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Morphostructural diversity, body typology, and phenotypic classification reveal distinct biotype subpopulations in extensively raised Q'ara llamas (*Lama glama*)

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Abstract

The objective of this study was to evaluate the morphostructural diversity, body conformation, and typological classification of extensively raised Q'ara llamas in the south-central Peruvian Andes. A total of 196 llamas were randomly selected from Chuschi (n=96) and Chipao (n=100) districts. The effects of district, sex, and age on zoometric measurements and indices were analyzed using generalized linear model (GLM) and Multivariate Analysis. Male Chuschi: [Neck length (NL) (65.90±0.67), posterior neck circumference (RNC) (48.90±0.88), height at the withers (WH) (103.00±0.90), chest width (CW) (25.40±0.42), Perimeter thoracic (PT) (120.00±1.29), and dorsosternal diameter (DSD) (44.50±0.41)] were broader and taller compared to female from Chuschi and those from Chipao ($p<0.05$). Female llama from Chuschi showed harmonious development of PT and DSD as they aged ($p<0.05$); among males, group with four permanent incisors (4D) showed the greatest increase in PT ($p<0.05$). In Chipao, females in group with two permanent incisors (2D) had RNC; in males, [(WH), Rump height (RL), rump width (RW), CW, PT and DSD] increased from the 2D group with complete dentition (CD), indicating harmonious growth ($p<0.05$). The llamas from the Chuschi district are more compact and heavier than those from Chipao. Multivariate Analysis revealed no strict separation between individuals by location, and grouped females into three clusters by body size. In conclusion, these findings demonstrated that

there was low morphostructural variability among Q'ara llama populations. The detected biotypic subpopulations provide a valuable basis for the implementation of conservation policies and the selection of breeding animals.

Keywords: Zoometric traits; Body conformation indices; Morphotype; Biotype; Llama

1. Introduction

Llama husbandry is one of the most important economic activities for small and medium-scale producers in the Andean highlands, particularly those with limited economic resources (Instituto Nacional de Innovacion Agraria-INIA). Since domestication, llamas have played a key role in food security for Andean families, serving as a source of meat, fiber, hides, and manure, which are critical to household economies (Zarrin et al., 2020). After Bolivia, Peru has the second largest population of llamas in the world, with over 1,075,480 individuals (INEI, 2012; MINAGRI, 2022).

Llamas possess remarkable attributes, including their ability to thrive in harsh, high-altitude environments. Their padded feet contribute to sustainable soil and plant management, and their selective grazing habits help protect fragile ecosystems (Mallma et al., 2021; MIDAGRI, 2019). In recent years, llama production has drawn increased scientific attention, with local governments beginning to integrate this species into livestock development plans due to their resilience in poor pasture environments (Roque and Ormachea, 2018). Despite these strengths, llamas remain undervalued within the regional livestock production chain. Extensive and mixed farming systems prevail, with little emphasis on genetic improvement programs (MIDAGRI, 2019).

Several studies have documented the phenotypic and genetic characteristics of llamas in various South American countries, particularly in Peru, which is essentially one of the first steps toward the sustainable use of an animal resource (Yacobaccio, 2010; Quispe et al., 2015; Paredes Rojas, 2012; Ormachea et al., 2022; Merlo-Maydana et al., 2024). Native animals such as llamas are invaluable, irreplaceable sources of genetic diversity. Their recognition, conservation, and promotion hold scientific, cultural, and ethical importance (Antunović et al., 2007; Maksimović et al., 2023). However, the llama faces displacement issues and decline population due to the introduction of new livestock species, such as cattle and sheep (INIA). For this reason, it is considered a vulnerable species that requires a specific conservation plan. Furthermore, there are few reports on this important zoogenetic resource, which is native to the Andes.

Phenotypic variation in animal populations results from adaptation to specific environments, driven by evolutionary forces such as mutation, selection, and migration that influence allele frequency (Deribe et al., 2021). Understanding the morphostructural diversity, body typology, and phenotypic traits of local llamas through zoometric studies enables the evaluation of body and ethnological indices, which help predict the productive orientation of the species (Ormachea et al., 2020; Ormachea et al., 2021).

Zoometric characterization involves describing and interpreting the physical traits of a local genotype or breed (Scherf and Pilling, 2019). Morphometric evaluation has been considered a foundational tool in developing conservation and genetic improvement programs (Deribe et al., 2021). Effective breeding programs rely on sustainable use of genetic variability within an ecosystem, aiming to enhance productive traits and standardize morphometric features (Monau et al., 2020). However, morphometric traits of llamas in many Andean regions remain poorly documented, despite their use as phenotypic markers for animal selection.

For example, traits such as pelvic area, thoracic perimeter, and thigh volume are potential indicators of meat production capacity, while early life body weight has been widely used as a selection criterion (Leyva and Falcón, 2012; Zea et al., 2012). The increasing consumption of llama meat, owing to its nutritional quality, highlights the need to improve productive traits (Canaza-Cayo et al., 2015). However, the lack of phenotypic standards and meat yield benchmarks limits the development of market-oriented llama farming systems (Canaza-Cayo et al., 2015). Given these gaps and the relevance of generating information, the objective of this study was to evaluate the morphostructural diversity, body typology, and phenotypic classification of extensively raised Q'ara llamas in the south-central Peruvian Andes.

2. Materials and Methods

2.1. Ethical statement

The farmers gave their written consent to record the zoometric characteristics of the animals and the photographic panel in Fig. 3. The authors declare that the research was conducted in accordance with the European Union Code of Conduct (http://ec.europa.eu/environment/chemicals/lab_animals/legislation_en.htm) and Peruvian National Law No. 30407, "Animal Protection and Welfare" for studies involving animals.

2.2 Study area

The study was conducted in the districts of Chuschi and Chipao (**Fig. 1**), located in the Ayacucho region (southern Peru). These areas are characterized by cold-dry climates (~4,200 meters above sea level), with a short rainy season from December to March and a long dry season from April to November. Temperatures range from 0.1°C (July) to 28.7°C (November), with an annual mean of 7°C and annual rainfall averaging 400 mm (SENAMHI, 2018).

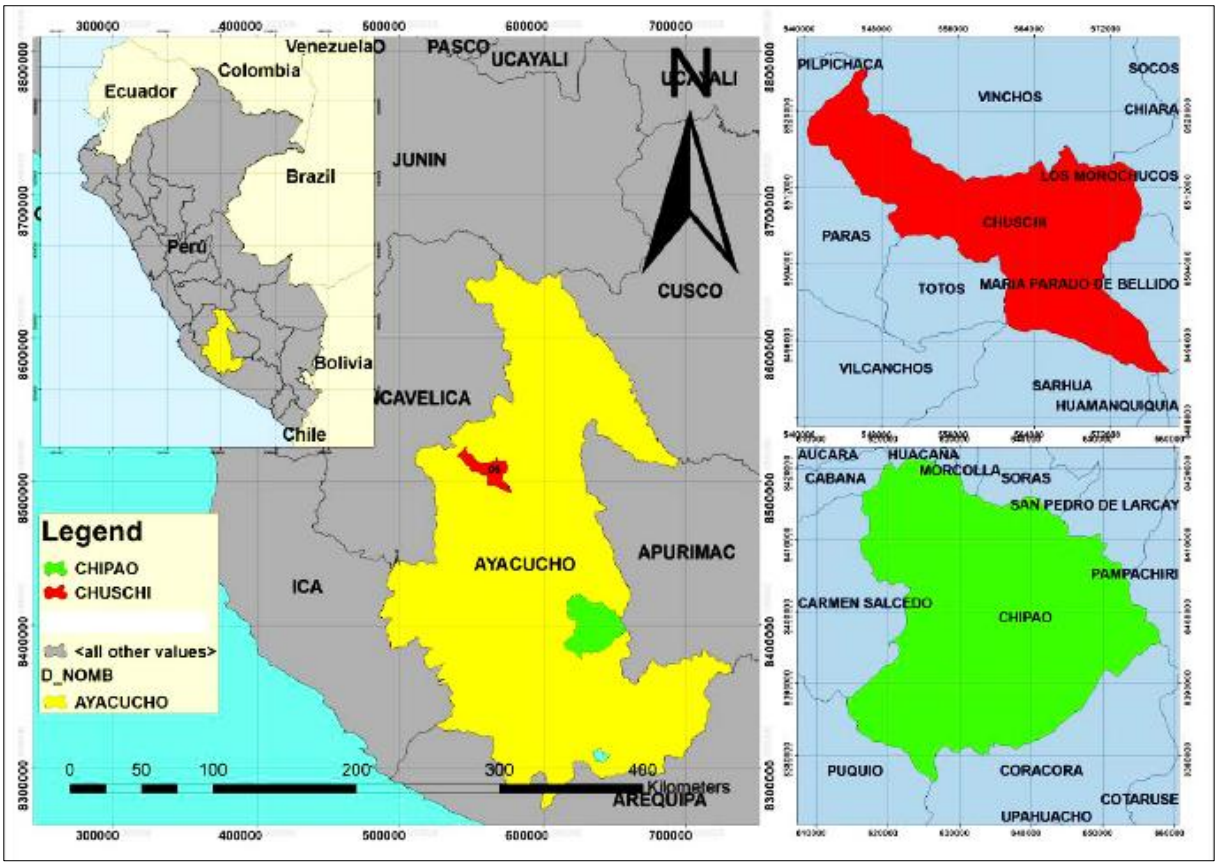

Fig. 1 Location of sample collection

2.3. Animal management

The ecosystem in which llama rearing takes place is characterized by gentle slopes, small wetlands (bofedales), and vast expanses of grasslands, with vegetation composed of native grasses, sedges, rosaceae, asteraceae, and leguminous species. Llamas primarily feed on fiber-rich grasses, particularly Nassella brachyphylla (*Stipa brachyphylla*), Jarava ichu (*Stipa ichu*), Bromus catharticus (*Bromus unioloides*) and *Festuca rigescens*, which belongs to the Poaceae family. (Trillo et al., 2021).

2.4 Study design and sampling procedure

A descriptive cross-sectional study was conducted between August and December 2024. Llamas were randomly selected to minimize selection bias in biotype representation, ensuring that each individual in the population had an equal probability of being included in the sample (Otzen and Manterola, 2017). The sample size was determined using a 95% confidence level and an absolute precision of 7%, applying the standard formula for minimum sample size estimation in populations of known size:

$$n = \frac{N * (Z)^2 * (p * q)}{(d)^2 * (N - 1) + ((Z)^2 * (p * q))}$$

Where ‘N’ = sample size; ‘Z’ = confidence level; ‘p’ = probability of the event occurring; ‘q (1 − p)’ = probability of the event not occurring; ‘d’ = margin of error.

A total of 196 llamas (52 males and 144 females) over two permanent incisors (2D) were selected from the districts of Chuschi (n = 96) and Chipao (n = 100). Each district contributed seven herds, ranging from 12 to 15 llamas per herd, depending on herd size, with a similar representation of animals across age group. The adult (CD) category was the most represented, accounting for 57.1% of the total sample (Table 1). Only animals showing clear Q’ara breed characteristics were included in the study, which was distinguished by a well-proportioned body with short, less voluminous wool, an angular build, and a slender frame, a hairless head, and a neck covered with short fibers and hairs along the back edge, excluding intermediate and Ch’aku phenotypes.

Table 1. Distribution of sampled Q’ara llamas (*Lama glama*).

District	Herds (n)	Male	Female	Age 2D	Age 4D	Adult (CD)
Chipao	7	23	77	27	15	58
Chuschi	7	29	67	24	18	54
Total	14	52	144	51	33	112

2.4. Zoometric traits and indices

Thirteen zoometric traits were recorded following anatomical landmarks, using a millimeter tape and a wooden measuring stick (zoometric bar) with Vernier-type precision. The measurements included: Wither Height (WH), Chest Width (CW), Rump Length (RL), Rump Height (RH), Rump Width (RW), Body Length (BL), Front Cannon Bone Circumference (FCBC), Rear Cannon Bone Circumference (RCBC), Thoracic Thoracic Perimeter (TP), Dorsal-Sternal Diameter (DSD), Neck Length (NL), Front Neck Circumference (FNC), and Rear Neck Circumference (RNC) (Table 2; Fig. 2).

Table 2. Zoometric Measurements Recorded in Q’ara Llamas

Measurement (Abbr.)	Anatomical Description	Reference(s)
Wither Height (WH)	Distance (cm) from the top of the withers to the ground.	Ablondi et al., 2023
Chest Width (CW)	Distance (cm) between the right and left scapulo-humeral joints.	Quispe et al., 2020
Rump Length (RL)	Distance (cm) from the hip point to the ischial tuberosity.	Ablondi et al., 2023

Rump Height (RH)	Distance (cm) from the ground to the highest point of the rump.	Ablondi et al., 2023
Rump Width (RW)	Distance (cm) between the outermost points of the hips.	Ablondi et al., 2023
Body Length (BL)	Distance (cm) from the scapulo-humeral joint to the ischial tuberosity.	Ablondi et al., 2023
Front Cannon Circum. (FCBC)	Circumference (cm) of the mid-metacarpal region.	Ormachea et al.,2022
Rear Cannon Circum. (RCBC)	Circumference (cm) of the mid-metatarsal region.	Ormachea et al.,2022
Thoracic Perimeter (TP)	Circumference (cm) passing over the sternum and seventh thoracic vertebra.	Ablondi et al., 2023
Dorsal-Sternal Diameter (DSD)	Distance (cm) from the dorsal line to the sternal region.	Ormachea et al.,2022
Neck Length (NL)	Distance (cm) from the atlanto-occipital joint to the front of the scapulo-humeral joint.	Ormachea et al.,2022
Front Neck Circum. (FNC)	Circumference (cm) between the 1st and 2nd cervical vertebrae.	Ormachea et al.,2022
Rear Neck Circum. (RNC)	Circumference (cm) between the 6th and 7th cervical vertebrae.	Ormachea et al.,2022

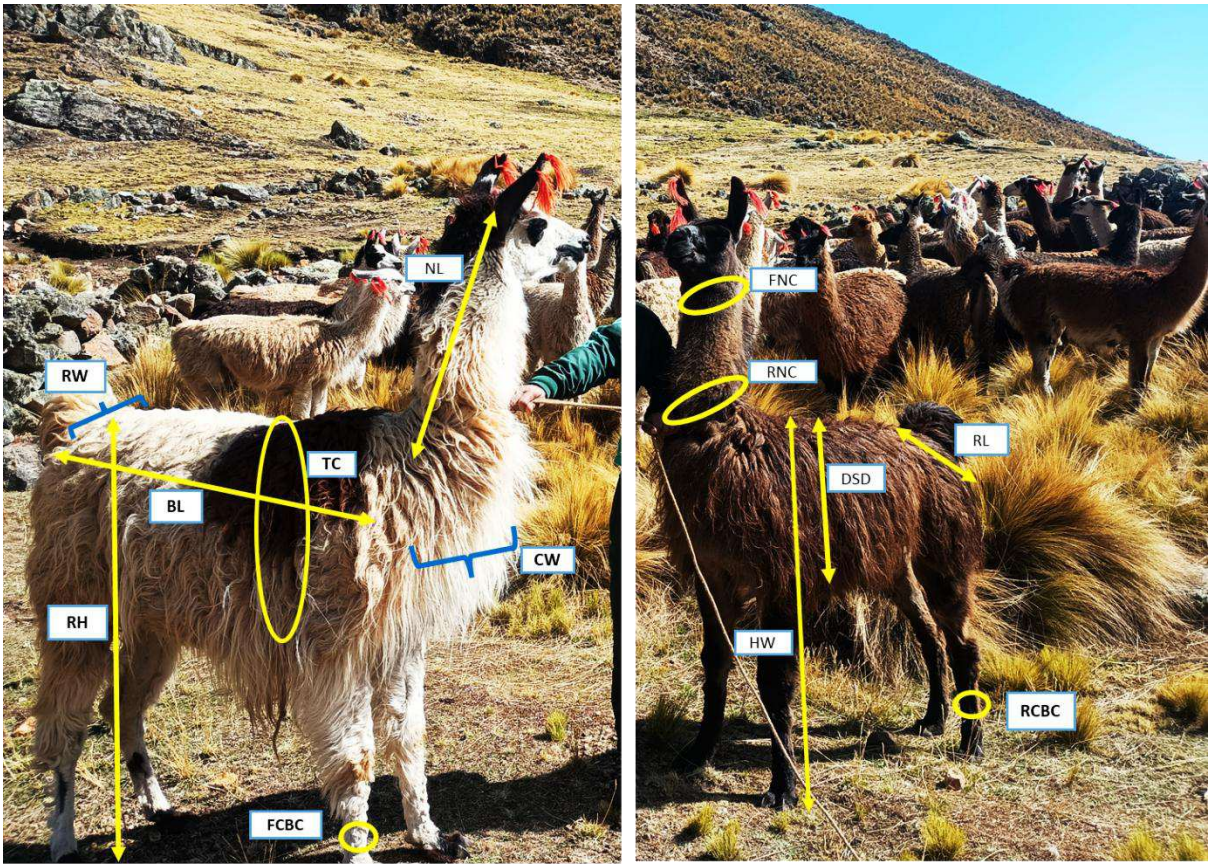

Fig. 2 Zoometric variables evaluated in Q'ara llamas(*Lama glama*).

The following zoometric indices were estimated based on the recorded body measurements: Body Index (BI = BL/TP × 100), Pelvic Index (PI = RW/RL × 100), Proportionality Index (PPI = WH/BL × 100), Dactyl-Thoracic Index (DTI = FCBC/TP × 100), Transversal Pelvic Index (TPI = RW/WH × 100), Longitudinal Pelvic Index (LPI = RL/WH × 100), Relative Cannon Thickness Index (RTI = RCBC/WH × 100), Anamorphosis Index (AI = TP^2/WH), and Thoracic Development Index (TDI = TP/WH) (Getaneh et al., 2022; Lendechy et al., 2023).

2.5. Statistical analysis

Descriptive statistics were applied to the quantitative linear zoometric traits for all animals (females and males). For inferential analysis, estimated marginal means (EMMs), and standard error (S.E.) were estimated by district, sex, and age group using emmeans software package (Lenth, 2023). Zoometric characteristics and indices were analyzed using a generalized linear model (GLM). A gamma probability distribution was used for model fitting. District, sex, and age were included as fixed effects. Due to sample imbalance between sexes and age groups, differences were assessed using a Type III ANOVA. Means by age groups were compared using Tukey's post hoc test. Additionally, from the raw data the coefficients of variation (CV) were calculated to determine the degree of relative dispersion of the analyzed variable.

$$Yijk = \mu + Di + Sj + Ak + \varepsilon ijk$$

Where; Yijk = body measurements and zoometric indices, μ = general mean, Di= i-th district effect (i = 1, 2), Sj = j-th sex effect (j = 1, 2), Aj = j-th age effect (j = 1, 2, 3), εijk = residual

For the multivariate analysis, only data from females were selected in order to ensure homogeneity of the sample and eliminate confounding effects resulting sexual dimorphism. A principal component analysis (PCA) and hierarchical clustering on principal components (HCPC) were conducted using the FactoMineR and factoextra package in R (Yano, 2021). PCA was performed to reduce the dimensionality of the 13 zoometric variables, and hierarchical cluster analysis of principal components (HCPC) was performed to identify the biotypes. Euclidean distance was used as the similarity measure, and Ward's method was used as the clustering criterion. Group differences were evaluated by ANOVA, and significance was set at $p < 0.05$ or $p < 0.001$. All statistical analyses were performed in R version 4.4.2.

3. Results

3.1. Zoometric measurements

The differences in the zoometric measurements of flames by district and sex are presented in Table 3. Table 3 shows the differences in the zometric measurements of llamas by district and sex. It was observed that male llamas from Chuschi had longer necks, greater neck thickness, a more developed thorax, and sturdier legs compared to female llamas from Chuschi and llamas from Chipao ($p < 0.05$). It was found that males had a larger body size, while females, on the other hand, had a wider rump ($p < 0.05$). In terms of variation, female llamas from Chuschi exhibited the lowest coefficient of variation (CV) for RH at 3.84%, and male llamas from Chuschi had the highest CV for RL at 12.30%.

Table 3. Estimated marginal means (EMM ± SE), coefficients of variation (CV), and p-values for zoometric measurements in extensively raised Q'ara llamas by district and sex.

Zoometric Traits	Chuschi (n=96) EMM ± SE (CV%)		Chipao (n=100) EMM ± SE (CV%)		p-value		
	F	M	F	M	District	Sex	D*S
Neck Length (NL)	65.50 ± 0.44 ^{a} (5.83)	65.90 ± 0.67 ^{a} (6.04)	65.10 ± 0.41^{a} (5.02)	62.80 ± 0.72 ^{b} (5.20)	NS	**	*
Front Neck Circumference (FNC)	31.70 ± 0.37^{b} (8.13)	36.80 ± 0.65 ^{a} (7.61)	31.70 ± 0.34 ^{b} (11.20)	34.50 ± 0.69^{a} (10.10)	NS	***	*
Rear Neck Circumference (RNC)	44.90 ± 0.53 ^{b} (10.50)	48.90 ± 0.88 ^{a} (8.24)	43.90 ± 0.49 ^{b} (9.50)	44.20 ± 0.90 ^{b} (9.05)	NS	NS	*
Wither Height (WH)	100.00 ± 0.57 ^{b} (5.16)	103.00 ± 0.90 ^{a} (5.66)	101.00 ± 0.54 ^{a} (3.97)	101.00 ± 0.98 ^{a} (4.03)	NS	NS	*
Rump Height (RH)	102.00 ± 0.55 ^{a} (4.66)	105.00 ± 0.85 ^{a} (5.29)	103.00 ± 0.52 ^{a} (3.84)	103.00 ± 0.94 ^{a} (3.98)	NS	NS	NS
Rump Length (RL)	26.20 ± 0.25 ^{a} (6.77)	26.60 ± 0.39 ^{a} (12.30)	26.30 ± 0.24 ^{a} (7.32)	25.50 ± 0.42 ^{a} (7.4)	NS	NS	NS
Rump Width (RW)	25.10 ± 0.22 ^{a} (6.29)	24.80 ± 0.34^{ab} (8.15)	25.70 ± 0.21 ^{a} (8.28)	24.20 ± 0.34 ^{b} (6.49)	NS	**	NS
Body Length (BL)	93.50 ± 0.67 ^{a} (5.65)	96.30 ± 1.06 ^{a} (5.75)	92.20 ± 0.62 ^{a} (6.24)	92.80 ± 1.14 ^{a} (5.85)	NS	NS	NS
Chest Width (CW)	23.70 ± 0.26 ^{b} (8.52)	25.40 ± 0.42 ^{a} (9.95)	24.30 ± 0.25 ^{b} (9.00)	24.40 ± 0.45 ^{b} (8.96)	NS	NS	*
Thoracic Perimeter (TP)	116.00 ± 0.82 ^{b} (5.22)	120.00 ± 1.29 ^{a} (5.35)	113.00 ± 0.75 ^{b} (6.14)	112.00 ± 1.36 ^{b} (6.76)	*	NS	*
Dorsal-Sternal Diameter (DSD)	44.00 ± 0.26^{ab} (4.59)	44.50 ± 0.41 ^{a} (5.20)	43.90 ± 0.24 ^{b} (5.45)	42.50 ± 0.43 ^{c} (4.10)	NS	**	**
Front Cannon Circumference	11.50 ± 0.11^{b} (7.24)	12.80 ± 0.18 ^{a} (7.54)	11.10 ± 0.10^{c} (8.82)	12.00 ± 0.19 ^{b} (6.24)	**	***	NS

(FCBC)							
Rear Cannon Circumference (RCBC)	11.10 ± 0.10 [b] (7.04)	12.30 ± 0.17 [a] (6.06)	10.70 ± 0.09 [c] (8.87)	11.50 ± 0.18 [b] (7.00)	**	***	NS

The different letters (a, b) in a row indicate significant differences ($p < 0.05$). NS: Not significant; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

The differences in zometric measurements among llamas by district, sex, and age are presented in Table 4. Female llamas from Chuschi showed harmonious development of PT and DSD as they aged ($p < 0.05$). Males exhibited greater hip width as they grew; meanwhile, group 4D showed the greatest increase in TP ($p < 0.05$). In Chipao, females in group 2D had a larger neck area; among males, HW, RL, RW, BL, CW, PT, and DSD increased from group 2D to CD, indicating harmonious growth ($p < 0.05$). In terms of variation, males Llamas from group 4D in Chipao exhibited the lowest coefficient of variation (CV) for RH at 2.04%, and the highest CV for RL at 14.20%.

Table 4. Estimated marginal means (EMM ± SE), coefficients of variation (CV), and p-values of zoometric measurements in extensively raised Q'ara llamas by districts, sex, and age group

Zoometric Traits	Chuschi (n=96) EMM ± SE (CV%)						Chipao (n=100) EMM ± SE (CV%)					
	F			M			F			M		
	2D	4D	CD	2D	4D	CD	2D	4D	CD	2D	4D	CD
Neck Length (NL)	6 4.20 ± 0.89 (6.04)	6 6.00 ± 1.16 (4.71)	6 5.80 ± 0.57 (4.61)	6 5.80 ± 1.29 (4.06)	6 5.10 ± 1.28 (5.41)	6 6.50 ± 1.02 (5.88)	6 5.70 ± 0.82 (6.93)	64. 70 ± 1.20 (7.00)	65 .00 ± 0.52 (5.16)	62. 40 ± 1.31 (6.40)	62. 20 ± 1.41 (5.97)	63. 50 ± 1.12 (6.31)
Front Neck Circumference (FNC)	3 2.10 ± 0.77 (10.20)	3 1.20 ± 0.95 (13.70)	3 1.70 ± 0.47 (11.30)	3 7.20 ± 1.26 (8.92)	3 8.50 ± 1.30 (6.05)	3 5.50 ± 0.94 (12.20)	3 2.60 ± 0.70 (6.78)	32. 60 ± 1.04 (4.88)	31 .20 ± 0.43 (8.80)	35. 10 ± 1.27 (6.66)	34. 50 ± 1.35 (12.30)	34. 10 ± 1.03 (4.88)
Rear Neck Circumference (RNC)	4 4.80 ± 1.07 (8.67)	4 4.10 ± 1.33 (10.80)	4 5.10 ± 0.67 (9.66)	4 9.20 ± 1.66 (7.18)	5 0.50 ± 1.71 (8.60)	4 7.70 ± 1.26 (10.30)	4 6.00 ± 0.98[a] (8.72)	43. 40 ± 1.38[ab] (10.20)	43 .20 ±0.60[b] (10.90)	45. 10 ± 1.63[ab] (5.64)	40. 50 ± 1.58[b] (6.39)	45. 80 ± 1.38[a] (7.48)
Wither Height (WH)	9 9.90 ± 1.16 (4.21)	1 00.90 ± 1.48 (4.59)	1 00.10 ± 0.72 (3.80)	1 02.10 ± 1.67 (4.49)	1 04.90 ± 1.71 (5.38)	1 02.60 ± 1.32 (2.47)	1 01.10 ± 1.05 (5.68)	10 3.40 ± 1.59 (5.36)	10 0.10 ± 0.67 (4.82)	96. 70 ± 1.69[b] (4.77)	10 1.50 ± 1.92[ab] (6.13)	102 .60 ± 1.50 [a] (5.04)
Rump Height (RH)	1 01.80 ± 1.10 (4.25)	1 03.30 ± 1.42 (3.98)	1 02.40 ± 0.69 (3.70)	1 04.90 ± 1.61 (4.51)	1 06.90 ± 1.64 (4.78)	1 03.80 ± 1.25 (2.83)	1 03.20 ± 1.00 (5.52)	10 5.20 ± 1.52 (4.74)	10 2.90 ± 0.64 (4.26)	99. 40 ± 1.63[b] (4.53)	10 4.70 ± 1.85[ab] (4.47)	104 .80 ± 1.44 [a] (5.38)
Rump Length (RL)	2 5.80 ± 0.50 (8.93)	2 6.00 ± 0.63 (7.90)	2 6.50 ± 0.32 (6.55)	2 6.00 ± 0.71 (10.50)	2 6.90 ± 0.73 (7.81)	2 6.80 ± 0.57 (5.01)	2 6.10 ± 0.45 (7.55)	26. 90 ± 0.69 (3.92)	26 .30 ± 0.29 (6.90)	23. 40 ± 0.68[b](11.50)	27. 30 ± 0.86[a](14.20)	25. 90 ± 0.63[a] (8.81)
Rump Width (RW)	2 4.60 ± 0.44 (7.17)	2 4.50 ± 0.55 (6.67)	2 5.40 ± 0.28 (8.86)	2 3.50 ± 0.59[b] (6.53)	2 4.80 ± 0.62[ab] (7.30)	2 5.60 ± 0.50[a] (3.75)	2 5.80 ± 0.41 (6.09)	25. 60 ± 0.61 (8.15)	25 .60 ± 0.26 (6.12)	23. 00 ± 0.62[b] (4.35)	24. 30 ± 0.71[ab] (4.98)	25. 10 ± 0.56[a] (9.89)
Body Length (BL)	9 1.50 ± 1.33 (6.48)	9 1.30 ± 1.68 (7.78)	9 4.80 ± 0.86 (5.48)	9 6.50 ± 1.98 (2.41)	9 8.00 ± 2.01 (7.36)	9 5.20 ± 1.53 (6.42)	9 1.80 ± 1.19 (5.26)	94. 00 ± 1.82 (5.16)	92 .10 ± 0.77 (5.93)	88. 70 ± 1.95 (4.40)	94. 00 ± 2.23 (5.17)	94. 90 ± 1.74 (5.52)
Chest Width (CW)	2	2	2	2	2	2	2	24.	24	22.	24.	25.

	3.80 ± 0.52 (8.20)	2.80 ± 0.63 (7.40)	3.80 ± 0.33 (9.58)	6.00 ± 0.81 (9.86)	5.00 ± 0.78 (11.70)	5.20 ± 0.61 (6.70)	4.20 ± 0.48 (6.67)	90 ± 0.73 (7.09)	.10 ± 0.31 (9.47)	10 ± 0.73[b] (9.90)	80 ± 0.89[ab] (8.61)	70 ± 0.71[a] (6.37)
Thoracic Perimeter (TP)	1 10.00 ± 1.50[a] (5.25)	1 16.00 ± 1.99[ab] (4.89)	1 18.00 ± 1.00[b] (5.82)	1 15.00 ± 2.22[a] (3.59)	1 25.00 ± 2.41 [b] (9.81)	1 20.00 ± 1.80[ab] (3.98)	1 13.00 ± 1.37 (6.45)	11 4.00 ± 2.06 (5.69)	11 3.00 ± 0.89 (4.66)	10 8.00 ± 2.23[a] (4.12)	11 2.00 ± 2.49[ab] (2.04)	116 .00 ± 1.99 b (5.97)
Dorsal-Sternal Diameter (DSD)	4 2.70 ± 0.51[b] (5.91)	4 3.50 ± 0.66[ab] (4.93)	4 4.60 ± 0.33 a (4.95)	4 4.20 ± 0.75 (3.62)	4 4.30 ± 0.75 (5.22)	4 4.80 ± 0.60 (3.85)	4 3.60 ± 0.47 (5.39)	44. 20 ± 0.71 (3.88)	43 .90 ± 0.30 (4.41)	41. 10 ± 0.75[b] (4.74)	42. 30 ± 0.83[ab] (2.86)	43. 60 ± 0.66[a] (5.53)
Front Cannon Circumference (FCBC)	1 1.40 ± 0.22 (7.96)	1 1.20 ± 0.27 (10.10)	1 1.60 ± 0.14 (8.81)	1 3.10 ± 0.35 (3.79)	1 3.30 ± 0.36 (7.49)	1 2.30 ± 0.26 (3.94)	1 1.20 ± 0.19 (7.58)	11. 50 ± 0.29 (6.87)	10 .90 ± 0.12 (6.94)	11. 70 ± 0.34 (6.91)	12. 00 ± 0.37 (10.50)	12. 20 ± 0.29 (6.17)
Rear Cannon Circumference (RCBC)	1 1.10 ± 0.21 (5.92)	1 0.70 ± 0.25 (10.20)	1 1.30 ± 0.13 (9.27)	1 2.60 ± 0.33 (5.50)	1 2.70 ± 0.33 (6.97)	1 1.80 ± 0.24 (6.54)	1 1.00 ± 0.18 (7.31)	11. 10 ± 0.27 (7.31)	10 .60 ± 0.11 (6.50)	11. 20 ± 0.31 (5.06)	11. 50 ± 0.35(9.53)	11. 80 ± 0.28(3.62)

200 Different letters (a,b) in a row indicate significant differences among age groups within the same district and by gender ($p < 0.05$).

3.2. Zoometric indices

As shown in Table 5, zoometric indices were observed by district and sex. Llamas from Chuschi exhibited more favorable values in AI, and TDI, indicating a more balanced body conformation and greater thoracic capacity ($p < 0.05$). In contrast, PI and PPI was significantly higher in llamas from Chipao, suggesting a relatively wider pelvic structure animal of quadrangular biotype ($p < 0.05$). Female llamas have higher TPI scores, indicating greater maternal aptitude; males have higher thoracic-digital index scores, indicating that they are heavier. In this study, males were found to have higher RTI scores, indicating a good balance for long-distance travel ($p < 0.05$). Notably, the lowest variability was recorded for PPI in male llamas from Chuschi (CV = 4.23 %), while the highest was observed for PI (CV = 14.50 %) in the same male Chuschi flames.

Table 5. Comparison of Zoometric Indices in extensively raised Q'ara llamas from Chuschi and Chipao Districts (Ayacucho, Peru). D*S?

Zoometric Index	Chuschi (n=96) EMM ± SE (CV%)		Chipao (n=100) EMM ± SE (CV%)		p-value		
	F	M	F	M	District	Sex	D*S
Body Index (BI)	81.00 ± 0.58 (5.65)	80.50 ± 0.87 (4.83)	81.50 ± 0.54 (6.20)	82.60 ± 1.00 (6.13)	NS	NS	NS
Pelvic Index (PI)	95.80 ± 0.99 ab (7.82)	93.40 ± 1.47 ^{b} (14.50)	97.90 ± 0.95 ^{a} (7.31)	96.30 ± 1.70 ab (5.99)	*	NS	NS
Proportionality Index (PPI)	107.00 ± 0.64 (5.11)	107.00 ± 0.97 (4.23)	109.00 ± 0.61 (4.60)	108.00 ± 1.11 (5.43)	*	NS	NS
Dactyl-Thoracic Index (DTI)	9.97 ± 0.09 ^{b} (6.76)	10.69 ± 0.14 ^{a} (5.87)	9.78 ± 0.08 ^{b} (7.51)	10.68 ± 0.16 ^{a} (8.26)	NS	**	NS
Transversal Pelvic Index (TPI)	25.00 ± 0.21 ab (6.21)	24.10 ± 0.31 ^{b} (6.98)	25.50 ± 0.20 ^{a} (7.95)	24.10 ± 0.35 ^{b} (5.90)	NS	*	NS
Longitudinal Pelvic Index (LPI)	26.20 ± 0.23 (6.88)	25.80 ± 0.34 (10.90)	26.10 ± 0.21 (6.18)	25.40 ± 0.38 (5.60)	NS	NS	NS
Relative Cannon Thickness Index (RTI)	11.50 ± 0.10 ^{b} (6.78)	12.40 ± 0.17 ^{a} (5.89)	11.00 ± 0.09 ^{c} (8.30)	11.90 ± 0.18 ^{ab} (7.63)	***	**	NS
Anamorphosis Index (AI)	134.00 ± 1.66 a (9.24)	140.00 ± 2.63 a (8.09)	128.00 ± 1.47 b (10.90)	126.00 ± 2.66^{b} (11.80)	**	NS	NS
Thoracic Development Index (TDI)	1.15 ± 0.01^{a} (5.41)	1.16 ± 0.01 ^{a} (4.46)	1.13 ± 0.01 ^{b} (5.51)	1.12 ± 0.01 ^{ab} (5.20)	**	NS	NS

The different letters (a, b, c) in a row indicate significant differences ($p < 0.05$). NS: Not significant; *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

The differences in zometric indices among llamas by district, sex, and age are presented in Table 6. Female Chuschi llamas, specifically those in group 2D, had higher DTI values compared to adults, as did the males, indicating that young females and males are well-suited for walking long distances ($p < 0.05$). Adult

females have greater thoracic capacity and a balanced body conformation, while males had relatively wider hips than juveniles ($p < 0.05$). In Chipao, no significant differences were observed in zoometric indices, except those males in the 4D group had a larger rump area compared to the other age groups ($p < 0.05$).

Table 6. Estimated marginal means (EMM ± SE), coefficients of variation (CV), and p-values of zoometric indices in extensively raised Q'ara llamas by districts, sex, and age group

Zoometric Index	Chuschi (n=96) EMM ± SE (CV%)						Chipao (n=100) EMM ± SE (CV%)					
	F			M			F			M		
	2D	4D	CD	2D	4D	CD	2D	4D	CD	2D	4D	CD
Body Index (BI)	83.20 ± 1.20(6.38)	79.10 ± 1.44(8.20)	80.70 ± 0.73(5.37)	83.80 ± 1.71(2.82)	78.50 ± 1.60(5.24)	79.80 ± 1.28(7.25)	81.70 ± 1.05(6.78)	82.80 ± 1.59(5.51)	81.20 ± 0.68(5.23)	82.00 ± 1.79(4.00)	83.90 ± 1.98(5.32)	82.20 ± 1.50(5.30)
Pelvic Index (PI)	95.70 ± 2.02(6.60)	94.40 ± 2.52(4.66)	96.10 ± 1.27(8.12)	90.80 ± 2.72(6.57)	92.50 ± 2.77(6.57)	95.60 ± 2.24(4.78)	99.00 ± 1.87(6.99)	95.40 ± 2.69(8.45)	97.90 ± 1.19(8.09)	99.50 ± 3.18(14.30)	90.20 ± 3.11(12.20)	97.60 ± 2.61(15.80)
Proportionality Index (PPI)	109.00 ± 1.32(4.61)	111.00 ± 1.69(4.38)	106.00 ± 0.80(4.04)	106.00 ± 1.81(3.90)	107.00 ± 1.83(4.59)	108.00 ± 1.45(6.72)	110.00 ± 1.19(3.95)	110.00 ± 1.77(2.82)	109.00 ± 0.76(5.86)	109.00 ± 1.99(4.40)	108.00 ± 2.13(5.85)	108.00 ± 1.65(3.36)
Dactyl-Thoracic Index (DTI)	10.39 ± 0.18[a] (7.06)	9.63 ± 0.21[ab] (7.52)	9.90 ± 0.11[b] (7.16)	10.34 ± 0.28[a] (4.20)	10.73 ± 0.26[ab] (12.10)	10.27 ± 0.20[b] (4.73)	9.97 ± 0.15(6.98)	10.12 ± 0.23(5.55)	9.64 ± 0.10(6.57)	10.81 ± 0.28(3.66)	10.70 ± 0.30(8.83)	10.57 ± 0.23(5.46)
Transversal Pelvic Index (TPI)	24.60 ± 0.42(5.07)	24.30 ± 0.52(7.25)	25.40 ± 0.27(8.73)	23.00 ± 0.55[b] (3.79)	23.70 ± 0.57[ab] (6.61)	25.00 ± 0.47[a] (4.18)	25.50 ± 0.39(5.33)	24.80 ± 0.56(8.57)	25.60 ± 0.25(6.08)	23.80 ± 0.61(5.85)	24.00 ± 0.67(8.01)	24.40 ± 0.52(7.58)
Longitudinal Pelvic Index (LPI)	25.80 ± 0.45(6.68)	25.80 ± 0.57(6.51)	26.40 ± 0.29(5.85)	25.40 ± 0.63(6.86)	25.60 ± 0.63(5.68)	26.20 ± 0.51(4.83)	25.80 ± 0.40(6.04)	26.10 ± 0.61(6.54)	26.30 ± 0.27(7.31)	24.20 ± 0.64[b] (10.30)	26.90 ± 0.77[a](12.80)	25.30 ± 0.56[ab] (9.17)
Relative Cannon Thickness Index (RTI)	11.50 ± 0.21(8.66)	11.00 ± 0.26(8.49)	11.60 ± 0.13(8.01)	11.80 ± 0.33(6.11)	12.70 ± 0.33(10.10)	11.00 ± 0.24(5.16)	11.10 ± 0.18(7.51)	11.10 ± 0.27(6.41)	11.90 ± 0.12(6.57)	12.10 ± 0.33(6.20)	11.80 ± 0.35(6.94)	11.90 ± 0.28(5.46)
Anamorphosis Index (AI)	122.00 ± 2.88[b] (9.33)	13.00 ± 3.98[ab] (9.60)	139.00 ± 2.05[a](9.84)	130.00 ± 4.36(6.25)	15.00 ± 5.01(15.20)	140.00 ± 3.67(9.21)	126.00 ± 2.67(9.54)	12.00 ± 3.96(10.30)	129.00 ± 1.76(9.02)	12.00 ± 4.34(6.45)	12.00 ± 4.79(5.78)	13.00 ± 3.91(9.17)
Thoracic Development Index (TDI)	1.10 ± 0.01[b]	1.15 ± 0.02[ab]	1.18 ± 0.01[a]	1.13 ± 0.02(4.14)	1.19 ± 0.02(5.12)	1.17 ± 0.02(5.29)	1.12 ± 0.01(4.81)	1.10 ± 0.02(5.85)	1.13 ± 0.01(5.51)	1.12 ± 0.02(3.73)	1.11 ± 0.02(5.77)	1.13 ± 0.02(4.43)

	(5.05)	(5.77)	(4.66)

Different letters (a,b) in a row indicate significant differences between age groups within the same district and by gender ($p < 0.05$).

3.2. Principal Component Analysis (PCA) and Hierarchical Clustering on Principal Components (HCPC)

A principal component analysis (PCA) was conducted to evaluate the multivariate morphostructural variation in female llamas based on 13 zoometric traits. In Chuschi, according to the scree plot, only the first three dimensions met the average inertia criterion; together, they explained 73.40% of the total variance: PC1 explained 45.70%, PC2 explained 17.10%, and PC3 explained 10.6%. In Chipao, the first two dimensions were retained; together, they explained 59.90% of the total variance: PC1 explained 47.50%, and PC2 explained 12.40%. Meanwhile, for the combined data, according to the scree plot, three dimensions were retained, explaining 68.70% of the total variance: PC1 explained 45.1%, PC2 explained 14.70%, and PC3 explained 8.90% (Fig. 3).

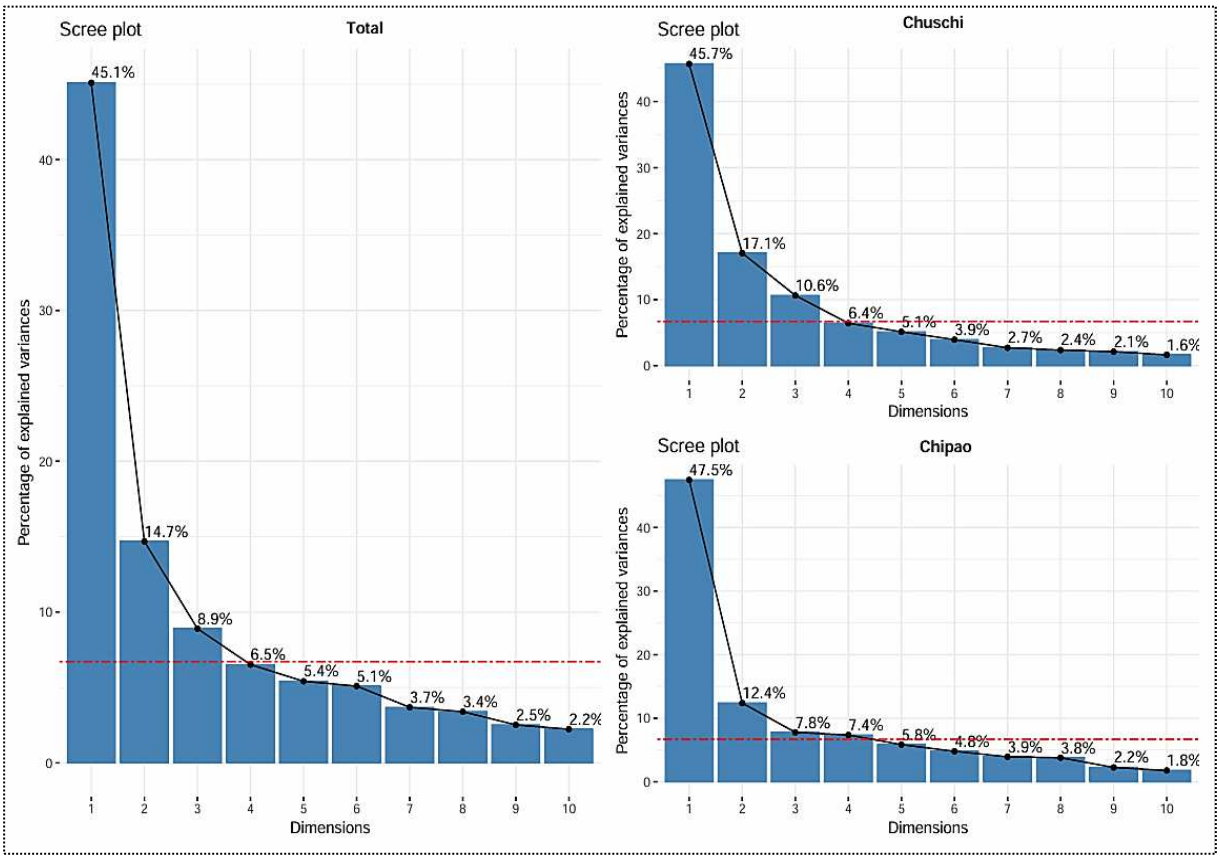

Fig. 3 Left: PCA scree plot showing the variance explained by each principal component of the dataset. Top right: PCA scree plot showing the variance explained for Chuschi Q'ara llamas; and bottom right: PCA scree plot showing the variance explained for Chipao Q'ara llamas.

As shown in the PCA biplot (Fig. 4), it is demonstrated that female llamas exhibit moderate to high (64.7%) morpho-structural dispersion among animals. PC1 was positively associated with most size-related

traits, including NL, FNC, RNC and TP, suggesting that this component reflects total body size. PC2 showed contrasting loadings, with negative contributions from DSD, RH, RW and RL, and positive contributions from RCBC, FCBC and FNC. This pattern indicates that PC2 captures shape-related variation. No clear separation was observed between individuals from Chuschi and Chipao. However, greater dispersion of individuals from Chuschi along the PCA axes suggests higher intra-population morpho-structural variability in that district.

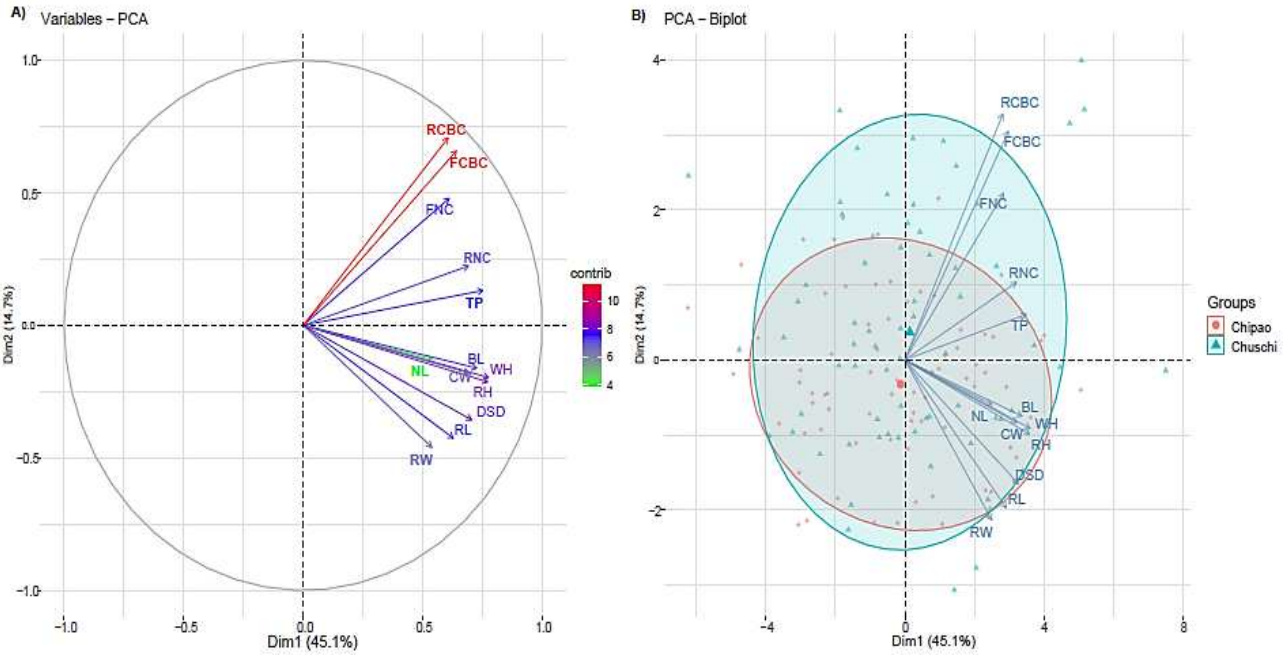

Fig. 4 (A) Principal Component Analysis (PCA) showing the correlation of zoometric traits with principal components. (B) Scatter plot illustrating the distribution of 144 female Q'ara llamas from the Chuschi and Chipao districts based on the first two principal components. Wither Height (WH), Chest Width (CW), Rump Length (RL), Rump Height (RH), Rump Width (RW), Body Length (BL), Thoracic Perimeter (TP), Dorsal-Sternal Diameter (DSD), Neck Length (NL), Front Neck Circumference (FNC), Rear Neck Circum. (RNC), Front Cannon Circumference (FCBC), Rear Cannon Circumference (RCBC).

Hierarchical cluster analysis based on principal components (HCPC) was performed for each district and for the data as a whole (Fig. 5). In the Chuschi district, two distinct morphostructural groups were identified among the female llamas studied; similarly, in the Chiapo district, two morphostructural groups were identified. Analysis of the combined data revealed three distinct morphostructural groups, corresponding to small, medium, and large body sizes. This classification was consistent with the dispersion observed in the PCA factor map of the overall data, where the first two dimensions (Dim1 = 45.1%, Dim2 = 14.7%) together explained 59.8% of the total morphometric variation.

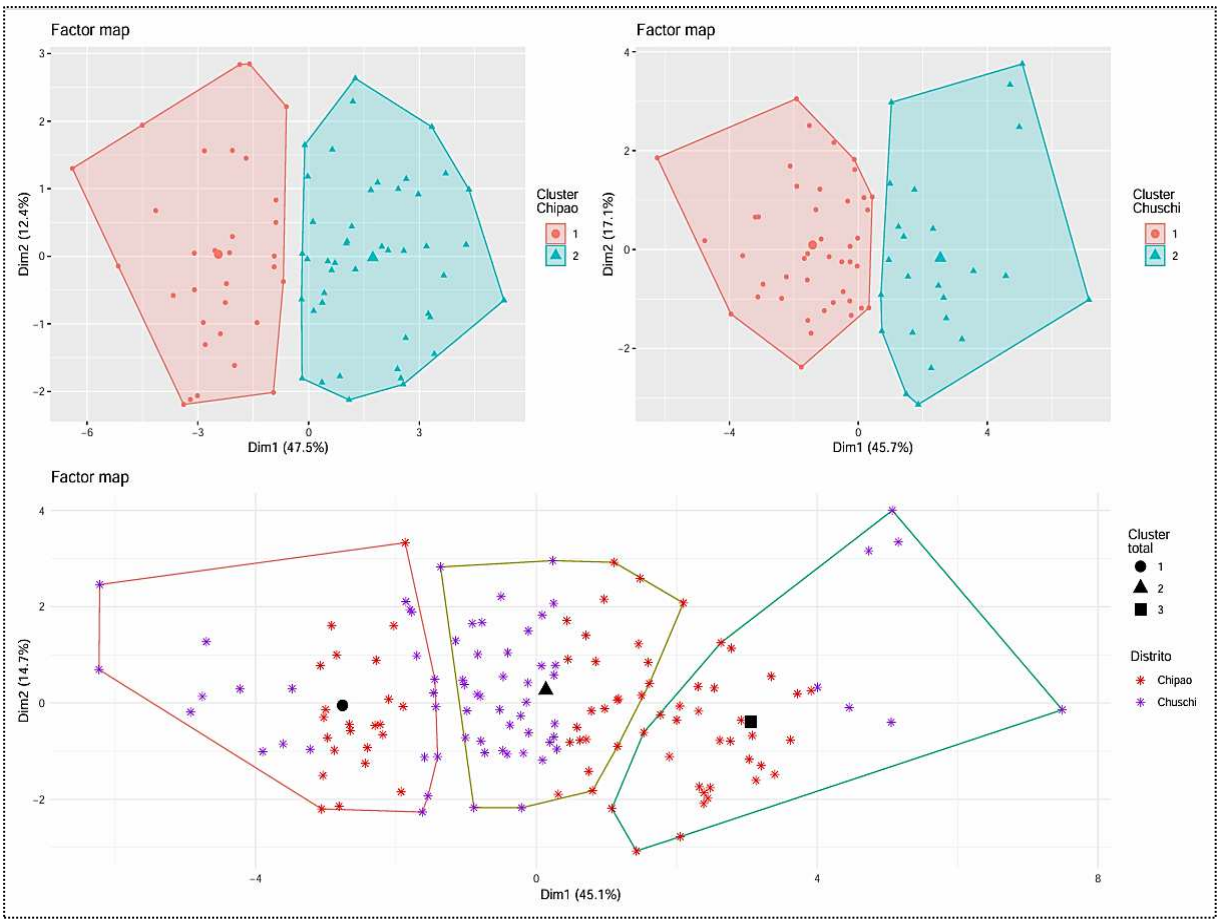

Fig. 5 A PCA factor map illustrating the spatial distribution of female llamas from Chuschi (purple) and Chiapao (red) across the three cluster. The three-cluster identified in the dendrogram are represented in red (Cluster 1), brown (Cluster 2), and green (Cluster 3).

Statistically significant differences ($p < 0.001$) were found among the three groups for all zoometric traits (Table 7). Cluster 1 represented small-bodied individuals, characterized by the lowest mean values in NL, FCBC, and BL. Cluster 2 included medium-sized animals, while Cluster 3 comprised large-bodied llamas, with the highest values for AC, AG and PT.

In terms of frequency, medium-sized morphotypes (Cluster 2) predominated in the overall population (43.75%), followed by small (30.56%) and large (25.69%) morphotypes. This pattern was observed in both districts, with Cluster 2 being the most frequent in Chuschi (22.22%) and Chipao (21.53%), while small-bodied llamas were slightly more common in Chipao (17.53%).

Table 7. Least square means (LSmeans), standard errors (SE), and coefficients of variation (CV) of 13 zoometric traits in female llamas grouped by morpho-structural classification (Ayacucho, Peru).

Zoometric Traits	Cluster 1 EMM ± SE (CV%)		Cluster 2 EMM ± SE (CV%)		Cluster 3 EMM ± SE (CV%)	
	Chuschi	**Chipao**	**Chuschi**	**Chipao**	**Chuschi**	**Chipao**
Neck Length (NL)	64.00 ± 0.71 ^{aA} (4.39)	62.40 ± 0.61^{A} (5.79)	65.30 ± 0.56 ^{b} (4.91)	65.60 ± 0.57 (4.89)	67.50 ± 0.82 ^{b} (4.59)	67.60 ± 0.71 (4.09)
Front Neck Circumference (FNC)	29.40 ± 0.56^{bA} (7.88)	30.00 ± 0.50B (7.68)	31.70 ± 0.47^{a} (9.36)	32.00 ± 0.48 (7.22)	34.50 ± 0.72 (11.60)	33.30 ± 0.61 (6.31)
Rear Neck Circumference (RNC)	41.50 ± 0.78 (6.74)	40.40 ± 0.66 (8.53)	45.00 ± 0.65 (7.04)	44.90 ± 0.66 (8.62)	48.90 ± 1.00 (8.74)	46.70 ± 0.83 (9.40)
Wither Height (WH)	96.80 ± 0.69 (3.09)	96.70 ± 0.60 (3.75)	99.80 ± 0.55 (2.02)	100.10 ± 0.56 (3.47)	105.10 ± 0.81 (3.02)	106.70 ± 0.72 (3.04)
Rump Height (RH)	99.40 ± 0.66 (2.97)	99.30 ± 0.58 (3.87)	101.70 ± 0.52 (2.14)	102.80 ± 0.54 (2.74)	107.20 ± 0.78 (2.96)	108.50 ± 0.69 (2.75)
Rump Length (RL)	24.90 ± 0.33 (6.61)	24.90 ± 0.29 (6.23)	26.00 ± 0.26 (5.48)	26.50 ± 0.27 (5.94)	28.20 ± 0.40 (5.79)	27.60 ± 0.34 (3.88)
Rump Width (RW)	23.90 ± 0.34 (6.55)	24.50 ± 0.30 (5.64)	24.80 ± 0.27 (7.13)	25.60 ± 0.28 (5.72)	26.90 ± 0.41 (7.59)	27.00 ± 0.36 (3.25)
Body Length (BL)	88.10 ± 0.85 (4.74)	88.20 ± 0.74 (3.90)	93.30 ± 0.69 (4.19)	91.90 ± 0.69 (4.04)	100.20 ± 1.05 (3.58)	97.40 ± 0.89 (4.57)
Chest Width (CW)	22.10 ± 0.34 (4.15)	22.50 ± 0.30 (8.91)	23.50 ± 0.28 (6.94)	24.70 ± 0.30 (6.14)	26.00 ± 0.44 (8.21)	25.80 ± 0.38 (4.58)
Thoracic Perimeter (TP)	109.00 ± 1.12 (5.86)	108.00 ± 0.96 (4.89)	116.00 ± 0.92 (4.14)	109.00 ± 1.12 (4.17)	121.00 ± 1.35 (4.87)	118.00 ± 1.15 (2.62)
Dorsal-Sternal Diameter (DSD)	42.20 ± 0.37 (4.97)	41.90 ± 0.32 (3.47)	44.10 ± 0.30 (4.18)	44.20 ± 0.31 (3.15)	45.80 ± 0.44 (5.05)	45.80 ± 0.39 (2.28)
Front Cannon Circumference (FCBC)	10.80 ± 0.16 (6.96)	10.30 ± 0.14 (5.53)	11.70 ± 0.14 (7.18)	11.20 ± 0.13 (4.72)	12.00 ± 0.20 (9.86)	11.70 ± 0.17 (5.81)
Rear Cannon Circumference (RCBC)	10.40 ± 0.16 (6.53)	10.20 ± 0.14 (6.62)	11.40 ± 0.14 (7.76)	10.80 ± 0.13 (5.34)	11.60 ± 0.20 (8.95)	11.30 ± 0.17 (5.32)
Llamas (%)	13.19	17.36	22.22	21.53	11.11	14.58

Different superscript letters (a,b,c) within a row and between clusters indicate significant differences among groups ($p < 0.05$).

4. Discussion

Zoometric evaluations are fundamental tools for characterizing morphostructural variability within and between animal populations (Akounda at al., 2023). Extensive morphometric assessments have been conducted for various livestock species worldwide (Akounda at al., 2023; Ormachea et al., 2023; Lendechy, at al., 2023; Rojas-Espinoza et al., 2023). In the case of llamas, most studies have been reported in Peru (Quispe et al., 2015; Machaca et al., 2020; Quispe et al., 2020; Ormachea at la., 2022) and Bolivia (Quispe, 2014; Merlo-Maydana et al., 2024), reflecting regional interest in conserving and improving this native species.

In our analysis, llamas from different districts exhibited similar body size and rump structure. However, llamas from the Chuschi district appear to be relatively heavier, with a more developed chest and sturdier limbs. These findings suggest that environmental and management factors in each sector of the region may influence key morpho-structural traits relevant to the region's functional and productive potential. When compared to animals from other Peruvian regions, the llamas in this region exhibited similar body sizes to those reported in Puno (Quispe et al., 2015; Ormachea et al., 2022), but were generally smaller than animals from Pasco and Junín (Mendoza, 2015; Quina, 2015). However, it is slightly taller than llamas described in Cusco (Quispe et al., 2020; Machaca et al., 2020), and clearly superior to Bolivian llamas (Merlo-Maydana at al., 2024). The small body size of llamas in Bolivia appears to be part of a trend often attributed to the harsher environmental conditions of the Altiplano (Quispe, 2014; Ormachea et al., 2022; Merlo-Maydana at al., 2024). These morphostructural differences between populations probably reflect the combined influence of genetic makeup and environmental factors, including local management practices. Natural and artificial selection, mating systems, and herd structure all contribute to shaping the genetic and phenotypic profiles of local populations (Renieri et al., 2009; Yakubu et al., 2011). Males and females were similar in body size and chest depth; however, males were the ones that maintained a robust skeletal structure in the shank and neck, with a slightly wider build and a longer rump; while females were found to be relatively wider at the hips. These findings between males and females demonstrate moderate sexual dimorphism. These results do not align with those from llamas in Cusco (Quispe et al., 2020) and Puno (Ormachea et al., 2022), who reported superiority in all phenotypic traits, confirming clear overall sexual dimorphism. This variability may be related to agroecological factors, nutritional limitations, and selection criteria that livestock farmers may be employing.

Body size and leg robustness remained similar across age groups, suggesting that llamas undergo marked body growth until they have two permanent teeth (2D). Meanwhile, older llamas (CD) were the

individuals that exhibited the widest rump and most developed thorax, suggesting that our study is consistent with the more developed rump of multiparous females and the energy storage typical of camelids of reproductive age. The rump surface area of young llamas (2D) suggests that the llamas are not yet fully developed. The morphostructure at different ages of llamas from this region expresses similarity with llamas from Puno (Ormachea et al., 2022); however, it is smaller than the llamas of Junín and Pasco (Mendoza, 2015; Quina 2015). Zoometric indices offer deeper insight into the functional conformation of animals. Lower PPI values and higher PI, DTI, and RTI values were particularly useful for assessing the' suitability of animal for meat production (Barragán, 2017; Dauda 2018; Silva-Jarquin et al., 2019). In this study, llamas from the Chipao district showed IDP values slightly higher than those from Chuschi. This suggests that Chipao llamas have a squarer, less compact build, with height predominating over body length. The llamas from Chuschi showed significantly higher values for IRC, AI, and DTI, indicating that they are animals with greater body depth and respiratory capacity to withstand high altitudes (Khargharia et al., 2015), with limbs strong enough to graze on rugged terrain. These findings suggest that environmental factors and the breeder's empirical selection may influence key morphostructural traits relevant to functional and productive potential, which is particularly important for this endangered breed. Compared to other studies, llamas from the Puno region contrast in that they are longer, but with smaller pelvic area than llamas from this region (Quispe et al., 2015). The relatively low values IPT and IPL suggest limited pelvic musculature and, therefore, potentially reduced carcass yield. This variation may reflect adaptive responses to agro-ecological differences, or microevolutionary patterns in geographically similar but environmentally distinct regions (Ablondi et al., 2023). The zootechnical characteristics of llamas are poorly documented, which limits our understanding of the productive orientation of the species. In ruminants such as sheep, goats, and cattle, zootechnical indices are known to be predictors of productive orientation (meat, milk) (Bravo and Sepúlveda, 2010; Silva-Jarquin et al., 2019; Rojas-Espinoza et al., 2023). However, in pseudoruminants such as llamas, this has not been fully documented. It is very likely that the zoometric index standards used as predictors in ruminants can be used in pseudoruminants. Nevertheless, further studies on the characterization of zoometric indices are suggested to help validate the predictive standards for the productive capacity and resilience of this important species, which has declined significantly in this region, understanding that llamas have a different morphology from ruminants.

PCA analysis suggests that the llamas in this study do not show strict morphostructural separation between individuals and populations. Overlap was observed between the two populations for most traits; however, the Chuschi llamas show greater variability in the shank and neck, suggesting a biotype with greater

skeletal strength. This scenario could be explained by low gene flow and the continuous erosion of genetic inheritance that would exist between populations (Akounda et al., 2023); or the possible common or close origin they come from (Maksimović et al., 2023). The hierarchical clustering analysis allowed for the identification of three distinct female morphotypes (small, medium, and large). This grouping not only highlights the within-population variability but also emphasizes the importance of body size as a potential selection criterion in breeding programs. The predominance of large individuals (25.69%), with the desire to improve meat potential, is suggested to select llamas with larger body size, good thoracic capacity and high pelvic indices. TP, WH and RW of larger individuals, easily accessible in field conditions, could serve as non-invasive proxies for estimating productive aptitude in extensive systems. Integrating these zoometric markers into selection schemes would enhance the efficiency of on-farm decision-making and genetic resource management in rural Andean communities (Maksimović et al., 2023). Previous research has demonstrated that early body size and weight gain are directly correlated with meat yield in camelids (Canaza-Cayo, et al., 2015), and linear measurements such as BL, TP, and WH are commonly used as heritable selection criteria (Dossa et al., 2009; Maksimović et al., 2023).

In addition to the natural selection and crossbreeding used by cattle breeders (Dossa et al., 2007), the role of climatic and nutritional factors in shaping morphostructural traits cannot be overlooked. In areas where pasture is not abundant, animals move long distances in search of food, using the energy acquired to transport themselves; on the contrary, in areas where there is sufficient pasture, animals easily adopt a robust appearance (Whannou et al., 2022). Likewise, studies in South American camelids have shown that animals raised at higher altitudes tend to exhibit broader chests and more robust thoracic structures to compensate for hypoxic conditions (Mendoza, 2015). Overall, the results indicate moderate morphostructural homogeneity among the llama populations of Ayacucho. This Q'ara breed, classified as a meat breed due to the phenotypic characteristics it retains, is currently threatened by social, such as changes in the raising of other livestock species, and political factors that could lead to its extinction in this region of Peru, where the population has already declined drastically; however, by identifying these biotypes using HPCP, the present study provides conservation organizations with information that establishes a phenotypic baseline for these Q'ara llama populations. Likewise, this information will be key to developing sustainable conservation and breeding strategies, with social, cultural, and scientific responsibility, adapting them to the local needs of the region.

5. Conclusions

Q'ara llamas from Chuschi were found to be slightly longer, greater thoracic depth and good leg support compared to those from Chipao. Moderate sexual dimorphism was identified. It was confirmed that young llamas have a less developed rump and thoracic depth. According to the zoometric indices related to productive potential, it was determined that the llamas from Chuschi are more rectangular in shape and more compact, and light animals capable of traveling long distances, which are indicative of good meat aptitude. Researchers are encouraged to conduct studies that standardize zoometric indices according to the morphology of the llama, classified as a pseudoruminant, and to clearly understand how they relate to productive and resilience traits.

The llamas showed low variability in their morphological traits, suggesting a lack of morphostructural heterogeneity between populations. Furthermore, three female llama morphotypes were identified in the region, with medium and small-sized individuals being the most prevalent. This size-based classification provides useful information for selecting larger animals aimed at improving productive parameters. Additionally, these findings will be valuable for developing conservation strategies for this important endangered zoogenetic resource, promoting the sustainable use of genetic material to establish a local ecotype with desirable meat-producing traits.

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Author contributions

Walter Palomino Guerrera: Conceptualization, Methodology, Investigation, Software, Data Curation, Writing-Original Draft Preparation, Visualization, Review and Editing; Hamilton Guzman Santaria: Methodology, Investigation; Mijail Contreras Huamani: Conceptualization, Visualization, Investigation, Supervision, Validation, Review and Editing; Manuel Garcia-Herreros: Visualization, Validation, Review and Editing.

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