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Pelvic Shape Variation in Domestic Rabbits: Influence of Sex, Breed and Reproductive Status

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ABSTRACT

The present study investigates the influence of biological and functional factors—namely, sex, reproductive status, age and breed—on pelvic morphology in domestic rabbits (*Oryctolagus cuniculus*) using two-dimensional geometric morphometric methods. A total of 38 skeletally mature individuals (19 males and 19 females, of which 13 were nulliparous and 6 had a history of parturition) were examined through pelvic radiographs. Landmark-based shape analysis was conducted on digitized radiographic images to quantify morphological variation. Procrustes ANOVA results indicated no statistically significant shape differences between males and females, nor between parous and nulliparous females. Additionally, no significant pelvic shape variation was detected among different breeds. A multivariate model incorporating both age and sex also failed to reveal a meaningful association with shape variability. Principal component analysis (PCA) revealed that the first two principal components accounted for a substantial proportion of overall shape variation, yet this variation did not correspond with any of the investigated biological categories. These findings suggest that pelvic morphology in domestic rabbits remains relatively stable regardless of sex, reproductive status, or breed, with shape variation largely reflecting individual-level differences rather than group-level functional or developmental constraints. This study contributes to the anatomical understanding of lagomorphs and provides a baseline for future research exploring the functional morphology and clinical assessment of the pelvic region in rabbits.

1 | Introduction

The pelvis is one of the central components of the mammalian skeletal system, functioning as both a critical structure for locomotion by connecting the hindlimbs to the axial skeleton and as a key anatomical site involved in reproductive processes. In species such as humans, the pelvis is considered the most reliable skeletal region for sex estimation and obstetric evaluation due to its pronounced morphological differences between sexes (Gonzalez et al. 2009; Rmoutilová et al. 2017). However, in small domestic mammals such as rabbits (*Oryctolagus cuniculus*), which are commonly used in laboratory settings and as companion animals, the morphological variation and functional anatomy of the pelvic structure remain poorly understood.

Previous studies in humans and domestic animals have demonstrated that pelvic morphology can exhibit significant differences related to sex (Cox 2021; Nganvongpanit et al. 2016a; Manuta

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et al. 2023), reproductive history (Stansfield et al. 2023), and genetic background (Özkan et al. 2024). For instance, in canines, geometric morphometric analyses have identified sex-specific variations in pelvic canal width and the structure of the crista iliaca (Özkan et al. 2024). Similarly, research on human os coxae has shown that female pelvic morphology tends to be more constrained than male morphology—a phenomenon attributed to the evolutionary trade-off between bipedal locomotion and childbirth, commonly referred to as the 'obstetrical dilemma' (Candelas González et al. 2016).

Despite this, it remains unclear whether similar patterns of morphological divergence exist in rabbits or whether their pelvic anatomy reflects a more conservative design with limited sexual dimorphism. Investigating whether the rabbit pelvis is shaped in response to functional reproductive and locomotor demands is crucial for addressing a significant knowledge gap in veterinary anatomy and evolutionary morphology. Moreover, it is unknown whether parturition induces measurable changes in the bony pelvis of rabbits, as has been debated in human studies (Stansfield et al. 2023; Rmoutilová et al. 2017).

Geometric morphometrics, compared to traditional morphometric techniques, offers a more sensitive and statistically robust approach to assessing shape variation, particularly in complex (Eravci Yalin et al. 2025; Gundemir and Szara 2025; Manuta et al. 2024), curved anatomical structures such as the pelvis (Cox 2021; Gonzalez et al. 2009; Milella et al. 2014; Jashari et al. 2022). This method allows for the quantification of shape independently of size and orientation and has been successfully applied to detect subtle differences both between individuals and among defined biological groups (Álvarez et al. 2013; Torres-Tamayo et al. 2020). Techniques such as semilandmark analysis and Procrustes superimposition have proven effective in identifying shape changes and functional constraints in various mammalian taxa (Rmoutilová et al. 2017; Candelas González et al. 2016; Szara et al. 2023).

The present study aims to investigate the effects of biological variables such as sex, reproductive status, age, and breed on pelvic shape in domestic rabbits by using two-dimensional (2D) geometric morphometric methods applied to standardized radiographic images. The goal is to determine whether shape variation is primarily explained by group-level functional or developmental factors, or whether it is dominated by individual-level differences. This work not only enhances our anatomical understanding of rabbit skeletal morphology but also provides foundational data for clinical veterinary applications, breeding strategies, and comparative morphological studies across mammalian taxa.

2 | Materials and Methods

2.1 | Animals and Landmarks

A total of 38 adult domestic rabbits (*O. cuniculus*) were included in this study, comprising 19 males and 19 females. Among the females, 13 were nulliparous, and 6 had a known history of parturition (Table 1). All individuals were skeletally mature and aged between 1.0 and 2.5 years. The rabbits belonged to several different breeds, including Holland Lop ($n = 18$), Rex ($n = 3$), New Zealand ($n = 2$), Dwarf ($n = 2$), Belgian ($n = 1$), Ankara ($n = 1$) and mixed breed ($n = 11$).

TABLE 1 | Summary of the rabbits used in the study.

Sex	Reproductive status	Number of individuals	Age range (years)
Female	Nulliparous	13	1.0–2.5
Female	Multiparous	6	1.5–2.5
Male	—	19	1.0–2.5
Total		38	1.0–2.5

Standardized pelvic radiographs were obtained from live animals using dorsoventral projection without sedation, ensuring minimal stress and optimal positioning. The imaging procedures were performed in accordance with animal welfare regulations, and the study was exempted from ethics committee approval according to the institutional decision (Decision No: 2025/26). Only radiographs showing clear anatomical structures and no signs of injury or deformity were included in the morphometric analysis. Breed information was recorded when available.

For the geometric morphometric analysis, radiographic images of 38 adult rabbits were initially converted into PNG format and then into thin-plate spline (TPS) files using the tpsUtil software (Version 1.74). Following this, a total of 26 homologous anatomical landmarks were digitized on each radiograph using tpsDig (Version 2), as illustrated in Figure 1. These landmarks were selected on the basis of their clear visibility and anatomical relevance to pelvic morphology. The resulting coordinate data were converted into '.tps' format and subsequently imported into R (Version 4.4.2) for geometric morphometric analysis.

2.2 | Statistical Analysis

All morphometric analyses were carried out using R version 4.4.2 with the geomorph package. The dataset of pelvic landmarks obtained from radiographs was first subjected to generalized Procrustes analysis (GPA) in order to remove non-shape variation related to position, orientation and scale. This step provided standardized shape coordinates that were used in all subsequent analyses.

To explore the major axes of shape variation, principal component analysis (PCA) was applied to the Procrustes-aligned coordinates. The first two principal components were visualized using scatterplots, and shape changes associated with these axes were illustrated using TPS deformation grids. The percentage of total variation explained by the first principal component (PC1) and second principal component (PC2) was calculated and used to interpret the relevance of each component.

Group differences in shape were assessed using Procrustes ANOVA models. First, the potential influence of sex on pelvic shape was tested by comparing male and female individuals. Then, within the female group, the effect of reproductive status, specifically, whether the individual had given birth, was

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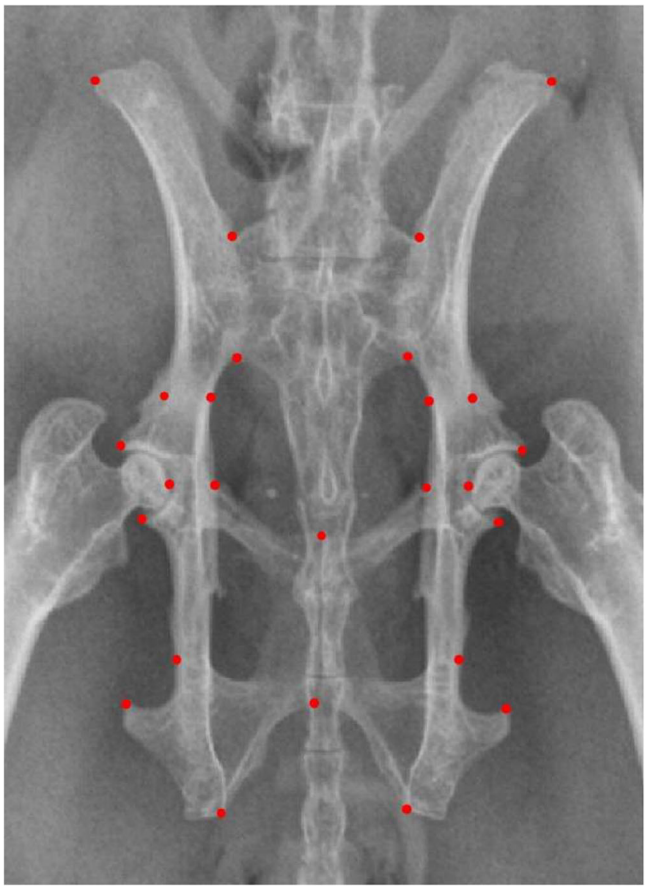


FIGURE 1 | Ventro-dorsal (VD) radiographic image of a rabbit pelvis (coxae) with 26 homologous landmark points indicated in red. Landmarks were placed on anatomically consistent, homologous locations to capture shape variation for geometric morphometric analysis.

evaluated. Additionally, breed-related differences were examined to identify any patterns linked to genetic background. Finally, a multivariate model incorporating both age (as a continuous variable) and sex (as a categorical factor) was implemented to determine their combined effects on shape.

All models were fitted using a residual randomization permutation procedure with 1000 iterations to obtain robust significance estimates. PCA and TPS visualizations were used in parallel with the statistical results to interpret shape variation more clearly.

3 | Results

PCA revealed the main axes of shape variation in the rabbit pelvis (Figure 2). PC1 accounted for 36.9% of the total shape variation, whereas PC2 explained an additional 14.0%, together capturing more than half of the overall variation (50.9%). The scatterplot of PC1 versus PC2, with individuals coloured by sex, did not reveal a clear clustering pattern between females and males, suggesting high individual variability and considerable shape overlap between sexes.

Shape deformation grids corresponding to the extremes of PC1 and PC2 indicate the morphological directions associated with these axes. Along PC1, variation was primarily characterized by medio-lateral compression and elongation in the pelvic structure. In contrast, PC2 variation reflected vertical displacement patterns and localized expansions or contractions in the posterior pelvic region. Despite the visual differences along these components, these shape changes did not correspond to distinct group separations.

A total of 38 pelvic radiographs were analysed to explore the effects of sex, parity status (birth-giving vs. non-birth-giving females), age and breed on pelvic shape in rabbits using 2D geometric morphometric methods. Landmark configurations were aligned via GPA, and variation in shape was subsequently assessed through a series of Procrustes ANOVA models (Table 2).

Initial analyses focused on potential sexual dimorphism in pelvic morphology. The Procrustes ANOVA revealed that sex did not significantly influence pelvic shape ($F = 0.4240$, $p = 0.9341$), accounting for only 1.2% of the total shape variation. The Z-score (−1.52) further suggested a negligible effect. These results indicate that no statistically meaningful shape differences exist between male and female rabbits within the sample examined, suggesting limited or absent sexual dimorphism in pelvic morphology at the level captured by 2D landmarks.

To evaluate the impact of reproductive history, a subset of female individuals was analysed to compare nulliparous and parous rabbits. The analysis again revealed no statistically significant difference in pelvic shape between these groups ($F = 0.7258$, $p = 0.6583$), with parity explaining only 2.0% of the total variance. This suggests that the experience of parturition does not result in consistent or directional shape changes in the pelvis, at least among the individuals measured.

We further examined the joint effects of age and sex using a multivariate Procrustes ANOVA. Although sex continued to show no significant contribution to shape variation ($F = 0.4240$, $p = 0.9341$), age accounted for a slightly greater proportion of shape variation (4.3%), though this trend did not reach statistical significance ($F = 1.4895$, $p = 0.1419$). The positive Z-score (1.08) may point to a weak but potentially biologically relevant trend in which pelvic shape subtly shifts with increasing age. However, the lack of significance suggests that these changes are either highly individual or not pronounced enough to detect with the available sample size.

Lastly, the potential for breed-specific pelvic shape differences was assessed in a subset of 28 individuals representing six different breeds. Breed accounted for 17.2% of the variation in shape, but the overall effect was not statistically significant ($F = 0.9169$, $p = 0.5954$). Although this proportion of explained variance is notably higher than that attributed to sex or parity, the lack of statistical significance—along with a negative Z-score (−0.24)—suggests that breed-related pelvic shape differences are not strongly expressed or consistent in the present sample. Nevertheless, the relatively higher Rsq may indicate an underlying breed effect that could become more evident with increased sample size or breed-specific stratification.

Collectively, these findings suggest that pelvic shape variation in rabbits is predominantly individual-based, with no statistically

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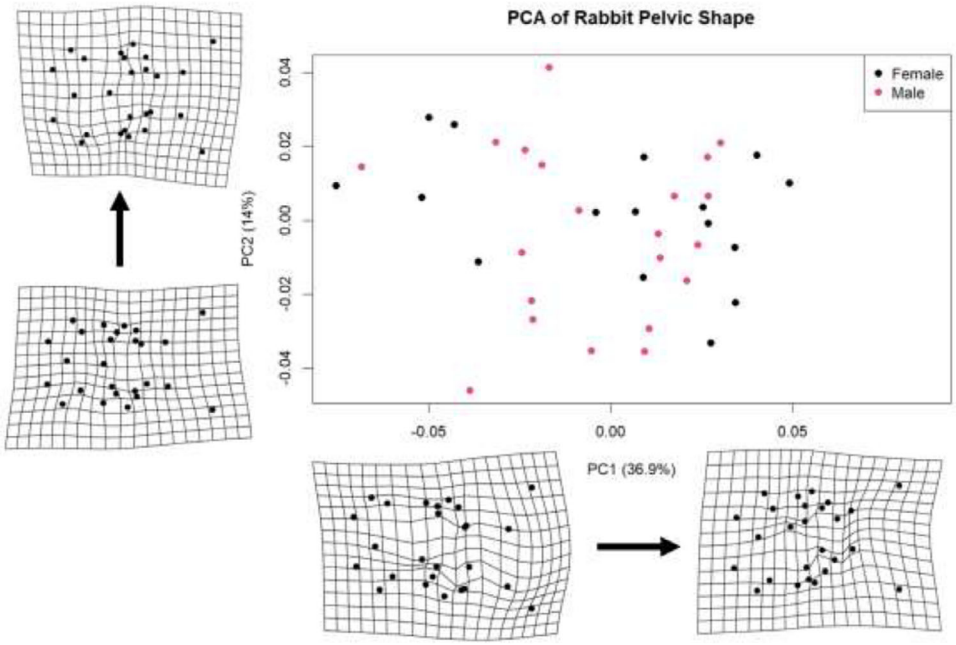


FIGURE 2 | Visualization of shape variation along principal components PC1 and PC2 with corresponding deformation grids showing positive and negative extremes. PCA, principal component analysis.

TABLE 2 | Procrustes ANOVA results evaluating the effects of sex, parity, age and breed on rabbit pelvic shape.

Effect	Df	SS	MS	Rsq	*F*	*Z*	*p* value
Sex	1	0.000529	0.000529	0.00439	0.1587	−3.75	0.999
Residuals	36	0.120080	0.003336	0.99561			
Parity (females only)	1	0.002384	0.002384	0.01976	0.7258	−0.42	0.6583
Residuals	36	0.118226	0.003284	0.98024			
Age	1	0.004718	0.004718	0.04266	1.4895	1.08	0.1419
Sex (covariate model)	1	0.001343	0.001343	0.01214	0.4240	−1.52	0.9341
Residuals	33	0.104525	0.003167	0.94519			
Breed	5	0.014524	0.002905	0.17245	0.9169	−0.24	0.5954
Residuals	22	0.069700	0.003168	0.82755			

Note: Rsq = proportion of explained variance (R^2); F = F-statistic; Z = effect size based on permutation-derived Z-scores; p value = statistical significance based on 1000 random permutations.

Abbreviations: Df, degrees of freedom; MS, mean square; SS, sum of squares.

significant effects of sex, reproductive status, age or breed detected. Although certain variables (particularly age and breed) show non-significant but relatively higher proportions of explained variance, the current dataset does not provide sufficient evidence to attribute shape differences to these factors with confidence. Future studies with larger, more balanced samples and higher resolution shape data may help clarify the subtle patterns suggested by the present analyses.

4 | Discussion

This study demonstrated that pelvic morphology in domestic rabbits (*O. cuniculus*) does not exhibit statistically significant shape variation based on key biological variables, such as sex, reproductive status, age or breed. Two-dimensional geometric morphometric analyses revealed that pelvic shape is largely influenced by individual-level variation rather than group-level differences. These findings suggest that the rabbit pelvis represents a relatively conservative morphological structure, minimally affected by sex or reproduction-related biological factors.

In contrast, the pelvis in humans and several other mammalian species often displays marked morphological differences associated with sex and reproductive function. In humans, the female pelvis is characteristically wider and adapted for childbirth, representing a clear example of sexual dimorphism (González et al. 2016; Waltenberger et al. 2020). Likewise, geometric morphometric studies in dogs have shown that females tend to have wider pelvic canals and different iliac flare angles compared to

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males (Nganvongpanit et al. 2016b; Özkan et al. 2024). However, this study found no such significant pelvic shape differences between sexes in rabbits, suggesting that in species subject to lower mechanical and reproductive demands, pelvic morphology may remain more evolutionarily conserved.

No significant differences in pelvic morphology were found between parous and nulliparous females. Human studies have reported various skeletal and muscular alterations in the pelvis associated with childbirth, including changes in pelvic shape, parturition scars and asymmetric mechanical loading (Waltenberger et al. 2020; Mitteroecker et al. 2023). However, whether such changes occur is contingent on the amount of biomechanical stress during delivery and the species-specific reproductive anatomy. In small mammals such as rabbits, the relatively small size of neonates and minimal strain on the birth canal may not be sufficient to induce post-parturition pelvic remodelling.

Regarding age, the sample in this study was limited to adult individuals, potentially restricting the detection of age-related variation. In humans, age-related degenerative changes in the pelvis, such as reductions in bone mass and alterations in pelvic symmetry, have been documented, particularly in elderly populations (Steyn et al. 2004; Schultz 1949). However, in rabbits, the skeleton appears to stabilize after reaching adulthood, possibly explaining the absence of age-related pelvic shape changes.

Breed-based variation in pelvic morphology was also not observed. In contrast, dogs of different functional breeds often exhibit distinct pelvic shapes, likely due to artificial selection pressures or biomechanical specialization (Özkan et al. 2024). The lack of such differences in rabbits may reflect limited selective breeding for skeletal features or a relatively homogeneous functional lifestyle across breeds.

A notable aspect of this study is the predominance of individual-level variation over group-based differences. This suggests that genetic variability, developmental plasticity, and microenvironmental factors play substantial roles in shaping pelvic morphology (Milella et al. 2014; Álvarez et al. 2013). Moreover, morphometric research frequently reports greater within-population variability than between-group differences, a pattern that appears consistent in this dataset (Adams and Funk 1997).

Allometry, or the relationship between size and shape, is another key consideration in morphological studies (Gündemir et al. 2025; Eravci Yalin et al. 2024) However, in this analysis, shape variation was evaluated independently of size, and no strong allometric effects were detected. This finding supports the idea that pelvic shape changes are not primarily governed by growth-related factors but instead by developmental and genetic influences (Auerbach and Sylvester 2010). In light of these findings, caution must be exercised when making interspecies comparisons of pelvic morphology. Morphological patterns observed in humans or dogs such as strong sexual dimorphism or parity-related remodelling may not be directly applicable to small mammals like rabbits. This study contributes to our understanding of pelvic evolution and highlights the importance of species-specific analyses in assessing functional and morphological adaptations.

This study demonstrated that pelvic morphology in domestic rabbits (*O. cuniculus*) does not show significant variation based on sex, age, reproductive status or breed. Geometric morphometric analysis revealed considerable individual-level variation, with no statistically significant differences between groups. These findings suggest that the pelvis in this species is highly conserved, likely due to limited functional demands and weak selective pressures.

Author Contributions

Ebuderda Günay: conceptualization, investigation. **Emine İrem Deveci**: investigation, supervision. **Ekin Sevim Topkaya**: investigation, supervision, editing. **Merver Yilmaz**: conceptualization, investigation. **Muhammed Taha Temir**: conceptualization, investigation, software. **Aslihan Baykal Uğur**: conceptualization, editing. **Zeynep Günay Uçmak**: investigation, software. **Barıs Can Guzel**: supervision, writing – original draft, writing – review and editing. **Oleksii O. Melnyk**: writing – original draft, writing and review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study can be requested from the corresponding author.

Peer Review

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