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ORIGINAL ARTICLE

Correlations among morphometric traits, functional performance, and gluteal temperature in the Peruvian Paso horse

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ABSTRACT. The morphometric traits of the Peruvian Paso horse (PPH) constitute a fundamental basis for establishing selection criteria aimed at optimizing functional performance. However, to date, no study has linked traits such as morphometric and gluteal temperature differences with functional performance during the paso gait. The present study aimed to determine the correlations between morphometric traits, functional performance, and gluteal temperature based on the evaluation of 151 individuals for which 35 traits were measured. Total and partial correlations were calculated to assess the relationships among these variables. Correlation analyses were performed using Pearson, Spearman, and Kendall methods, with partial effects controlled through MANCOVA. The results revealed that the PPH's gait stems from coordinated forelimb–hindlimb neuromuscular control despite lateral-sequence decoupling; key morphometric traits are linked to performance and gluteal thermal patterns, supporting their use in selective breeding; and infrared thermography, combined with morphometric and kinematic data, offers a valuable non-invasive assessment tool advancing evidence-based breeding and management for this breed. This study represents the first comprehensive correlation analysis of the PPH, providing key insights for the selection of individuals with superior functional performance and greater biomechanical efficiency.

Keywords: equine, gait, Peru, overreach, functional traits, thermography, extension, Peruvian Paso.

INTRODUCTION

The Peruvian Paso horse (PPH) is a native breed of Peru, officially recognized as such under Peruvian Law Decree No. 25919. Since 1985, the National Association of Breeders and Owners of the Peruvian Paso Horse (ANCPCPP) has made significant efforts to develop and preserve this breed through selective breeding based on desirable phenotypic traits (Torres, 2017). This breed is renowned for its smooth gait, which is characterized by a four-beat lateral sequence gait (Vilela *et al*., 2025). Historically, selection within the breed has relied on morphological and functional criteria; however, the relationship between these traits and underlying physiological characteristics remains poorly understood. To maintain the genetic purity and functional integrity of this breed, morphometric (or hypometric) measurements have been employed since 1961, encompassing both linear and angular variables. These include measurements of the height, length, girth, and angles of the back and hock (Barrantes *et al*., 2009). Morphometric profiles across equine breeds reflect their specific adaptations and intended uses. For instance, Brazilian sport horses typically exhibit elevated values across most morphometric traits, reflecting a robust conformation compared to other breeds, such as the PPH or the English Thoroughbred. In contrast, smaller-sized breeds display distinct structural robustness that may be advantageous for high-impact activities (Rezende *et al*., 2021). Such information is critical in animal selection, enabling the identification of individuals whose conformation aligns with the expected performance and breed standard of the PPH.

Regarding functional traits—such as overreach (Distance between the footprint of the hind hoof and the front hoof on the same side during locomotion), acuteness (Maximum angle between an imaginary vertical line through the elbow and the humeral axis), term (Angle formed between the midline of the chest width and the lateral edge of the suspended hoof during mid-swing, viewed from the front) and vertical acceleration (Root mean square of vertical accelerations at the level of the croup during paso llano over horizontal displacement)—recent findings have reported preliminary heritability estimates and correlations between functional and morphometric traits as part of ongoing genetic improvement initiatives (Vilela *et al*., 2025; Vilela & Quintana, 2023; Vilela *et al*., 2022; Torres, 2017). Nevertheless, potential confounding factors influencing the correlation values have not yet been fully accounted for. Therefore, a more comprehensive study is required to accurately determine both total and partial correlations among morphometric traits and their associations with functional characteristics. Additionally, as reported by Texeira *et al*. (2020), infrared thermography (IRT) has emerged as a valuable tool for assessing surface temperature changes in horses during exercise, serving as a potential indicator of performance. Studies in Spanish and Arabian horses have demonstrated that ocular infrared temperature correlates with performance and stress levels (Soroko *et al*., 2019; Sanchez *et al*., 2016; Bartolomé *et al*., 2013), suggesting that IRT could be effectively applied to the PPH to optimize training regimens and competitive performance.

Therefore, the main aim of this study was to determine the associations among morphometric traits, functional performance and gluteal temperature in the PPH by (i) determining the total and partial correlations among morphometric traits; (ii) assessing the total and partial correlations among functional traits and gluteal temperature, and (iii) evaluating the total and partial correlations between morphometric and functional traits, and gluteal temperature.

MATERIAL AND METHODS

Animals

The animals selected for evaluation were sourced from breeding farms registered with the ANCPCPP, and all individuals included in the study possessed official genealogical registration, ensuring their genetic authenticity within the breed. Measurements of linear, angular, functional, and gluteal temperature differences were recorded for 151 horses, with a higher proportion of females than males (19% males, 81% females). All animals were maintained under similar management conditions and received a diet based on forage and commercial concentrates. Data collection was carried out between October 2021 and March 2023. Measurements were performed on a level surface following a standardized protocol for area measurement and animal stabilization.

All procedures and animal handling were conducted in accordance with animal welfare principles, ensuring no harm or distress to the animals.

Morphometric trait recording

Height at the withers, height at the croup, subpectoral height, and height at the midpoint of the back were measured using an aluminum equine caliper with a built-in spirit level (NC Equine, UK). Thoracic girth, metacarpal circumference, metatarsal circumference, forelimb pastern circumference, and hindlimb pastern circumference were recorded using a flexible tape measure (SUMVIBE model 3M-3Y, USA). Angular measurements, including back inclination angle, hock angle, coxofemoral angle, scapulohumeral angle, femorotibial angle, and brachial angle, were obtained using a digital goniometer (GemRed model 82305, USA). All angular measurements were performed in triplicate and the arithmetic mean was used for subsequent analyses.

Linear measurements (Table 1), including the length of the humerus, femur, metacarpal, metatarsal, body, croup, neck, and head, and the width of the chest and croup were recorded using a 5-m steel tape measure (Stanley Black & Decker, USA). The length of the forelimb and hindlimb pasterns were measured using a digital electronic caliper (Ubermann, Germany). All measurements were performed by two veterinarians and one animal science engineer specializing in equine morphometry. Prior to data collection, the observers completed a six-day standardization protocol under the supervision of an equine anatomist, comprising a theoretical review of anatomical landmarks and hands-on practical sessions on live horses.

Table 1.
Conceptualization of each measurement, including its sequential number, abbreviation, trait definition, and unit of measurement.

No.	Abbreviation	Trait	Unit
1	WH	Withers height. – Perpendicular distance from the inter-scapular region vertically down to the ground surface	cm
2	CRH	Croup height. – Distance from the highest point of the sacroiliac joint to the ground surface	cm
3	SH	Sub-pectoral height. – Perpendicular distance from the most ventral point of the sternum at the girth level to the ground surface	cm
4	MDH	Mid-dorsal height. – Distance from the midpoint of the back (spinous process of the 12th–13th thoracic vertebrae) to the ground surface	cm
5	CHW	Chest width. – Distance between the cranio-lateral points of the scapulohumeral joints	cm
6	TG	Thoracic girth. – Perimeter around the thorax at the level of the 7th–8th thoracic vertebrae and the caudal sternal region, immediately posterior to the elbow	cm
7	BL	Body length. – Straight-line distance from the cranio-lateral point of the shoulder to the tip of the ischium	cm
8	MC	Metacarpal circumference. – Perimeter around the middle third of the metacarpal bone	cm
9	MT	Metatarsal circumference. – Perimeter around the middle third of the metatarsal bone	cm
10	BIA	Back inclination angle. – Angle formed between the direction axis of the scapular spine and an imaginary horizontal line	degrees
11	HA	Hock angle. – Internal angle formed by the intersection of the tibia and metatarsal bone axes	degrees

12	SHA	Scapulohumeral angle. – Internal angle formed between the lateral humeral tubercle and the projection of the scapular spine	degrees
13	FTA	Femorotibial angle. – Internal angle formed by the lateral epicondyles of the femur and tibia at the stifle region	degrees
14	BA	Brachial angle. – Acute angle formed between the humerus and a horizontal line	degrees
15	CFA	Coxofemoral angle. – Acute angle formed between between the longitudinal axis of the pelvis and the longitudinal axis of the femur	degrees
16	FPL	Forelimb pastern length. – Distance from the proximal end of the first phalanx to the distal end of the second phalanx, in forelimb	cm
17	HPL	Hindlimb pastern length. – Distance from the proximal end of the first phalanx to the distal end of the second phalanx, in hindlimb	cm
18	NL	Neck length. – Distance from the wing of the atlas to the inter-scapular region	cm
19	UL	Upper arm length. – Distance from the supraglenoid tubercle of the scapula to the humeroradial joint	cm
20	FL	Femur length. – Straight-line measurement from the greater trochanter of the femur to the femorotibial (patellar) joint	cm
21	FPP	Forelimb pastern perimeter. – Diameter of the proximal first phalanx of the forelimb	cm
22	HPP	Hindlimb pastern perimeter. – Diameter of the proximal first phalanx of the hindlimb	cm
23	CW	Croup width. – Straight-line distance between the cranio-lateral points of the coxal tuberosities	cm
24	CL	Croup length. – Distance from the cranial point of the coxal tuberosity to the most caudal point of the ischiatic tuberosity	cm
25	HW	Head width – Distance between the outermost edges of the eye orbits	cm
26	HL	Head length – Distance from the upper lip to the median point between the ears along the midline	cm
27	MCL	Metacarpal length – Distance from the distal end of the ulna to the midpoint of the carpal joint	cm
28	MTL	Metatarsal length – Distance from the caudal tarsal bone to the central tarsal bone of the metatarsus	cm
29	EXT	Extension. – Maximum angle formed between the front hoof edge and a vertical line at the level of the elbow	degrees
30	OVR	Overreach. – Distance between the footprint of the hind hoof and the front hoof on the same side during locomotion	cm
31	TER	Term. – Angle formed between the midline of the chest width and the lateral edge of the suspended hoof during mid-swing, viewed from the front	degrees
32	ACS	Acuteness. – Maximum angle between an imaginary vertical line through the elbow and the humeral axis	degrees
33	GTD	Gluteal temperature difference. – Difference between resting and post-exercise (after 100 m of paso llano) surface temperature at mid-gluteal level	°C
34	GTDX	Maximum gluteal temperature difference. – Difference between resting and post-exercise (after 100 m of paso llano) surface temperature at the site of maximum thermal increase in the gluteal region	°C
35	RMS	Vertical acceleration. – Root mean square (RMS) of vertical accelerations at the level of the croup during paso llano over horizontal displacement	m/s^2

Recording of functional traits

Functional traits —including overreach, extension, term, acuteness and vertical acceleration (see definitions in Table 1)— were assessed through video recording of each animal performing the paso llano gait led by a handler over a 50 m straight track at a speed ranging between 2.5 and 4 m/s. The recordings were captured using a smartphone camera with a resolution of 1920 × 1080 pixels at 60 fps (Motorola Edge 30 Fusion, USA). The camera was mounted on a professional tripod (Benro T980, USA) at a height of 1.3 m above ground level, spatially aligned along the X, Y, and Z axes, and positioned perpendicularly at approximately 12 m from the animal's trajectory. Lateral movement was recorded from the left side of the animal; for the "term" trait, the camera was repositioned to capture frontal movement.

Anatomical landmarks were marked with adhesive tape (4 × 4 cm) to enhance the visibility of the key joint and body segment movements during gait analysis. All videos were saved in MP4 format and subsequently processed using Kinovea software, version 0.9.5 (http://www.kinovea.org/). Measurements for overreach, extension, acuteness and term were performed from three to five consecutive strides (one measurement per stride), and the arithmetic mean was calculated for use in subsequent analyses of total correlations with other recorded traits. For correlation analyses exclusively among functional variables, all individual stride measurements were included.

Vertical acceleration was recorded continuously throughout the lateral displacement of each animal, with data sampled at 15-millisecond intervals. A 10-cm adhesive tape strip, placed parallel to the ground plane on the animal's flank within the camera's field of view, served as a spatial calibration reference. All video frames captured during the paso llano were filtered using a second-order, two-pass low-pass Butterworth filter to reduce high-frequency noise and improve signal accuracy. Vertical acceleration values were averaged using the root mean square (RMS) method and calculated according to the following formula:

$$\left(\sqrt{\frac{\sum a_i^2}{n}}\right)$$

where a_i^2 represents the individual acceleration measurements and n is the total number of samples. This approach ensured a robust and standardized quantification of dynamic movement patterns, enabling precise evaluation of functional performance in the PPH.

Recording of gluteal temperature

Gluteal temperature difference (GTD) and maximum gluteal temperature difference (GTDX) were measured using an infrared thermal imaging camera (HTI-19, Dongguan Xintai Instrument Co., Ltd., China), with a resolution of 320 × 240 px and a thermal sensitivity of 300 mK, set at an emissivity coefficient of 0.95. Measurements were taken at a fixed distance of 20 cm from the skin surface, in accordance with the manufacturer's operational guidelines. Thermal images were captured in degrees Celsius, both before and immediately after the paso llano exercise, under standardized environmental conditions. Imaging was performed in the same anatomical region and under consistent positioning relative to solar exposure to minimize external thermal interference. The final variable used in the analysis was calculated as the difference between post-exercise and pre-exercise temperatures for both mean gluteal temperature and maximum gluteal temperature.

All thermal recordings were conducted by trained operators, ensuring a perpendicular alignment of the camera to the target area to avoid angular distortion. Ambient temperature and relative humidity were recorded during each session to account for potential environmental effects on surface temperature readings. The operational definition of each study variable is summarized in Table 1.

Statistical analysis

In all analyses, the threshold for statistical significance was set at $P < 0.05$. Both complete and partial correlation analyses were performed using Jamovi® (v. 2.4), an open-source statistical platform based on R, available at https://www.jamovi.org.

Descriptive statistical analysis was performed for each variable. Normality was assessed using the Anderson–Darling test. Variable pairs conforming to a normal distribution were analyzed using Pearson's correlation coefficient, with statistical significance defined as $P < 0.05$. For variable pairs violating the assumption of normality, Spearman's rank correlation or Kendall's tau-b correlation was employed, selected according to the extent of tied ranks in the data. The correlations are discussed below according to the classification proposed by Akoglu (2018), where correlations below 0.30 are considered weak, those between 0.30 and 0.50 moderate, and those above 0.50 strong.

For the repeated-measures functional traits (overreach, term, acuteness and extension) repeated measures correlation (rmcorr) was applied using the rmcorr function implemented via the web-based Shiny application: https://lmarusich.shinyapps.io/shiny_rmcorr/. This approach accounts for non-independence among repeated observations within individuals. Confidence intervals for all correlation coefficients were reported at the 95% level.

To account for potential confounding effects, multivariate analysis of covariance (MANCOVA) of morphometric traits was initially performed to control for the effects of breeder, sex, age, and their interactions. Subsequently, partial correlation analyses (Pearson, Spearman, or Kendall, as appropriate) were conducted, adjusting for covariates that were statistically significant in the MANCOVA model.

Similarly, for functional traits and gluteal temperature differences, a MANCOVA was applied to evaluate the influence of breeder, sex, age, velocity, and their interaction terms on each variable. A final comprehensive MANCOVA was conducted across all trait categories (morphometric, functional, and gluteal temperature differences) to assess the effects of breeder, age, sex, velocity, and their interactions. Partial correlations were computed, adjusting for significant covariates identified in these models.

RESULTS

The descriptive statistics for all traits are presented in Table 2. The overall MANCOVA, including all the variables, revealed a significant effect of breeder ($P < 0.001$). Consequently, partial correlations among all the variables were adjusted for this factor. For functional and gluteal temperature differences traits, the covariate velocity mean was 2.91 m/s (SD = 0.566), and normality was confirmed via the Anderson–Darling test ($P = 0.862$). The mean age of the animals was 8.02 ± 2.56 years.

Table 2.
Descriptive statistical summary of each trait, including the number of observations (animals), median, mean, standard error of the mean (SEM), standard deviation (SD), coefficient of variation, minimum and maximum values, and the *P*-value from the Anderson–Darling normality test.

N°	Trait	Animals	Median	Mean	SEM	SD	Coefficient of variation	Minimum	Maximum	Anderson Darling test *P*-value
1	WH	151	145	145.05	0.241	2.957	0.02	137	153	0.307
2	CRH	151	146.5	146.023	0.291	3.577	0.024	132	155	0.099
3	SH	151	74	74.533	0.203	2.496	0.033	67	81	0.19
4	MDH	151	137	137.539	0.294	3.61	0.026	128.9	149	0.396
5	CHW	151	34	33.983	0.188	2.31	0.068	29	39	0.254
6	TG	151	177	176.858	0.595	7.311	0.041	155	198	0.321
7	BL	151	154	153.493	0.463	5.691	0.037	140	168	0.711
8	MC	151	17	17.517	0.07	0.861	0.049	15	20	< 0.001
9	MT	151	19	18.662	0.071	0.869	0.047	17	21	< 0.001
10	BIA	151	63	63.166	0.35	4.296	0.068	49.333	77	0.115
11	HA	151	139.333	139.03	0.32	3.932	0.028	129.667	154.667	0.069
12	SHA	151	90.8	91.665	0.247	3.033	0.033	81.333	103.333	< 0.001
13	FTA	151	122	124.215	0.409	5.026	0.04	116.667	139.333	< 0.001
14	BA	151	121.567	123.033	0.448	5.502	0.045	110.667	158.833	< 0.001
15	CFA	151	91	91.685	0.231	2.837	0.031	85	104.333	< 0.001
16	FPL	151	11.175	11.263	0.111	1.366	0.121	7.959	23	< 0.001
17	HPL	151	11.093	11.262	0.1	1.232	0.109	7.808	21	< 0.001
18	NL	151	61	60.556	0.309	3.792	0.063	48	69	0.469
19	UL	151	35	34.805	0.2	2.462	0.071	29	53	0.018
20	FL	151	36	35.874	0.205	2.519	0.07	29	44	0.201
21	FPP	151	17	16.689	0.073	0.898	0.054	14	21	< 0.001
22	HPP	151	18	17.563	0.067	0.825	0.047	15.5	21	< 0.001
23	CW	151	34	34.854	0.361	4.436	0.127	25	56	0.061
24	CL	151	49	49.166	0.306	3.765	0.077	32	58	0.061
25	HW	151	22	22.404	0.102	1.247	0.056	20	31	< 0.001
26	HL	151	61	61.437	0.188	2.315	0.038	56	68	0.203
27	MCL	151	27	26.557	0.141	1.737	0.065	22	30	0.017
28	MTL	151	31	30.566	0.14	1.714	0.056	26	35	0.056
29	EXT	137	42.36	42.163	0.393	4.595	0.109	22.067	55.333	0.349
30	OVR	139	26.394	27.417	1.788	21.08	0.769	-14.037	72.44	0.779
31	TER	140	25.21	25.257	0.502	5.943	0.235	8.933	43.467	0.853
32	ACS	137	71.44	71.432	0.58	6.784	0.095	52.033	87.367	0.889
33	GTD	88	1.5	1.601	0.215	2.017	1.26	-3.4	9.4	0.33
34	GTDX	88	0.65	1.045	0.319	2.994	2.864	-6.6	13.1	0.069
35	RMS	138	2.551	2.637	0.079	0.928	0.352	0.851	5.359	0.818

1. Withers height; 2. Croup height; 3. Sub-pectoral height; 4. Mid-dorsal height; 5. Chest width; 6. Thoracic girth; 7. Body length; 8. Metacarpal circumference; 9. Metatarsal circumference; 10. Back inclination angle; 11. Hock angle; 12. Scapulo-humeral angle; 13. Femorotibial angle; 14. Brachial angle; 15. Coxofemoral angle; 16. Forelimb pastern length; 17. Hindlimb pastern length; 18. Neck length; 19. Upper arm length; 20. Femur length; 21. Forelimb pastern perimeter; 22. Hindlimb pastern perimeter; 23. Croup width; 24. Croup length; 25. Head width; 26. Head length; 27. Metacarpal length; 28. Metatarsal length; 29. Extension; 30. Overreach; 31. Term; 32. Acuteness; 33. Gluteal temperature difference; 34. Maximum gluteal temperature difference; 35. Vertical acceleration by root mean square; SEM: standard error of the mean; SD: standard deviation.

Correlation between functional traits and gluteal temperature difference

The MANCOVA applied to functional and gluteal temperature differences revealed significant effects of breeder ($P < 0.001$) and velocity ($P < 0.001$), but no significant effects of sex ($P = 0.297$) or age ($P = 0.537$). Therefore, breeder and velocity were included as covariates in the partial correlation model for functional traits. Additionally, rmcorr was performed among functional traits. Figure 1 displays the rmcorr results, showing significant associations ($P < 0.001$) between term (Figure 2) and acuteness, and between acuteness and extension.

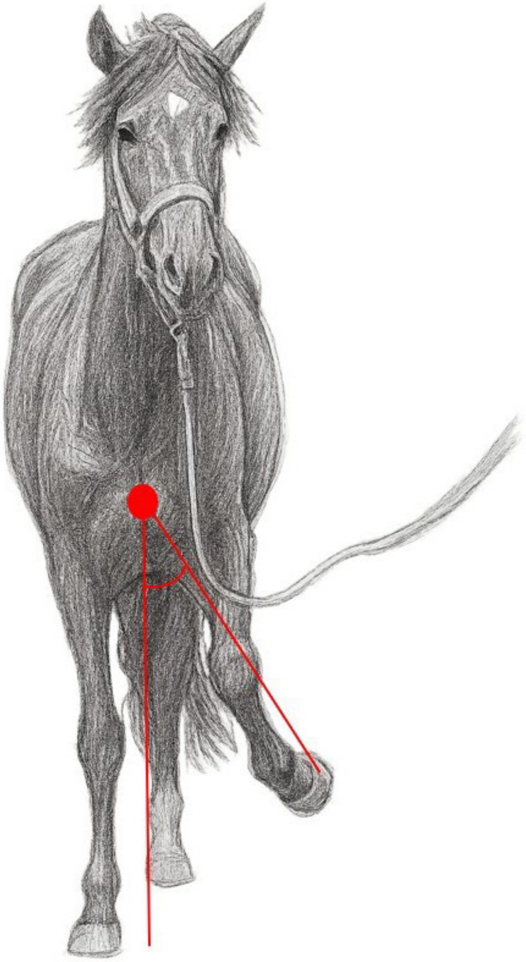

Figure 2.
Graphic representation of the trait ”Term”, indicating with a red dot the angular vertex used for measurement.

Partial Pearson correlations between functional traits and GTD, adjusted for breeder and velocity, are presented in Table 3. All functional and gluteal temperature differences variables met the assumptions of normality; hence, non-parametric partial correlations (Spearman and Kendall) were not computed.

Table 3.
Partial correlation matrix between functional traits and gluteal temperature differences. GTD: Gluteal temperature difference; GTDX: Maximum gluteal temperature difference; RMS: Root mean square of vertical acceleration. Partial correlations controlled for Velocity and Breeder.

	Extension	**Overreach**	**term**	**Acuteness**	**GTD**	**GTDX**	**RMS**
Extension	—						
Overreach	0.212**	—					
Term	-0.062	-0.087	—				
Acuteness	0.599***	0.017	0.313***	—			
GTD	0.194*	0.056	-0.091	0.295***	—		
GTDX	0.119	0.099	-0.047	0.12	0.377***	—	
RMS	-0.164*	-0.3***	-0.094	-0.082	-0.088	-0.344***	—

Correlation among morphometric traits

MANCOVA applied to morphometric traits revealed significant effects of breeder ($P < 0.001$), sex ($P < 0.001$) and age ($P = 0.005$). Therefore, these covariates were included in the partial correlation analyses. Supplementary Data 1a presents the partial Pearson, Spearman, and Kendall correlations among morphometric traits. The corresponding total (unadjusted) Pearson, Spearman, and Kendall correlation matrices are provided in Supplementary Data 1c, 1d, and 1e, respectively.

Correlation among morphometric and functional traits, and gluteal temperature

The comprehensive MANCOVA across all trait categories showed a significant effect of breeder ($P < 0.001$), but no significant effects of sex ($P = 0.078$), age ($P = 0.726$), or velocity ($P = 0.052$). Thus, partial correlations among all traits were adjusted solely for breeder. The resulting matrix of partial correlations, controlling for breeder effect, is presented in Supplementary Data 1b. Complete matrices of Pearson, Spearman, and Kendall correlations are available in Supplementary Data 1c, 1d, and 1e, respectively. Figure 3 presents the correlations among all variables using a heatmap for improved clarity.

DISCUSSION

Table 2 presents a descriptive summary of the morphometric, functional, and gluteal temperature differences traits of the PPH, including mean values, standard deviations, and coefficients of variation. Withers and croup height exhibited low coefficients of variation, indicating high homogeneity and measurement consistency for these conformational traits. Previous studies on the Menorquina Purebred have reported similar stability in body size measurements, suggesting moderate heritability for these morphological characteristics in specialized horse breeds (Perdomo-González *et al.*, 2022). In contrast, angu-

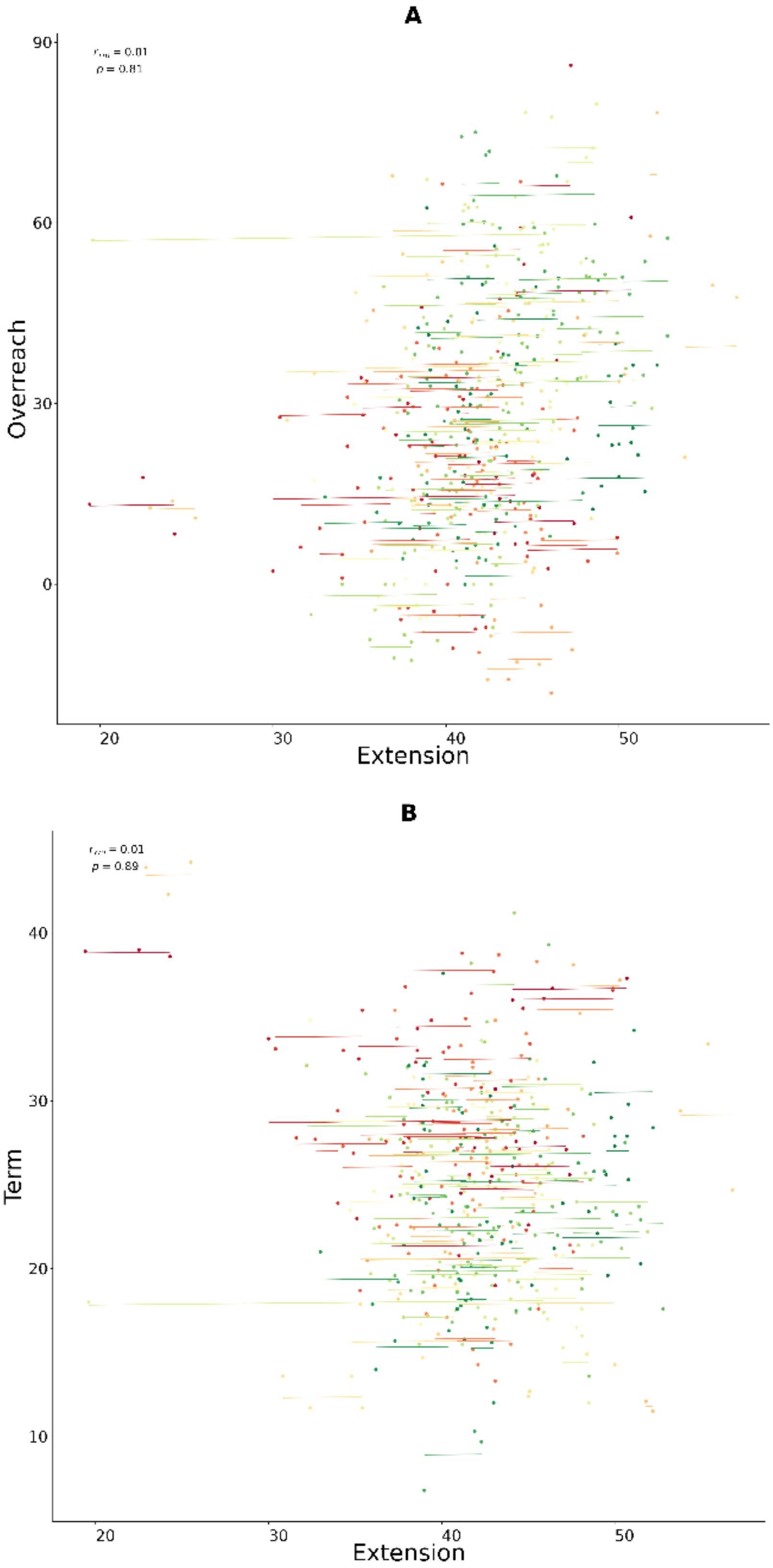

Figure 1. (A,B)
Repeated measures correlations and Degrees of freedom among functional traits. A: rrm(351) = 0.01, 95% CI [-0.092, 0.117], *P* = 0.815. B: rrm(321) = 0.01, 95% CI [-0.101, 0.117], *P* = 0.885.

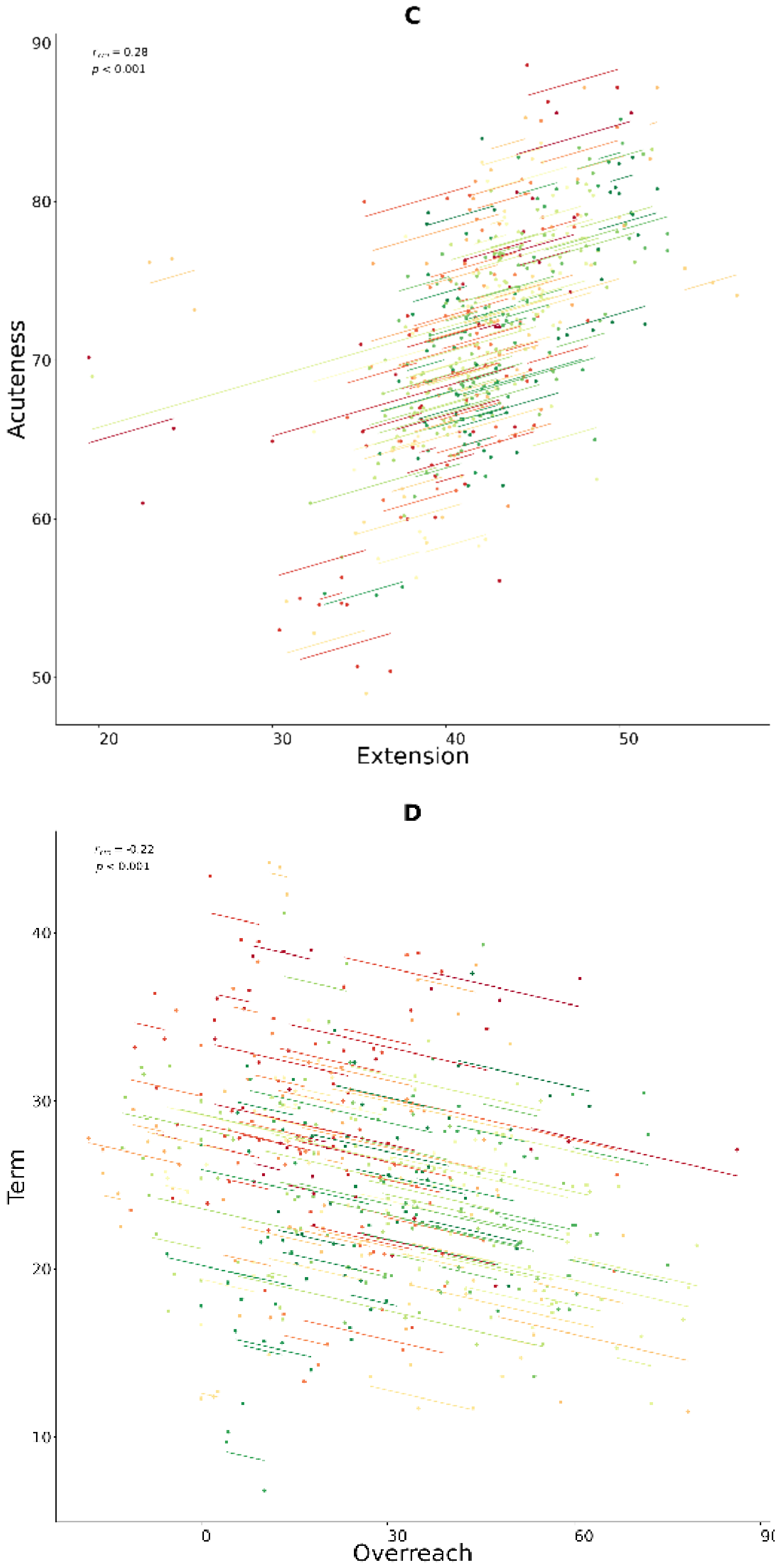

Figure 1. (C,D)
Repeated measures correlations and Degrees of freedom among functional traits. C: rrm(355) = 0.28, 95% CI [0.177, 0.369], *P* < 0.001. D: rrm(328) = -0.22, 95% CI [-0.321, -0.115], *P* < 0.001.

Figure 1. (E,F)
Repeated measures correlations and Degrees of freedom among functional traits. E: rrm(357) = 0.05, 95% CI [-0.054, 0.152], *P* = 0.351. F: rrm(328) = -0.09, 95% CI [-0.197, 0.017], *P* = 0.097.

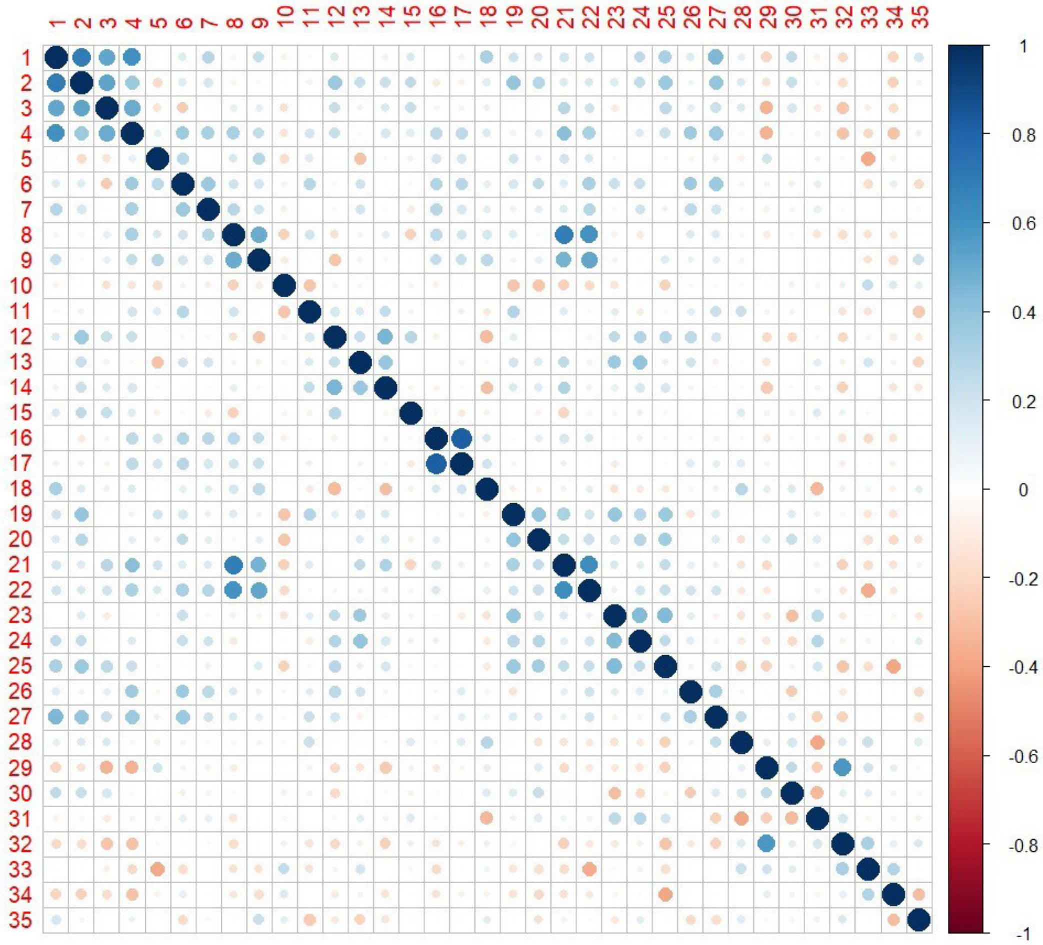

Figure 3.
Correlations among all traits. Blue circles represent positive correlations; orange circles represent negative correlations. Circle diameter and transparency indicate the magnitude of the correlation.

1. Withers height; 2. Croup height; 3. Sub-pectoral height; 4. Mid-dorsal height; 5. Chest width; 6. Thoracic girth; 7. Body length; 8. Metacarpal circumference; 9. Metatarsal circumference; 10. Back inclination angle; 11. Hock angle; 12. Scapulohumeral angle; 13. Femorotibial angle; 14. Brachial angle; 15. Coxofemoral angle; 16. Forelimb pastern length; 17. Hindlimb pastern length; 18. Neck length; 19. Upper arm length; 20. Femur length; 21. Forelimb pastern perimeter; 22. Hindlimb pastern perimeter; 23. Croup width; 24. Croup length; 25. Head width; 26. Head length; 27. Metacarpal length; 28. Metatarsal length; 29. Extension; 30. Overreach; 31. Term; 32. Acuteness; 33. Gluteal temperature difference; 34. Maximum gluteal temperature difference; 35. Vertical acceleration by root mean square.

lar measurements showed greater variability, particularly in the coxofemoral and brachial angles, which displayed higher dispersion. This increased variation may be associated with selective breeding practices favoring individuals with specific conformational traits aimed at enhancing joint flexibility and range of motion, which are key determinants of the functional performance of the PPH.

Correlation between functional and gluteal temperature

The partial correlation matrix between functional traits and gluteal temperature differences variables, specifically gluteal temperature differential and vertical acceleration, revealed meaningful associations between locomotor dynamics and muscular thermal patterns. The partial and total correlations between extension and overreach were positive, albeit of moderate to weak magnitude in repeated-measures analysis. This positive association suggests that horses exhibiting greater overreach (hind limb engagement) also tend to display greater anterior limb extension, reflecting coordinated biomechanical synergy between fore and hind limbs during the paso llano.

The correlation between extension and acuteness was consistently positive across all analytical methods, indicating that increased extension of the forelimbs is associated with greater sharpness (acuteness) of movement. This highlights the importance of breed-specific biomechanics in executing the characteristic gait. Effective propulsion in equines relies on posterior limb extension, which may be enhanced by a more inclined scapula and a closed shoulder angle (Redaelli *et al*., 2014; Fercher, 2016). Although extension was measured in the forelimbs in this study, the biomechanical interdependence between the anterior and posterior limbs suggests that forelimb extension may serve as an indirect indicator of the overall propulsive efficiency. Posterior limb extension in horses is governed by joint mobility and activity of the hip and stifle extensor muscles (Rhodin *et al*., 2009). In the PPH, which has a gait characterized by lateral sequence movement and reduced distal joint flexion, overreach may be influenced by hock joint stability and coordination of the hindquarter (Hobbs & Clayton, 2013). Therefore, the relationship between forelimb extension and overreach may reflect the integrated neuromuscular control required for smooth and efficient locomotion.

The weak rmcorr between extension and overreach may indicate biomechanical compensation, whereby the mechanical design of the paso llano minimizes dependence on tarsal flexion to optimize movement fluidity.

This biomechanical compensation is similar among different breeds. Studies on Pyrenean Catalan Horses and Thoroughbreds have shown significant asymmetries and compensatory movements, suggesting biomechanical adaptations across different breeds (Parés-Casanova & López Navarro, 2020; Pfau *et al*., 2018; Forbes *et al*., 2024). Some horses exhibit more forelimb movement that is not matched by hindlimb movement, as seen in general-purpose horses and warmblood riding horses (Wilson *et al*., 2016; Rhodin *et al*., 2017). In the case of the Colombian Paso Fino, this breed shows unique biomechanical characteristics, including insulin dysregulation and upper airway mechanics issues, which may influence their gait and movement patterns (Breuhaus, 2019; Joó *et al*., 2021).

The positive correlation between extension and acuteness further underscores the role of precise neuromuscular control in achieving an efficient stride without compromising stability (Rhodin *et al*., 2009). Horses with superior neuromuscular coordination may exhibit stronger correlations between these traits, suggesting that training and conditioning could modulate functional performance (McGowan & Hyytiäinen, 2017; Spigolon *et al*., 2017)

In trotting and galloping breeds, stronger correlations are typically observed between hock extension and flexion because of the greater reliance on diagonal gait mechanics for propulsion (Gómez-Álvarez *et al*., 2009). In contrast, the lateral gait pattern of the PPH reduces interdependence between limb movements (Nicodemus & Clayton, 2003), which may explain the weaker correlation observed. Additionally, individual variability within this breed, driven by anatomical conformation, training history, and neuromuscular adaptation, may further influence these kinematic relationships. Moreover, selective breeding in the PPH has historically prioritized gait smoothness over other functional traits, which may attenuate the functional dependency between extension and overreach. Additionally, investigating the role of spinal flexibility in facilitating smooth transitions between gaits could provide insights into the biomechanics of the Paso Fino breed.

The partial correlation between term and acuteness indicates a moderate relationship, although non-significant in repeated measures, suggesting that a more pronounced term (angular definition of foot placement; Figure 2) is associated with increased acuteness. Biomechanically, a greater term may produce a more defined kinematic pattern, enhancing movement sharpness (Rhodin *et al*., 2009). Acuteness in the PPH is linked to neuromuscular precision and coordination, involving selective activation of the flexor and extensor muscle groups. A more accentuated term may reflect greater engagement of these structures, contributing to the characteristic gait definition of this breed (Nicodemus & Clayton, 2003). Similarly, the weak positive partial correlation between extension and term suggests a mild association, likely influenced by multiple factors including overall conformation, musculature, and breeder-specific training regimens. Comparative studies in sport horses have shown that greater limb elevation and extension correlate with improved performance in jumping disciplines (Licart, 2019), suggesting that the relationship between acuteness and extension may be a common factor in equine athletic performance, despite differences in breed and discipline.

Applying IRT to the gluteal muscles of PPHs offers a non-invasive way to assess muscular activity and overall health (Howell *et al*., 2020; Yarnell *et al*., 2014). The weak correlation between stride extension and GTD suggests that factors such as metabolic efficiency and circulatory dynamics outweigh the influence of extension on post-exercise thermoregulation (Kruljc, 2023; Da Silva *et al*., 2022; Soroko *et al*., 2014). Conversely, the weak negative correlation between extension and vertical acceleration indicates that greater extension reduces vertical acceleration variability, likely due to a more stable gait and less vertical oscillation of the center of mass (Hobbs *et al*., 2018).

The moderate negative correlation between overreach and vertical acceleration suggests that higher overreach values are linked to lower vertical acceleration, likely due to improved force distribution and shock absorption, enhancing gait stability and reducing musculoskeletal impact (Gómez-Álvarez *et al*., 2009). Similarly, the negative correlation between vertical acceleration and GTD indicates that horses with lower vertical oscillation exhibit greater GTDs post-exercise, possibly due to more efficient blood flow and thermal regulation in controlled, low-impact movements (Lisboa *et al*., 2023; Soroko & Howell, 2018). The moderate positive correlation between acuteness and GTD supports the hypothesis that precise, rapid movements generate increased muscular heat, which is consistent with studies showing that dynamic movements require efficient muscle activation, resulting in elevated thermal output (Prochno *et al*., 2020; Soroko *et al*., 2017; Lisboa *et al*., 2023). These findings suggest that horses with higher GTD values may also achieve higher peak muscle temperatures, reflecting significant muscular effort during propulsion.

However, while these correlations are informative, infrared thermography alone cannot fully elucidate the underlying physiological mechanisms. Therefore, its integration with other biomechanical and diagnostic tools is recommended for comprehensive assessment of equine performance, particularly in high-demand disciplines such as those involving the PPH (Kruljc, 2023; Da Silva *et al*., 2022; Redaelli *et al*., 2014; Rietbroek *et al*., 2007; Texeira *et al*., 2020). Integrating such data would enable animal scientists and breeders to make informed decisions regarding training and welfare, ultimately enhancing long-term health and performance. However, further research is needed to elucidate the relationship between performance metrics of the PPH and infrared thermographic patterns.

Correlation among morphometric traits

Among the significant positive correlations, the moderate association between withers height and thoracic girth was noteworthy. This relationship indicates that taller horses tend to have a broader chest, a finding consistent with Müller *et al*. (2020) in Criollo horses, who reported that both withers height and thoracic girth are strongly influenced by genetic factors and vary according to sex. This suggests that these morphometric traits may serve as key selection criteria in genetic improvement programs aimed at optimizing conformation and body size.

Moderate positive correlations were also observed between forelimb and hindlimb cannon bone circumference and withers height, indicating that taller horses generally have thicker cannon bones. This may contribute to enhanced stability and load-bearing capacity. However, it should be noted that such correlations may also be influenced by genetic and biomechanical factors that shape the overall morphology, including the skeletal structure and limb musculature. Withers height may be related to the proportional development of other traits, such as cannon bone circumference and croup width, which are indicators of limb robustness (Padilha *et al*., 2017). Previous studies have established a direct relationship between withers height and skeletal structure across various horse breeds, highlighting its importance in determining load capacity and athletic performance (Gómez *et al*., 2012). Furthermore, Kawareti *et al*. (2017) observed that in growing horses' certain traits, such as cannon bone circumference, reach maturity early and stabilize over time, reinforcing their reliability as phenotypic markers in breeding programs.

The correlation observed between these two angles suggests a biomechanical relationship that influences gait patterns, whereby adjustments in one joint angle may affect the other to optimize stride efficiency. Biomechanical studies indicate that harmonious alignment of the scapulohumeral and coxofemoral angles is crucial for smooth, energy-efficient locomotion, enabling optimal utilization of propulsive forces during gait (Back & Clayton, 2012; Dos Santos *et al*., 2011). In the PPH, the alignment and structure of the hindlimbs, particularly the femur, are fundamental for providing the propulsion and stability required for its characteristic gait. This balance between forelimb and hindlimb joint angles is essential for movement efficiency and athletic longevity (Senna *et al*., 2015). Proper alignment and optimization of shoulder and hip joint angles not only promote biomechanically efficient performance, but also help reduce the risk of musculoskeletal injuries, ensuring the sustainability of physical exertion and preserving the structural integrity of the animal (Anderson & McIlwraith, 2004).

The low-to-moderate positive correlation between hock angle and humeral length indicates a direct biomechanical relationship. This finding aligns with those of previous studies assessing limb angulation and locomotor efficiency in lateral-gaited equines (Clayton & Hobbs, 2019; Schils *et al*., 2019). This biomechanical interdependence can be explained by the functional integration of anatomical structures influencing movement mechanics and breed-specific performance (Clayton *et al*., 2023). The hock angle is a key determinant of equine locomotor biomechanics, affecting the animal's ability to generate propulsion and maintain efficient stride patterns (Piché *et al*., 2020; Holmström, 2001). In gaited breeds, such as the PPH, hindlimb joint biomechanics play a crucial role in ensuring gait fluidity and lateral step stability (Weishaupt *et al*., 2009). A more open hock angle may be associated with a prolonged support phase, reduced vertical oscillation of the center of mass, improved shock absorption, and efficient force transmission, resulting in a smoother, more harmonious gait (Weishaupt *et al*., 2013; Back & Clayton, 2012). This is facilitated by enhanced flexion and extension capabilities, which optimize movement efficiency and reduce loading on the hindlimbs (Weeren & Crevier-Denoix, 2006).

The positive correlation observed in this study between humeral length and hock angle suggests that horses with longer humeri tend to exhibit a more open hock angle, potentially promoting greater hindlimb extension and a more efficient, harmonious gait pattern (Hobbs *et al*., 2018). From a functional standpoint, selecting individuals with favorable combinations of these traits could optimize the gait biomechanics of the PPH, enhancing stability and endurance during prolonged movement (Clayton & Hobbs, 2017). Understanding this anatomical relationship is essential for genetic programs seeking to preserve the functional and esthetic traits of the breed and ensure their transmission for performance and selective breeding.

The morphometric correlations identified in this study demonstrated that relationships between traits can vary when accounting for confounding factors, as revealed by partial correlation analyses. Age plays a critical role in morphometric correlations, particularly in developing horses. According to Kawareti *et al*. (2017), most morphological traits reach full development by approximately four years of age, with exceptions such as thoracic girth, which may continue to increase. This pattern suggests that, upon reaching maturity, horses tend to maintain a stable conformation, which is advantageous for planning training and nutritional management. Additionally, genetic influence on traits such as height and thoracic girth is substantial, as these are largely governed by additive genetic effects (Müller *et al*., 2020). Maternal and paternal effects vary depending on the animal's sex, highlighting their significance in genetic selection programs. Moreover, environmental factors, including nutrition and management practices, can influence thoracic and cannon bone circumference, particularly under the diverse rearing conditions found among PPH breeders (Kubistova *et al*., 2024; Gómez *et al*., 2008).

Correlation among morphometric, functional, and gluteal temperature difference

The total and partial correlations observed in this study were diverse, with many being non-significant. For clarity, the most relevant associations between functional traits, gluteal temperature differences, and morphometric characteristics are discussed below.

The results indicated negative correlations between forelimb extension and height-related measurements in the PPH. Although of moderate magnitude, these correlations suggest that, as withers and croup height increase, forelimb extension tends to decrease. Understanding these relationships is crucial in the context of equine morphometry and genetic improvement, as body proportions directly influence functionality and performance. Previous studies have demonstrated that specific morphometric traits can affect locomotion and movement efficiency across equine breeds. A biometric analysis of the Araucano Criollo horse identified significant associations between various body measurements, underscoring the importance of conformation in functional performance (Salamanca *et al*., 2017). Similarly, negative correlations between gait quality and morphometric traits have been reported in Campolina horses, suggesting that selection for specific gaits may require a different approach than selection based solely on morphological characteristics (Bussiman *et al*., 2018).

Furthermore, Müller *et al*. (2020) documented significant differences in limb lengths across equine breeds, which may influence athletic performance and musculoskeletal health. These findings are relevant when interpreting the negative correlations observed in this study, as they suggest that forelimb length may be inversely related to other body measurements, potentially affecting the biomechanics of the PPH. Notably, geometric morphometrics have been applied in studies of morphological variation across species, including equines, to better understand the relationships between body measurements and functional outcomes (Zelditch *et al*., 2012). Additionally, the integration of morphometric and phylogenetic analyses has led to significant advances in systematics and evolutionary biology (De Luna, 2020). Beyond height measurements, significant correlations between the scapular angle and forelimb extension reinforce the hypothesis that an optimal scapular conformation enhances locomotor efficiency, facilitating a broader and smoother characteristic gait. This finding aligns with research on the Pura Raza Menorquina, in which upper limb joint angles influenced the range of motion and agility, favoring desirable conformational traits (Perdomo-González *et al*., 2022). The weak positive correlation between thoracic girth and forelimb extension suggests that a more developed thorax may contribute to a wider, more stable stride, essential for the characteristic gait of PPHs. This observation is consistent with prior evidence linking thoracic girth to respiratory capacity and muscular strength, which are key attributes for optimal performance in endurance disciplines (Rezende *et al*., 2021).

This study identified low-to-moderate positive correlations between withers and croup height, and overreach in the PPH. These associations suggest a moderate relationship between morphological development and locomotor performance. Comparisons with studies on other breeds reveal similar patterns. For instance, Cervantes *et al*. (2009) reported a positive correlation between withers height and athletic performance in Arabian horses, indicating that height-based selection may be effective in genetic improvement programs. The present findings further emphasize the need for a holistic breeding approach that integrates both esthetic and functional traits.

A moderate positive correlation between overreach and femur length suggests that longer femurs enhance hindlimb engagement, with implications for the PPH biomechanics. This relationship should inform functional assessments using morphometric data across management conditions. Monteza Carranza (2021) provided valuable data on the PPH body proportions in Cutervo, Cajamarca, though not specifically addressing this correlation.

The correlation between overreach and extension ranged from low to moderate, suggesting that forelimb length may influence hindlimb engagement. According to Gregory (2014), an appropriate limb length is crucial for locomotor effectiveness and force distribution, implying that horses with longer limbs may achieve more efficient and powerful movements. Such traits could lead to more effective overreach, enhancing propulsion and stride expansion. The positive correlation between overreach and extension may also reflect the tendency of horses with longer limbs to exhibit greater stride length, improving movement efficiency and optimal energy utilization during propulsion (Procópio *et al*., 2003). Thus, the morphological development of the forelimbs appears to play a significant role in the efficiency of overreach in the PPH.

In this study, term correlated weakly with croup width ($r = +0.17$) and negatively with metacarpal and metatarsal lengths (−0.178 and −0.167, respectively), indicating complex trait–performance interactions. The positive link with croup width may reflect greater hindquarter musculature, consistent with Bussiman *et al*. (2018), who associated a wider croup with enhanced propulsion and load bearing. The negative correlations suggest that longer distal limbs may reduce term expression, possibly reflecting a biomechanical trade-off between fore- and hindlimb proportions in the PPH. Hoyt *et al*. (2000) noted that shorter limbs affect gait and stride, potentially limiting performance.

Acuteness exhibited the highest number of significant morphometric correlations, albeit of low magnitude, indicating a trend in which increased body measurements are associated with reduced sharpness of movement. Greater acuteness involves a more pronounced elevation of the forelimb, influencing stride dynamics and load distribution. The negative correlations between acuteness and subpectoral and dorsal height suggest that horses with higher forelimb lift tend to have a more compact thoracic and dorsal conformation. This may reflect functional adaptations favoring the distinctive gait of PPHs, in which an elevated forelimb movement contributes to a more refined and accentuated stride. The weak negative correlation with brachial angle indicates that a more closed angle may facilitate greater flexion and extension, enhancing mechanical efficiency, which is desirable in disciplines requiring rhythmic, stylized movement. However, the low correlation strength suggests a weak association, potentially modulated by management and training practices. These observations align with findings in Pura Raza Menorquina horses, in which morphometric traits showed limited functional correlation unless environmental and management factors were considered (Perdomo-González *et al*., 2022), highlighting the need for integrated selection strategies.

This study also investigated the relationship between GTD and morphometric traits. This is supported by human studies showing that surface temperature can be influenced by body composition and anthropometric indices (Fernández-Cuevas *et al*., 2015). In equines, infrared thermography aids in identifying thermal anomalies indicative of inflammation or injury (Turner, 1991). Most correlations were negative, suggesting that horses with larger body dimensions or girths exhibit smaller post-exercise increases in gluteal temperature. This may be due to the enhanced thermoregulatory capacity in more robust animals, possibly resulting from greater muscle mass facilitating heat dissipation (Lidiany *et al*., 2024; Soroko *et al*., 2019; Teixeira *et al*., 2020).

However, the spatial distribution of GTD does not always align with the region of highest thermal increase, likely due to the complex anatomy and physiology of the gluteal region. The gluteus medius, a primary locomotor muscle, experiences significant loading during movement (Boffi, 2011). During exercise, differential activation across muscle regions can lead to variable metabolic heat production, and consequently, heterogeneous surface temperature patterns.

Additional factors, such as blood flow distribution, adipose tissue presence, and individual horse characteristics, can influence heat dissipation and thermal patterns. Highly vascularized areas may exhibit more efficient cooling, resulting in lower surface temperature rises despite high underlying muscular activity (Turner, 1991). It is also important to note that thermography measures skin surface temperature, which may not uniformly reflect internal metabolic activity due to variations in tissue thermal conductivity and external factors such as ambient temperature and humidity (Turner, 1991).

Moderate positive correlations between gluteal temperature differences and back inclination, metatarsal length, and acuteness suggest that certain anatomical traits may increase post-exercise gluteal heat. Higher acuteness may reflect gait mechanics that generate more heat during the paso llano. Low-to-moderate correlation values imply additional influences such as fitness, training, nutrition, and environment. Future studies could use infrared thermography to non-invasively assess thermal patterns and their links to functional and morphometric traits.

Vertical acceleration during the paso llano is a key parameter for assessing the smoothness and efficiency of the characteristic gait of the PPH. The correlation values obtained between RMS-measured vertical acceleration and various morphological and functional variables provided detailed insights into how physical conformation influences movement dynamics. A previous study by the authors established vertical acceleration as an objective indicator of gait smoothness (Vilela & Quintana, 2023).

The positive correlation between vertical acceleration and withers height suggests that taller individuals may exhibit greater vertical oscillation during the paso llano. This is consistent with prior studies indicating that increased height elevates the center of gravity, influencing vertical movement dynamics (Barrantes *et al*., 2009). Conversely, negative correlations were observed with hock angle (-0.322), femorotibial angle (-0.211), and femur length (-0.184), indicating that greater joint flexion and shorter femurs are associated with reduced vertical acceleration. Enhanced joint flexion improves shock absorption during stance, decreasing transmitted vertical forces and overall oscillation. This mechanism is documented in other breeds, in which increased hindlimb angulation contributes to smoother, more efficient gaits (Monteza Carranza, 2021; Procópio *et al*., 2003). Moreover, negative correlations with the coxofemoral angle highlight its role in gait stability. Greater flexibility of this joint may reduce vertical displacement, enhancing stride control and consistency. These findings suggest that genetic improvement programs should prioritize specific joint angles to preserve the signature smoothness and gait regularity of PPHs.

The negative correlation of -0.305 between vertical acceleration and maximum GTD suggests an inverse relationship between gluteal muscular activity and vertical oscillation. A lower temperature differential may indicate less muscular activity or more efficient heat dissipation, which is potentially linked to a movement technique that minimizes vertical fluctuations. This is relevant, as reduced excessive muscular effort may enhance movement efficiency and decrease fatigue during exercise (Turner, 1991). Comparative studies in sport horses have shown that conformations favoring greater joint flexion and efficient musculature are associated with smoother gaits and lower vertical accelerations. Research on performance horses has linked increased hindlimb angulation to improved impact absorption and reduced vertical forces (Turner, 1991).

In conclusion, this study provides novel insights into the PPH by demonstrating that: first, its characteristic gait arises from a finely tuned neuromuscular coordination between forelimb and hindlimb kinematics, despite the inherent decoupling of limb movements in lateral-sequence gaits; second, key morphometric traits, including femur length, croup width, and specific joint angles, are significantly associated with functional performance and post-exercise gluteal thermal patterns, underscoring their value as selection criteria in breeding programs aimed at preserving both biomechanical efficiency and breed-specific conformation; and third, infrared thermography, when integrated with morphometric and kinematic analyses, serves as a promising non-invasive tool for assessing muscular activity and thermoregulatory responses, although its interpretation must account for confounding factors such as fitness, training, and environmental conditions to enable robust, evidence-based decisions in equine management and genetic improvement. These findings are pivotal for advancing our understanding of how conformation influences locomotor performance, biomechanical efficiency, and overall well-being in this unique breed, laying the foundation for evidence-based breeding and management strategies.

Competing interests statement

The authors state that records of eight animals owned by José Dextre were used. It is also stated that José Dextre was Chairman of the Board of the Universidad Científica del Sur during the development of the methodological phase of this research.

Ethics statement

The study was approved by the Institutional Committee of Ethics in Research with Animals and Biodiversity of the Universidad Cientifica del Sur (N° 078-CIEI-AB-CIENTÍFICA-2022)

Data availability statement

The datasets presented in this article are not readily available because they are part of an ongoing study. In addition, the data is not published due to privacy restrictions.

Author contributions

J.L.V.V. and P.G.M.Q.D., contributed to the conduct and design of the study. J.L.V.V., P.G.M.Q.D. and M.L.V.M., executed the experiment. J.L.V.V. organized, edited, processed and analyzed the data. All au¬thors interpreted the data, critically revised the manuscript for important intellectual content, and approved the final version.

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