loadings of the variables for the 1st canonical function among Lodha males and females

		1 st Canonical Function					
		Males			Females		
		Loadings	Squared loadings	Cross loadings	Loadings	Squared loadings	Cross loadings
<i>Set 1: Age and Body Composition measures (Independent set)</i>							
Age (years)		-.277	.080	-.259	-.111	.012	-.099
HT (cm)		.469 ^a	.219	.439	.490 ^a	.240	.440
WT (kg)		.953 ^a	.908	.892	.994 ^a	.988	.893
BMI (kg/m ²)		.874 ^a	.764	.818	.889 ^a	.790	.799
BFP (%)		.576 ^a	.332	.539	.775 ^a	.601	.697
SMP (%)		-.001	.000	-.001	-.694 ^a	.481	-.624
VF		.784 ^a	.615	.734	.780 ^a	.608	.700
<i>Set 2: Foot anthropometric variables (Dependent set)</i>							
LMH (cm)	Left	.409	.167	.383	.328	.107	.295
	Right	.418	.175	.391	.313	.098	.281
MMH (cm)	Left	.370	.134	.346	.355	.126	.319
	Right	.338	.114	.316	.429	.184	.385
AH (cm)	Left	.168	.028	.157	.005	.000	.005
	Right	.163	.027	.153	.045	.002	.041
1 st TH (cm)	Left	.382	.146	.357	.322	.104	.290

		1 st Canonical Function					
		Males			Females		
		Loadings	Squared loadings	Cross loadings	Loadings	Squared loadings	Cross loadings
BM (cm)	Right	.414	.171	.388	.363	.132	.326
	Left	.520 ^a	.270	.487	.342	.117	.307
AC (cm)	Right	.546 ^a	.298	.511	.390	.152	.350
	Left	.556 ^a	.309	.521	.729 ^a	.531	.655
HAC (cm)	Right	.558 ^a	.311	.522	.757 ^a	.573	.680
	Left	.675 ^a	.456	.632	.721 ^a	.520	.648
CG (cm)	Right	.680 ^a	.462	.637	.735 ^a	.540	.660
	Left	.987 ^a	.974	.924	.962 ^a	.925	.865
BG (cm)	Right	.975 ^a	.951	.913	.962 ^a	.925	.864
	Left	.653 ^a	.426	.611	.514 ^a	.264	.462
IG (cm)	Right	.623 ^a	.388	.583	.539 ^a	.291	.484
	Left	.712 ^a	.507	.666	.604 ^a	.365	.543
	Right	.707 ^a	.499	.662	.601 ^a	.361	.540

Note. ^a Loading (structure coefficient, r_s) $\geq .45$ (Sherry & Henson, 2005). Abbreviations: HT—Height, WT—Body weight, BMI—Body mass index, BFP—Body fat percentage, SMP—Skeletal muscle percentage, VF—Visceral fat level, LMH—Lateral malleolus height, MMH—Medial malleolus height, AH—Ankle height, 1st TH—1st toe height, BM—Bimalleolar breadth, AC—Ankle circumference, HAC—Heel-ankle circumference, CG—Calf girth, BG—Ball girth, IG—Instep girth.

Table 6 presents the loadings (structure coefficients) and cross-loadings of the variables for the 1st canonical function among Lodha males and females.

Males: The loadings of the body composition variables in the 1st canonical function revealed that except for age and skeletal muscle percentage, most other body composition measures including height, weight, BMI, body fat percentage, and visceral fat level had high canonical loadings, exceeding $|0.45|$. Thus, they made the most important contribution to the first canonical variate of their own set (Set 1: independent set). In the second set (Set 2, dependent set), loadings of the foot anthropometric variables on the 1st canonical function revealed that bimalleolar breadth, ankle and heel-ankle circumference, calf, ball, and instep girth loaded most strongly on the first canonical variate of their own set. This conclusion was primarily supported by the squared loadings (squared structure coefficient, r_s^2), which describe the amount of shared variance between the identified significant observed variables and their own canonical variate (Sherry & Henson, 2005). The loadings of the significant variables of the independent set (body composition) and dependent set (foot anthropometry) had the same sign (positive), indicating that they had a positive relationship (Figure 3a).

The cross-loading values revealed that weight, height, BMI, body fat percentage, and visceral fat level had high correlations with the canonical variate of foot anthropometric variables. These identified significant variables had a higher shared variance with the set of dependent variables (foot anthropometry). From the dependent set, bimalleolar breadth, ankle, and heel-ankle circumference, calf, ball, and instep girth exhibited high correlations with the canonical variate of the opposite set and were highly influenced by the changes in the independent variables (body composition). The variables with higher loading on their own canonical variate also had higher cross-loadings. The signs of cross-loadings of the identified variables from both sets are positive, depicting a positive relationship. Therefore, the malleolar and girth region of the foot was wider among taller and heavier males with higher body fat percentage and visceral fat, and slenderer among shorter and thinner males with lower body fat percentage and visceral fat.

Females: The loadings of the body composition variables for the 1st canonical function revealed that, except for age, all the body composition measures had high canonical loadings exceeding $|0.45|$,

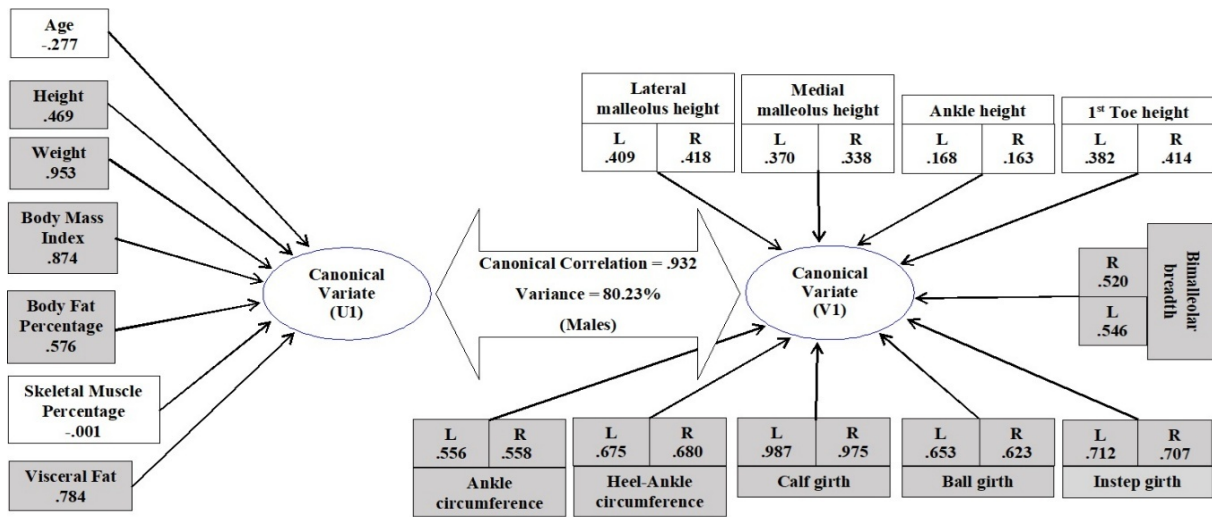


Figure 3a: Relationship between body composition and foot anthropometric variables among adult Lodha males based on loading values (structure coefficients)

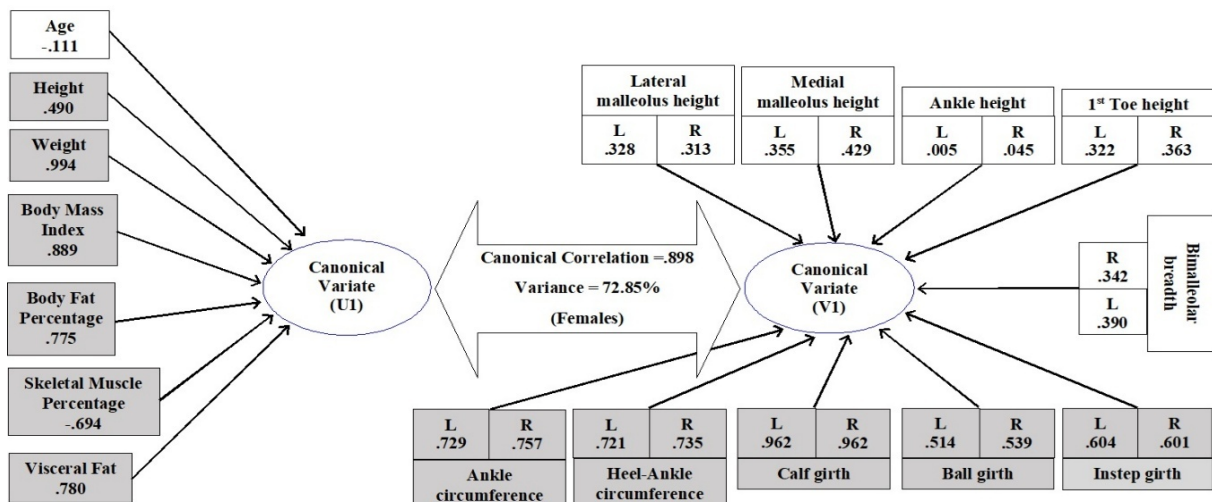


Figure 3b: Relationship between body composition and foot anthropometric variables among adult Lodha females based on loading values (structure coefficients)

and made a significant contribution to the first canonical variate of their own set (Set 1: independent set). Loadings of the foot anthropometric variables for the 1st canonical function revealed that ankle and heel-ankle circumference, calf, ball, and instep girth were the variables that contributed most to the first canonical variate of their own set (Set 2: dependent set). High values of squared loadings (r_s^2) supported this conclusion. The loadings of the significant variables of the independent set (body composition) and dependent set (foot anthropometry) had a positive sign, indicating a positive relationship, except for the loading of skeletal muscle percentage, which displayed a negative sign, indicating a negative (inverse) relationship (Figure 3b).

The cross-loadings revealed that all the body composition measures had a high correlation with the canonical variate of the opposite set. From the dependent set, ankle and heel-ankle circumference, calf, ball, and instep girth exhibited a high correlation with the canonical variate of the opposite set. The variables with higher loading also had higher cross-loading values. Except for skeletal muscle percentage, the sign of cross-loading values of all the identified variables from both sets was positive. Thus, height, weight, BMI, percent body fat, and visceral fat level were positively correlated, and skeletal muscle percentage was negatively correlated with ankle and heel-ankle circumference, calf, ball, and instep girth. Therefore, the girth region of the foot was wider among taller and heavier females with higher body fat percentage and visceral fat, and a lower skeletal muscle percentage, and slenderer among shorter and thinner females with lower body fat percentage and visceral fat and a higher skeletal muscle percentage.

3 Discussion

The present study, the first of its kind, assessed a multivariate relationship between body composition measures and foot anthropometric variables of the adult Lodha population using Canonical Correlation Analysis (CCA). Males were found to be taller, heavier, and have higher percentages of skeletal muscle and visceral fat than females. Females were found to have larger percentages of body fat than males. This confirms that women have proportionally more fat mass and males have more muscle mass (Schorr et al., 2018). Females typically accumulate adipose tissue around the hips and thighs. In contrast, males are more likely to accumulate adipose tissue around the trunk and abdomen (Bredella, 2017), as evidenced by higher visceral fat level in males in the present study.

When foot anthropometric variables were compared between males and females, it became apparent that males have larger feet with larger width, girth, and circumferential dimensions than females. This is consistent with the prior research that males have considerably longer, wider, and higher feet than females (Baba, 1974; Chaiwanichsiri et al., 2008; Hong et al., 2011; Krauss et al., 2008; Lee & Wang, 2015; Luo et al., 2009; Wunderlich & Cavanagh, 2001; Zhao et al., 2017). Males experience a longer growth phase of bone, including higher bone metabolism and mineralization due to high levels of testosterone. As a result, male bones are heavier and more robust in structure than female bones. These size differences in the bones of males and females are consequently represented in the anthropometric dimensions of the foot, resulting in larger foot dimensions in males (Addai et al., 2018; Bindurani et al., 2017; Ibeabuchi et al., 2018; Kadu & Yadav, 2020; Rahman et al., 2014).

When compared to other populations, ethnic disparities in dimensions of foot anthropometric variables were also observed. The medial malleolus height of adult Lodha males was found to be greater than the foot height (analogous to the medial malleolus height in the present study) of Santhal and Bengalee males (Ahmed et al., 2015). Similarly, Japanese and Taiwanese females had lower sphyrion height and fibular sphyrion height (analogous to medial and lateral malleolus height in the present study) (Lee et al., 2015) than the Lodha females in the present study. Similar findings had been reported by Hajaghazadeh et al. (2018) among North Iranian males. Mean 1st toe height among males of the North American population (Hawes & Sovak, 1994) was found to be lower than in the present study, but the opposite was reported by Lee & Wang (2015) among Japanese adults. Thus, Lodha males and females had taller feet than North American males, Santhal and Bengalee males, and Japanese and Taiwanese females, but shorter feet than Japanese adults.

Girth measurements were found to be higher among North Americans (Hawes & Sovak, 1994), Japanese and Taiwanese (Lee & Wang, 2015; Lee et al., 2015), Malay, Chinese, and Indians (Shariff et al., 2018) and North Iranians (Hajaghazadeh et al., 2018) than among the adult Lodha males and females of the present study, and lower among Japanese adults (Zhao et al., 2017). Furthermore, Lodha women were found to have smaller calf girth than Maasai and Korean women (Choi et al., 2014, 2015). Thus, the Lodha population of the current research exhibits a taller and slenderer foot shape than the majority of the populations across the globe. Such significant foot shape variation can be explained through genetic background, selective adaptation to various climatic zones or geographical regions, livelihood practices, and lifestyle factors (shoe-wearing habits), i.e., going barefoot or habitually or daily using different footwear (Ashizawa et al., 1997; Choi et al., 2015; Kouchi, 1998; Kusumoto et al., 1996; Oria et al., 2017).

Foot morphology also varies due to body weight and nutritional and socioeconomic status (Kouchi, 1998, 2003). Lodhas, the particularly vulnerable tribal group of Paschim Medinipur, are socioeconomically underdeveloped and have critical nutritional conditions (Bepari et al., 2015; Das & Bose, 2015), as illustrated in Table 2. Thus, slenderer foot shape among Lodhas could be intricately linked to nutrition and socioeconomic conditions that contribute to the development of the unique foot morphology among Lodhas.

In the present study, height showed the highest significant positive correlation with bimalleolar breadth (in males) and heel-ankle circumference (in both males and females). Height was also found to be significantly positively correlated with the majority of the foot anthropometric variables. Similar findings had been established by Singh & Phookan (1993), Tobias et al. (2014), and Ibeabuchi et al. (2020). Otherwise, body weight, BMI, body fat percentage, and visceral fat level exhibited the highest significant positive correlation with calf girth across both sexes, and skeletal muscle percentage showed the highest significant negative correlation with calf girth exclusively in females. This conclusion was reinforced by the findings of other investigations (Bonnefoy et al., 2002; de Lucena Ferretti et al., 2023; Durga et al., 2022; Khadivzadeh, 2002; Portero-McLellan et al., 2010). Calf girth is sensitive to muscle mass and body fat as it reflects whole body muscle mass as well as skeletal mass in addition to subcutaneous fat and fat-free mass (Baumgartner et al., 1995; González-Correa et al., 2020; Jonathan et al., 2013; Maeda et al., 2017; Slemenda, 1990; Tsai & Chang, 2011). Thus, the higher the muscle mass and body fat, the wider the foot. Body weight and BMI were significantly positively correlated with most of the foot anthropometric variables. This outcome was consistent with Ashizawa et al. (1997), Domjanić et al. (2013), and Chatha & Mohammad (2020).

Very few studies have examined the influence of being underweight on foot morphology, leaving a significant research void. The prevalence of flat feet among underweight males and females was reported as 24.83% and 36.36%, respectively (Vijaykumar et al., 2016). Ripka et al. (2017), Alimuddin et al. (2020), and Pathan et al. (2022) established the prevalence of high arch and flat arch among underweight participants. Thus, the underweight population has been found to have diminished and falling arches, which is a deviation from normal foot structure, but the etiology of such instances is unknown. Underweight populations are also vulnerable to gait problems and injury, as a serious lack of body mass can induce divergence from normal foot anatomy as well as alterations in fundamental motor functions like gait and postural balance, which can lead to various injuries (Tojo et al., 2018; Vangara et al., 2016). Because the nutritional status of the Indian tribal community is critical (Das & Bose, 2015), and no studies have focused on how body composition shapes foot morphology in ethnic populations of India, the present study focuses on the composite effect of body composition on height, width, and girth measurements of the foot among the Lodha population.

In the CCA analysis, the model depicted that, in males, the most significant predictors of bimalleolar breadth, ankle and heel-ankle circumference, calf, ball, and instep girth were height, weight, BMI, body fat percentage, and visceral fat level. Similarly, in females, the most significant predictor of ankle and heel-ankle circumference, calf, ball, and instep girth was found to be weight, height, BMI, body fat percentage, skeletal muscle percentage, and visceral fat level. Positive cross-loading values indicated that foot shape, particularly the malleolar region (in males) and girth region (both in males and females), was wider among taller and heavier participants with higher body fat percentage, and the shape was slenderer among shorter and thinner participants with lower body fat percentage. The results of several studies indirectly supported these findings (Güven et al., 2009; Price & Nester, 2016; Tománková et al., 2015; Zhao et al., 2017). No studies

linking skeletal muscle percentage and visceral fat level to foot morphology parameters have been reported so far in adults. The present study's findings are the first to address these relationships. Skeletal muscle percentage in females exhibited a significant negative correlation, and visceral fat level in both males and females exhibited a significant positive correlation with the majority of the foot anthropometric measures.

CCA analysis reported that the malleolar and girth region of the foot was wider among males with higher visceral fat, and slenderer among males with lower visceral fat. Furthermore, females with a lower percentage of skeletal muscle and more visceral fat had a wider foot girth, and the converse was observed among females with a higher percentage of skeletal muscle and less visceral fat. Skeletal muscle accounts for 40% of the total body weight (Kim et al., 2016), and visceral fat accounts for 10% of total body fat (Kadir & Mokodompis, 2023; Pausova, 2014). Ghosh & Malik (2010) reported that Santhal female labourers engaged in back-breaking work are lean to fat but muscular, whereas males were found to be lean and muscular. Lodha males and females engage in substantial agricultural and non-agricultural activity, resulting in a lean and muscular body shape. This is also evident from the foot anthropometric measurements of the present study.

The present study has some limitations. It was restricted to a single homogeneous ethnic population. So, findings cannot be generalized. Collecting data on the prevalence of foot-related symptoms could have made the study more extensive.

4 Conclusions

The present study of the adult Lodha population is among the limited studies that assessed the relationship between body composition measures and foot anthropometric variables using multivariate analysis. Height, weight, body mass index (BMI), body fat percentage, skeletal muscle percentage, and visceral fat level significantly shape the height, breadth, and girth of the foot. Any divergence from normal foot anatomy is likely to affect basic motor functions, leading to various ailments such as foot pain, loss of postural balance, and gait problems. Thus, raising awareness concerning foot health and addressing foot shape and dimension issues in adult tribal populations is crucial. Furthermore, India is a multi-ethnic country, and studies focusing on assessing the multivariate relationship between body composition measures and foot anthropometric variables in different ethnic groups will enable more sensitive comparisons between populations and establish population-specific standards. It is firmly believed that the findings of the present study will also contribute new knowledge to public health. To make generalizations, conducting research among diverse populations from different geographical locations is pertinent.

Acknowledgements: The authors are indebted to all the study participants who volunteered to participate in this study and wish to express gratitude for their cooperation.

Declaration of conflicting interests: The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding statement: The present study was supported by the University Grants Commission, India [Grant Ref. No. 190510581825, Dated: 29.11.2019].

Availability of data: The data sets analysed in the present study were collected for a doctoral dissertation. The authors would like not to publish the data for public access, as the doctoral degree has not yet been awarded.

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