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A Morphometric Analysis of the Digital Bones in Karagouniko Sheep and Hellenic Goat

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Simple Summary: The digital bones of artiodactyls are the subject of research in the fields of osteoarchaeology, evolution, physiology, and lameness. Measurements of the phalanges of an ovine species and a caprine species were recorded and some indexes of slenderness were calculated in order to present a dataset of values, which are useful in the aforementioned scientific disciplines. Differences were detected between the phalanges of the third and fourth digits, as well as the fore and hind limbs. Furthermore, the indexes calculated were found to be effective in differentiating the third phalanx between sheep and goats as well as in distinguishing between the fore and hind digits. The length of the first phalanx of the fourth fore digit for sheep and the length of the first phalanx of the fourth hind digit for goats were identified as the most useful parameters for the prediction of the lengths of the first and second phalanges. From an archaeological perspective, the prediction equations that were also calculated seem to be of significant value.

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Abstract: The phalanges of Karagouniko ewes and Hellenic goats were the subject of the present quantitative study, with the objective of determining whether any differences existed on the corresponding bones of the different digits. The lengths of the phalanges of the third and fourth digits of the fore and hind autopodia, the smallest diaphyseal breadths of the first and second phalanges, the breadths of the proximal and distal ends of the first and second phalanges, the lengths of the dorsal surfaces of the third phalanx, and the heights of the extensor processes of the third phalanx were measured. A total of 44 linear measurements were recorded for each animal species. The summation of the lengths of the digital bones revealed that the third frontal digit was longer than the fourth frontal digit in both animal species and the fourth hind digit was longer than the third hind digit in both animal species. Furthermore, the lengths of the third and fourth frontal digits were greater than those of the corresponding hind digits in both species. The findings of the current metric analysis suggest that the lengths of the paired digits differ in sheep and goat. The results indicate that the morphometry of the digital bones could be important from phylogenetic, biomechanical, and clinical aspects.

Keywords: ovine; caprine; phalanges; measurements

1. Introduction

Ruminants represent a diverse group of animals employed in the field of animal production and constitute a component of wild fauna. Their distinctive morphological characteristics, particularly those pertaining to distal portions of their limbs, are a hallmark of their anatomical configuration. Classified as artiodactyls, the autopodial bones of these creatures have consistently garnered research interest from a myriad of scientific disciplines, including evolutionary studies, archaeozoology, physiology, and pathology. The significance of research into digital bones is multifaceted, having inspired investigations into archaeology, adaptation, biomechanics, and pathology in animals (Table 1).

Table 1. Research on the digital bones of artiodactyls.

Animal	Species	Methodology/Field of Investigation	Reference
Cattle	*Bos taurus*	Measurements	Ocal et al., 2004 [1]
Cattle	*Bos taurus*	Osteoarcheology	Maldre 2007 [2]
Cattle	*Bos taurus*	Radiography	Muggli et al., 2011 [3]
Cattle	*Bos taurus*	Radiography	Muggli et al., 2016 [4]
Cattle	*Bos taurus*	Measurements	Gündemir et al., 2020 [5]
Sheep	*Ovis aries*	Measurements	Boessneck et al., 1964 [6]
Sheep	*Ovis aries*	Measurements	Clutton-Brock et al., 1990 [7]
Sheep	*Ovis aries*	Osteoarcheology	Moran and O'Connor 1994 [8]
Sheep	*Ovis aries*	Osteoarcheology	Maldre 2007 [2]
Sheep	*Ovis aries*	Osteoarcheology	Zeder and Lapharm 2010 [9]
Sheep	*Ovis aries*	Comparative anatomy	Blagojević et al., 2016 [10]
Goat	*Capra hircus*	Measurements	Boessneck et al., 1964 [6]
Goat	*Capra hircus*	Osteoarcheology	Zeder 2001 [11]
Goat	*Capra hircus*	Osteoarcheology	Badenhorst and Plug 2003 [12]
Goat	*Capra hircus*	Osteoarcheology	Clutton-Brock et al., 1990 [7]
Goat	*Capra hircus*	Osteoarcheology	Zeder and Lapharm 2010 [9]
Goat	*Capra hircus*	Measurements	Işbilir and Güzel 2023 [13]
Gazella	*Gazella subgutturosa*	Measurements	Demircioğlu et al., 2021 [14]
Chinkara	*Cazella bennettii*	Measurements	Din 2023 [15]
Fallow deer	*Dama dama*	Radiography	Keller et al., 2009 [16]
Fallow deer	*Dama dama*	Measurements	Trbojević Vukičević et al., 2012 [17]
Wild chamois	*Rupicarpa rupicarpa*	Radiography	Keller et al., 2009 [16]
Bison	*Bison bison*	Radiography	Keller et al., 2009 [16]
European moose	*Alces alces*	Radiography	Keller et al., 2009 [16]
Dromedary camel	*Camelus dromedarius*	Measurements	Bani Ismail et al., 2008 [18]
Dromedary camel	*Camelus dromedarius*	Computed tomography	Badawy 2011 [19]
Dromedary camel	*Camelus dromedarius*	Measurements	Nourinezhad et al., 2015 [20]
Roe deer	*Capreolus capreolus*	Comparative anatomy	Blagojević et al., 2016 [10]
Water buffalo	*Bubalus bubalis*	Measurements	Nourinezhad et al., 2012 [21]
Reindeer	*Rangifer tarandus*	Measurements	Galán López et al., 2022 [22]
Indian Blakbuck	*Antilope cervicarpa*	Measurements	Choudhary et al., 2016 [23]

The digital skeleton of the ruminants consists of two digits (third or medial or inner and fourth or lateral or outer). The skeleton of a fully developed digit consists of a proximal (first) phalanx, a middle (second) phalanx, and a distal (third) phalanx.

The digital bones of mammals have been the subject of discussion from the evolutionary point of view [24]. These skeletal elements are known to reflect ecology and locomotory habits in the animals. Furthermore, the phalanges have been identified as a valuable archaeological resource, facilitating the identification of excavated skeletal elements and enabling the study of animal adaptation [9].

Lameness is a prevalent health concern in domestic ruminants. Given that the great majority of lameness cases are attributed to digital and claw lesions, many researchers have explored the potential correlation between the anatomy of the autopodium and claw diseases [1,3,16].

Sheep and goats represent a substantial proportion of the total population of ruminants in Greece. However, the extant literature on the morphometry of the phalanges in these species, and especially in indigenous breeds, is limited. The Karagouniko sheep originates from central Greece, with the majority of the population being located in the Thessaly region. It is a lowland breed, characterized by its thin tail and mixed wool. The breed is notable for its relatively high milk production and its ability to adapt to marginal conditions [25]. The Hellenic goat is the primary breed in Greece. It is an indigenous breed that is also referred to as *Capra prisca* [26].

The objective of the present study was to provide osteometric data on the phalanges of Karagouniko sheep and Hellenic goats, with a view to assembling the morphological profile of these two animal species. The data thus obtained will facilitate comparisons with other ovine and caprine measurements, aid the interpretation of metric data, and provide further information on the profile of the metric parameters of both the sheep and goat. Furthermore, the potential relationships with functional morphology and their potential association with the pathology of the autopodium were evaluated.

2. Materials and Methods

The distal extremities of the fore and hind limbs from 30 ewes of the Karagouniko breed and 30 Hellenic goats aged more than 2 years (median age 3.7 years), based on the number of permanent incisors [27], were used in the study. The extremities were obtained from a commercial slaughterhouse and immediately subjected to identification (forelimbs and hind limbs) and grouping according to the animal. Subsequently, the autopodia were skinned, macerated, cleaned, and dried.

The first, second, and third phalanges were manually measured by the same person with the aid of a caliper, which had the capacity to measure up to 0.01 mm. The definition of linear measurements performed is depicted in Figure 1 and Table 2. The majority of measurements were taken according to the method previously described by von den Driesch [28], with an additional measurement in the third phalanx (height in the region of the extensor process). All linear measurements were in millimeters. In order to avoid errors during the measurements, the identical anatomical reference points, including the fovea articularis, the articular surface, the process, the protuberance, and the borders of the bones, were also considered. All parameters were measured three times, and the mean values were recorded. A series of indexes was calculated as the ratio of the length to the smaller width for the first and second phalanges and the ratio of the length to the height of the extensor process for the third phalanx (Table 3). The total length of the third and fourth digits was calculated by summing the lengths for the first and second phalanges and the length of the dorsal surface of the third phalanx of the relevant digits.

The data were analyzed using the statistical software package SPSS version 21. Paired-sample *t*-tests were run to compare the data obtained for each measurement between the fore and hind limbs and the third and fourth digit for each animal species. Pearson's correlation coefficient was used to identify potential linear relationships among the parameters evaluated. Linear regression analysis was used to create prediction equations using variables with a Pearson correlation coefficient higher than 0.7. A significance level of $p \leq 0.05$ was used in all comparisons.

Table 2. Definition of the measurements.

Goat	Sheep	Measurement
G3LF1	S3LF1	Length of the 1st phalanx of the fore 3rd digit
G4LF1	S4LF1	Length of the 1st phalanx of the fore 4th digit
G3LH1	S3LH1	Length of the 1st phalanx of the hind 3rd digit
G4LH1	S4LH1	Length of the 1st phalanx of the hind 4th digit
G3LF2	S3LF2	Length of the 2nd phalanx of the fore 3rd digit
G4LF2	S4LF2	Length of the 2nd phalanx of the fore 4th digit
G3LH2	S3LH2	Length of the 2nd phalanx of the hind 3rd digit
G4LH2	S4LH2	Length of the 2nd phalanx of the hind 4th digit
G3LF3	S3LF3	Length of the 3rd phalanx of the fore 3rd digit
G4LF3	S4LF3	Length of the 3rd phalanx of the fore 4th digit
G3LH3	S3LH3	Length of the 3rd phalanx of the hind 3rd digit
G4LH3	S4LH3	Length of the 3rd phalanx of the hind 4th digit
G3BpF1	S3BpF1	Breadth of the proximal end of the 1st phalanx of the fore 3rd digit
G4BpF1	S4BpF1	Breadth of the proximal end of the 1st phalanx of the fore 4th digit
G3BpH1	S3BpH1	Breadth of the proximal end of the 1st phalanx of the hind 3rd digit
G4BpH1	S4BpH1	Breadth of the proximal end of the 1st phalanx of the hind 4th digit
G3BdF1	S3BdF1	Breadth of the distal end of the 1st phalanx of the fore 3rd digit
G4BdF1	S4BdF1	Breadth of the distal end of the 1st phalanx of the fore 4th digit
G3BdH1	S3BdH1	Breadth of the distal end of the 1st phalanx of the hind 3rd digit
G4BdH1	S4BdH1	Breadth of the distal end of the 1st phalanx of the hind 4th digit
G3SDF1	S3SDF1	Smallest breadth of the diaphysis of the 1st phalanx of the fore 3rd digit
G4SDF1	S4SDF1	Smallest breadth of the diaphysis of the 1st phalanx of the fore 4th digit
G3SDH1	S3SDH1	Smallest breadth of the diaphysis of the 1st phalanx of the hind 3rd digit
G4SDH1	S4SDH1	Smallest breadth of the diaphysis of the 1st phalanx of the hind 4th digit
G3BpF2	S3BpF2	Breadth of the proximal end of the 2nd phalanx of the fore 3rd digit
G4BpF2	S4BpF2	Breadth of the proximal end of the 2nd phalanx of the fore 4th digit
G3BpH2	S3BpH2	Breadth of the proximal end of the 2nd phalanx of the hind 3rd digit
G4BpH2	S4BpH2	Breadth of the proximal end of the 2nd phalanx of the hind 4th digit
G3BdF2	S3BdF2	Breadth of the distal end of the 2nd phalanx of the fore 3rd digit
G4BdF2	S4BdF2	Breadth of the distal end of the 2nd phalanx of the fore 4th digit
G3BdH2	S3BdH2	Breadth of the distal end of the 2nd phalanx of the hind 3rd digit
G4BdH2	S4BdH2	Breadth of the distal end of the 2nd phalanx of the hind 4th digit
G3SDF2	S3SDF2	Smallest breadth of the diaphysis of the 2nd phalanx of the fore 3rd digit
G4SDF2	S4SDF2	Smallest breadth of the diaphysis of the 2nd phalanx of the fore 4th digit
G3SDH2	S3SDH2	Smallest breadth of the diaphysis of the 2nd phalanx of the hind 3rd digit
G4SDH2	S4SDH2	Smallest breadth of the diaphysis of the 2nd phalanx of the hind 4th digit
G3LdF3	S3LdF3	Length of the dorsal surface of the 3rd phalanx of the fore 3rd digit
G4LdF3	S4LdF3	Length of the dorsal surface of the 3rd phalanx of the fore 4th digit
G3LdH3	S3LdH3	Length of the dorsal surface of the 3rd phalanx of the hind 3rd digit
G4LdH3	S4LdH3	Length of the dorsal surface of the 3rd phalanx of the hind 4th digit
G3HpF3	S3HpF3	Height in the region of the extensor process of the 3rd phalanx of the fore 3rd digit
G4HpF3	S4HpF3	Height in the region of the extensor process of the 3rd phalanx of the fore 4th digit
G3HpH3	S3HpH3	Height in the region of the extensor process of the 3rd phalanx of the hind 3rd digit
G4HpH3	S4HpH3	Height in the region of the extensor process of the 3rd phalanx of the hind 4th digit
S3LF	G3LF	Length of the 1st phalanx + length of the 2nd phalanx + length of the dorsal surface of the 3rd phalanx

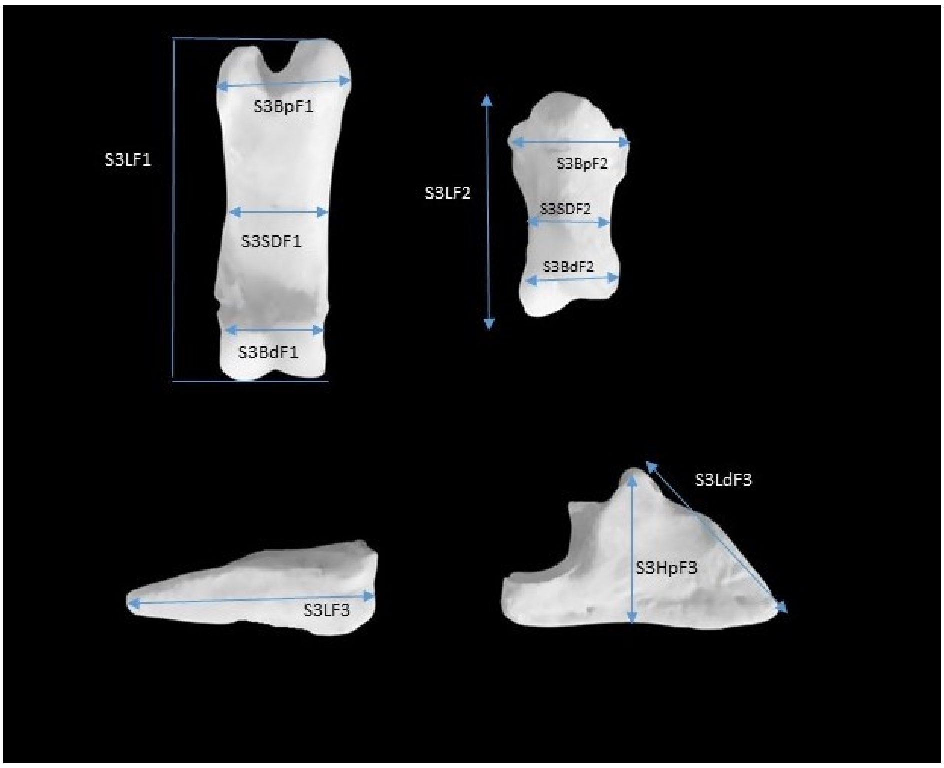

Figure 1. Measurements of the digital bones of the fore third digit.

Table 3. Definition of the indexes.

Sheep		Goats	
S3F1	S3LF1/S3SDF1	G3F1	G3LF1/G3SDF1
S4F1	S4LF1/S4SDF1	G4F1	G4LF1/G4SDF1
S3H1	S3LH1/S3SDH1	G3H1	G3LH1/G3SDH1
S4H1	S4LH1/S4SDH1	G4H1	G4LH1/G4SDH1
S3F2	S3LF2/S3SDF2	G3F2	G3LF2/G3SDF2
S4F2	S4LF2/S4SDF2	G4F2	G4LF2/G4SDF2
S3H2	S3LH2/S3SDH2	G3H2	G3LH2/G3SDH2
S4H2	S4LH2/S4SDH2	G4H2	G4LH2/G4SDH2
S3F3	S3LF3/S3HpF3	G3F3	G3LF3/G3HpF3
S4F3	S4LF3/S4HpF3	G4F3	G4LF3/G4HpF3
S3H3	S3LH3/S3HpH3	G3H3	G3LH3/G3HpH3
S4H3	S4LH3/S4HpH3	G4H3	G4LH3/G4HpH3

3. Results

The results of all bone measurements obtained for sheep are presented in Table S1 in Supplementary Materials, while those obtained for goats are presented in Table S2.

In sheep and goats, the length of the second and third phalanges of the fore third digit were significantly higher than those of the fourth digit ($p < 0.05$; Table 4). No significant difference was detected on the length of the first phalanx between the third and the fourth digits. Furthermore, a significant decrease in the length of the first phalanx in the hind third digit compared to the fourth hind digit was observed ($p < 0.05$; Table 4) in both sheep and goats. Additionally, a similar trend was noted for the length of the third phalanx in goats ($p < 0.05$; Table 4). Conversely, in sheep, the length of the third phalanx was found to be significantly higher at the third digit compared to the fourth digit ($p < 0.05$; Table 4). In goats, the length of the second phalanx was significantly higher in the third than the fourth hind digit ($p < 0.05$; Table 4). However, no significant difference was detected in sheep ($p > 0.05$; Table 4).

In sheep, the breadth of the proximal end of the first and second phalanges was significantly higher in the third than the fourth digit in fore and hind limbs ($p < 0.05$; Table 4). In goats, no such difference was observed ($p > 0.05$; Table 4), except for the first phalanx of the fore limbs ($p < 0.05$; Table 4). The breadth of the distal end of the phalanges was comparable between the third and fourth digits in both species in fore and hind limbs ($p > 0.05$; Table 4) with the exception of the first phalanx, where it was higher in the third than the fourth fore digit ($p < 0.05$; Table 4). Furthermore, the smallest breadth of the diaphysis of the first and second phalanx was significantly higher in the third than the fourth digit in fore and hind limbs in both species ($p < 0.05$; Table 4). However, this difference was not observed in the first digit of the hind limbs of goats ($p > 0.05$). In goats, the length of the dorsal surface of the third phalanx of the fore limbs was significantly higher in the third than the fourth digit ($p < 0.05$). In contrast, no significant differences were observed in sheep or hind limbs of goats ($p > 0.05$). However, in sheep and in the fore limb of goats, the height in the region of the extensor process of the third phalanx was significantly higher in the third than the fourth digit ($p < 0.05$). In the hind limb of goats, there was not such a difference ($p > 0.05$). In both species, the total length of the third digit was found to be significantly higher in the fore limb and significantly lower in the hind limb than the fourth digit.

Table 4. Mean and standard error (mean± SE) of the dimensions measured in sheep and goat phalanges in the fore and hind limbs and comparisons between the third and fourth digits.

	Mean ± SE	**Sig.**		**Mean ± SE**	**Sig.**
S3LF1 S4LF1	38.95 ± 0.50 38.6 ± 0.58	NS	G3LF1 G4LF1	39.521 ± 0.55 39.385 ± 0.54	NS
S3LH1 S4LH1	37.7 ± 0.45 38.63 ± 0.57	***	G3LH1 G4LH1	38.685 ± 0.64 39.25 ± 0.62	**
S3LF2 S4LF2	24.46 ± 0.35 24.03 ± 0.38	***	G3LF2 G4LF2	25.271 ± 0.37 24.928 ± 0.38	**
S3LH2 S4LH2	24.17 ± 0.37 24.06 ± 0.41	NS	G3LH2 G4LH2	24.735 ± 0.30 24.985 ± 0.30	*
S3LF3 S4LF3	34.31 ± 0.43 33.91 ± 0.41	*	G3LF3 G4LF3	40.91 ± 0.90 39.6 ± 0.82	**
S3LH3 S4LH3	32.05 ± 0.43 31.4 ± 0.45	***	G3LH3 G4LH3	36.63 ± 0.70 37.107 ± 0.59	NS
S3BpF1 S4BpF1	14.37 ± 0.19 13.98 ± 0.22	**	G3BpF1 G4BpF1	14.7 ± 015 14.291 ± 0.19	***
S3BpH1 S4BpH1	14.07 ± 0.18 13.34 ± 0.19	***	G3BpH1 G4BpH1	13.118 ± 0.20 13.1 ± 0.19	NS
S3BdF1 S4BdF1	13.92 ± 0.13 13.67 ± 0.15	*	G3BdF1 G4BdF1	14.525 ± 0.16 14.5 ± 0.20	NS
S3BdH1 S4BdH1	12.87 ± 0.09 12.38 ± 0.12	***	G3BdH1 G4BdH1	12.9 ± 0.18 12.72 ± 0.22	NS
S3SDF1 S4SDF1	12.3 ± 0.20 11.95 ± 0.23	***	G3SDF1 G4SDF1	12.508 ± 0.23 12.358 ± 0.22	*
S3SDH1 S4SDH1	11.46 ± 017 10.91 ± 0.20	***	G3SDH1 G4SDH1	11 ± 0.19 10.927 ± 0.21	NS

Table 4. *Cont.*

	Mean ± SE	Sig.		Mean ± SE	Sig.
S3BpF2 S4BpF2	13.49 ± 0.14 13.25 ± 0.18	*	G3BpF2 G4BpF2	14 ± 0.22 13.966 ± 0.22	NS
S3BpH2 S4BpH2	12.32 ± 0.10 12.05 ± 0.17	*	G3BpH2 G4BpH2	12.145 ± 0.17 12.054 ± 0.18	NS
S3BdF2 S4BdF2	11.17 ± 0.18 11.1 ± 0.20	NS	G3BdF2 G4BdF2	11.891 ± 0.17 11.691 ± 0.21	NS
S3BdH2 S4BdH2	10.19 ± 0.1 ± 0.1 10.16 ± 0.16	NS	G3BdH2 G4BdH2	10.29 ± 0.12 10.154 ± 0.11	NS
S3SDF2 S4SDF2	10.33 ± 0.12 10.1 ± 0.16	*	G3SDF2 G4SDF2	10.533 ± 0.17 10.341 ± 0.17	***
S3SDH2 S4SDH2	9.2 ± 0.15 8.71 ± 0.17	***	G3SDH2 G4SDH2	9.118 ± 0.17 8.954 ± 0.17	*
S3LdF3 S4LdF3	23.59 ± 0.29 23.63 ± 0.32	NS	G3LdF3 G4LdF3	31.525 ± 0.75 30.441 ± 0.63	*
S3LdH3 S4LdH3	23.14 ± 0.37 22.92 ± 0.38	NS	G3LdH3 G4LdH3	28.127 ± 0.46 28.027 ± 0.45	NS
S3HpF3 S4HpF3	18.65 ± 0.21 18.45 ± 0.26	NS	G3HpF3 G4HpF3	18.858 ± 0.25 18.591 ± 0.24	*
S3HpH3 S4HpH3	18.08 ± 0.19 17.53 ± 0.22	***	G3HpH3 G4HpH3	17.063 ± 0.22 16.945 ± 0.21	NS
S3LF S4LF	87.00 ± 0.97 86.266 ± 1.07	**	G3LF G4LF	96.108 ± 0.90 94.491 ± 0.89	***
S3LH S4LH	85.025 ± 1.00 85.625 ± 1.11	*	G3LH G4LH	90.836 ± 0.85 91.627 ± 0.80	**

NS: non-significant difference ($p > 0.05$); * significant difference at the level of $p \leq 0.05$; ** significant difference at the level of $p \leq 0.01$; *** significant difference at the level of $p \leq 0.001$.

The lengths of all phalanges of the third digit were found to be significantly higher in the fore compared to the hind limb in sheep and in goats ($p < 0.05$; Table 5). In the fourth digit, the lengths of the first and second phalanges were not significantly different between the fore and hind limb ($p > 0.05$; Table 5), whereas the length of the third phalanx was significantly higher in the fore than the hind limb ($p < 0.05$; Table 5). Furthermore, the breadth of the proximal and distal ends and the smallest breadth of the diaphysis of the first and second phalanges were significantly higher in the fore than the hind limb ($p < 0.05$; Table 5) in both species. Additionally, the length of the dorsal surface and the height in the region of the extensor process were also significantly higher in the fore compared to the hind limb ($p < 0.05$; Table 5). The total lengths of the third and fourth digits were significantly higher in the fore compared to the hind limb in both sheep and goats ($p < 0.05$; Table 5).

Table 5. Mean and standard error (mean ± SE) of the dimensions measured in sheep and goat phalanges in the third and fourth digits and comparisons between fore and hind limbs.

	Mean ± SE	Sig.		Mean ± SE	Sig.
S3LF1 S3LH1	38.95 ± 0.50 37.708 ± 0.45	***	G3LF1 G3LH1	39.521 ± 0.55 38.685 ± 0.63	*
S4LF1 S4LH1	38.6 ± 0.58 38.63 ± 0.57	NS	G4LF1 G4LH1	39.385 ± 0.54 39.250 ± 0.61	NS

Table 5. *Cont.*

	Mean ± SE	Sig.		Mean ± SE	Sig.
S3LF2 S3LH2	24.467 ± 0.35 24.175 ± 0.37	**	G3LF2 G3LH2	25.271 ± 0.37 24.735 ± 0.30	**
S4LF2 S4LH2	24.033 ± 0.38 24.066 ± 0.41	NS	G4LF2 G4LH2	24.928 ± 0.38 24.985 ± 0.30	NS
S3LF3 S3LH3	34.316 ± 0.42 32.058 ± 0.43	***	G3LF3 G3LH3	40.938 ± 0.97 36.630 ± 0.71	***
S4LF3 S4LH3	33.916 ± 0.41 31.400 ± 0.45	***	G4LF3 G4LH3	39.607 ± 0.82 37.178 ± 0.55	***
S3BpF1 S3BpH1	14.375 ± 0.19 14.075 ± 0.18	**	G3BpF1 G3BpH1	14.718 ± 0.16 13118 ± 0.20	***
S4BpF1 S4BpH1	13.983 ± 0.21 13.341 ± 0.19	***	G4BpF1 G4BpH1	14.272 ± 0.20 13.100 ± 0.19	***
S3BdF1 S3BdH1	13.925 ± 0.13 12.875 ± 0.1	***	G3BdF1 G3BdH1	14.490 ± 0.17 12.900 ± 0.18	***
S4BdF1 S4BdH1	13.675 ± 0.15 12.383 ± 0.2	***	G4BdF1 G4BdH1	14.472 ± 0.13 12.727 ± 0.22	***
S3SDF1 S3SDH1	12.300 ± 0.19 11.466 ± 0.16	***	G3SDF1 G3SDH1	12.300 ± 0.19 11.466 ± 0.17	***
S4SDF1 S4SDH1	11.950 ± 0.23 10.916 ± 0.20	***	G4SDF1 G4SDH1	12.300 ± 0.23 10.927 ± 0.21	***
S3BpF2 S3BpH2	13.491 ± 0.14 12.325 ± 0.1	***	G3BpF2 G3BpH2	13.954 ± 0.23 12.145 ± 0.17	***
S4BpF2 S4BpH2	13.250 ± 0.18 12.058 ± 0.17	***	G4BpF2 G4BpH2	13.890 ± 0.23 12.054 ± 0.18	***
S3BdF2 S3BdH2	11.175 ± 0.18 10.191 ± 0.10	***	G3BdF2 G3BdH2	11.872 ± 0.19 10.290 ± 0.12	***
S4BdF2 S4BdH2	11.108 ± 0.20 10.166 ± 0.15	***	G4BdF2 G4BdH2	11.709 ± 0.24 10.154 ± 0.11	***
S3SDF2 S3SDH2	10.333 ± 0,12 9.200 ± 0.15	***	G3SDF2 G3SDH2	10.472 ± 0.17 9.118 ± 0.17	***
S4SDF2 S4SDH2	10.108 ± 0.16 8.716 ± 0.17	***	G4SDF2 G4SDH2	10.281 ± 0.17 8.954 ± 0.16	***
S3LdF3 S3LdH3	23.591 ± 0.03 23.141 ± 0.29	*	G3LdF3 G3LdH3	31.518 ± 0.81 28.127 ± 0.46	***
S4LdF3 S4LdH3	23.633 ± 0.32 22.925 ± 0.38	***	G4LdF3 G4LdH3	30.509 ± 0.69 28.027 ± 0.45	***
S3HpF3 S3HpH3	18.658 ± 0.21 18.083 ± 0.20	***	G3HpF3 G3HpH3	18.763 ± 0.25 17.063 ± 0.22	***
S4HpF3 S4HpH3	18.458 ± 0.26 17.533 ± 0.22	***	G4HpF3 G4HpH3	18.518 ± 0.23 16.945 ± 0.21	***
S3LF S3LH	87.00 ± 0.97 85.025 ± 1.00	***	G3LF G3LH	95.663 ± 0.86 90.836 ± 0.85	***
S4LF S4LH	86.266 ± 1.07 85.625 ± 1.11	**	G4LF G4LH	94.054 ± 0.85 91.627 ± 0.80	**

NS: non-significant difference ($p > 0.05$); * significant difference at the level of $p \leq 0.05$; ** significant difference at the level of $p \leq 0.01$; *** significant difference at the level of $p \leq 0.001$.

In sheep, the index in the fore first phalanx was significantly lower in the third digit compared to the fourth, but the opposite was observed for the second phalanx ($p < 0.05$; Table 6). In the hind limb, the indexes for the first and second phalanges were significantly lower in the third compared to the fourth digit. The index for the third phalanx was not significantly different between the third and the fourth digit in either the fore or the hind limb. All indexes of the phalanges were significantly different between the fore and the hind digits, and the indexes of the first phalanx of the third and the fourth digits and of the second phalanx of the fourth digit were significantly higher in the hind than the fore limbs ($p < 0.05$; Table 6). The indexes of the second phalanx of the third digit and of the third phalanx of the third and fourth digits exhibited significantly higher values in the fore compared to hind limb ($p < 0.05$; Table 6). In goats, the indexes of the first fore and of the first and second hind phalanges were significantly higher in the third than in the fourth digit ($p < 0.05$; Table 6). The other indexes were not significantly different between the third and the fourth digits ($p > 0.05$; Table 6). Furthermore, the indexes in the first and second phalanges of the third and fourth digits were significantly higher in the hind than the fore limb ($p < 0.05$; Table 6). Conversely, the indexes of the third phalanx were not significantly different between the fore and the hind limbs in either the third or fourth digit. Between species, all indexes calculated for the third phalanx, the index for the second phalanx of the third fore digit, and the index of the first phalanx of the third hind digit were significantly higher in goats than in sheep ($p > 0.05$; Table 6). However, no other significant difference was detected on the indexes between species ($p > 0.05$; Table 6).

Table 6. Mean and standard error (mean ± SE) of the dimensions measured in sheep and goat phalanges and comparisons between the third and fourth digits between the fore and hind limb between sheep and goats.

Third vs. Fourth Digit	Mean ± SE	Sig.	Fore vs. Hind	Mean ± SE	Sig.	Sheep vs. Goats	Mean ± SE	Sig.
S3F1 S4F1	3.171 ± 0.05 3.236 ± 0.05	*	S3F1 S3H1	3.171 ± 0.05 3.291 ± 0.04	***	S3F1 G3F1	3.171 ± 0.05 3.157 ± 0.08	NS
S3H1 S4H1	3.291 ± 0.04 3.543 ± 0.04	***	S4F1 S4H1	3.236 ± 0.05 3.543 ± 0.04	***	S4F1 G4F1	3.236 ± 0.05 3.176 ± 0.07	NS
S3F2 S4F2	2.661 ± 0.03 2.378 ± 0.02	***	S3F2 S3H2	2.661 ± 0.03 2.629 ± 0.03	*	S3H1 G3H1	3.291 ± 0.04 3.479 ± 0.1	*
S3H2 S4H2	2.629 ± 0.03 2.763 ± 0.02	***	S4F2 S4H2	2.378 ± 0.02 2.763 ± 0.02	***	S4H1 G4H1	3.543 ± 0.04 3.560 ± 0.1	NS
S3F3 S4F3	1.839 ± 0.02 1.839 ± 0.03	NS	S3F3 S3H3	1.839 ± 0.02 1.773 ± 0.03	***	S3F2 G3F2	2.661 ± 0.03 2.402 ± 0.06	***
S3H3 S4H3	1.773 ± 0.03 1.792 ± 0.03	NS	S4F3 S4H3	1.839 ± 0.03 1.792 ± 0.03	*	S4F2 G4F2	2.378 ± 0.02 2.414 ± 0.05	NS
G3F1 G4F1	3.157 ± 0.08 3.176 ± 0.07	NS	G3F1 G3H1	3.157 ± 0.08 3.479 ± 0.1	***	S3H2 G3H2	2.629 ± 0.03 2.705 ± 0.07	NS
G3H1 G4H1	3.479 ± 0.1 3.560 ± 0.1	*	G4F1 G4H1	3.176 ± 0.07 3.560 ± 0.1	***	S4H2 G4H2	2.763 ± 0.02 2.785 ± 0.07	NS
G3F2 G4F2	2.402 ± 0.06 2.414 ± 0.05	NS	G3F2 G3H2	2.402 ± 0.06 2.705 ± 0.07	***	S3F3 G3F3	1.839 ± 0.02 2.178 ± 0.06	***
G3H2 G4H2	2.705 ± 0.07 2.785 ± 0.07	***	G4F2 G4H2	2.414 ± 0.05 2.785 ± 0.07	***	S4F3 G4F3	1.839 ± 0.03 2.141 ± 0.05	***

Table 6. *Cont.*

Third vs. Fourth Digit	Mean ± SE	Sig.	Fore vs. Hind	Mean ± SE	Sig.	Sheep vs. Goats	Mean ± SE	Sig.
G3F3 G4F3	2.178 ± 0.06 2.141 ± 0.05	NS	G3F3 G3H3	2.178 ± 0.06 2.134 ± 0.06	NS	S3H3 G3H3	1.773 ± 0.03 2.134 ± 0.06	***
G3H3 G4H3	2.134 ± 0.06 2.178 ± 0.05	NS	G4F3 G4H3	2.141 ± 0.05 2.178 ± 0.05	NS	S4H3 G4H3	1.792 ± 0.03 2.178 ± 0.05	***

NS: non-significant difference ($p > 0.05$); * significant difference at the level of $p \leq 0.05$; *** significant difference at the level of $p \leq 0.001$.

The prediction equations between measurements with R > 0.7 are presented in Table 7. The length of the first phalanx of the fourth fore digit for sheep and the first phalanx of the fourth hind digit in goats were the most useful measurements for the prediction of the lengths of the other bones, with R^2 values higher than 0.85. In sheep, the same measurement can be used for the prediction of the height in the region of the extensor process of the third phalanx, with R^2 higher than 0.73.

Table 7. Pearson correlation coefficients (R) and regression equations between the linearly related measurements in sheep and goats.

Sheep	R	R^2	Sig.	Goats	R	R^2	Sig.
S3LF1 = 8.049 + 0.801 × S4LF1	0.926	0.858	***	G3LF1 = 6.598+0.839 × G4LH1	0.935	0.875	***
S3LH1 = 9.491 + 0.731 ×S4LF1	0.939	0.881	***	G4LF1 = 6.591 + 0.836 × G4LH1	0.961	0.924	***
S4LH1 = 1.790 + 0.954 × S4LF1	0.972	0.944	***	G3LH1 = 0.808 + 1.006 × G4LH1	0.972	0.946	***
S3LF2 = 2.386 + 0.572 × S4LF1	0.945	0.894	***	G3LF2 = 3.355 + 0.558 × G4LH1	0.925	0.856	***
S4LF2 = 0.513 + 0.609 × S4LF1	0.929	0.863	***	G4LF2 = 4.106 + 0.531 × G4LH1	0.867	0.752	***
S3LH2 = 0.770 + 0.606 × S4LF1	0.940	0.883	***	G3LH2 = 6.864 + 0.455 × G4LH1	0.943	0.889	***
S4LH2 = 2.049 + 0.677 × S4LF1	0.954	0.910	***	G4LH2 = 7.231 + 0.452 × G4LH1	0.922	0.850	***
S3HpF3 = 8.276 + 0.269 × S4LF1	0.734	0.539	**				
S4HpF3 = 4.491 + 0.362 × S4LF1	0.810	0.656	**				
S3HpH3 = 8.177 + 0.257 × S4LF1	0.762	0.581	**				
S4HpH3 = 4.837 + 0.329 × S4LF1	0.859	0.738	***				

** significant difference at the level of $p \leq 0.01$; *** significant difference at the level of $p \leq 0.001$.

4. Discussion

The objective of this study was to provide osteometric data on the phalanges of Karagouniko sheep and Hellenic goats. These breeds were selected due to their importance as indigenous local breeds of the Mediterranean basin, and their morphotypes are certainly close to those that can be found on ancient archaeological sites [29], despite their differences in size from modern breeds. All measurements were made manually with the aid of a caliper to determine the absolute bone dimensions. This method was selected over X-rays or digital images, because direct manual measurements have advantages in terms of reliable identification of the exact location of anatomical points, as well as direct visibility.

An interesting finding of this study is the difference between the lengths of the third and fourth digits, as reflected by the differences in phalanx lengths and their sums. In the fore limbs, the third digit is longer than the fourth digit and the opposite occurs in the hind limbs in both sheep and goats. To the best of our knowledge, such information is scarce in the extant literature on sheep and goats. However, similar results have been obtained in studies of cattle [1]. Muggli et al. [3] investigated the length asymmetry of the bovine digits of the fore and hind limbs, finding that the first and second phalanges of the fourth digit were significantly longer than their counterparts of the third digit, whereas the third phalanx of the third digit was longer than its lateral partner. Furthermore, Keller et al. [17] investigated the autopodia of four species of wild artiodactyls using X-rays, revealing that the paired digits differed in length, with the fourth digit being longer than the third. The authors proposed that a longer outer digit might be advantageous on soft ground to maximize the stability of the center of the body mass during walking and also at faster speeds [17]. Additionally, the latter authors hypothesized that this anatomical variation may confer a competitive edge in contexts such as intra-species combat or evasive maneuvers in predator–prey interactions, owing to an enhanced grip strength.

The differences in the length of digits or digital bones have been suggested as risk factors for locomotor disorders and lameness in cattle [1,3,30]. However, such a connection seems to occur, at least in sheep, for fore but not for hind limbs. In a previous study, it was observed that the majority of lesions that cause lameness occur in the inner claw in both fore and hind limbs [31]. Similar results were obtained regarding the prevalence of white line lesions in the fore limbs of sheep [32], where most of them were detected at the claw of the third digit. These observations suggest that bone length is likely to be only one of several contributing factors to lameness, with other anatomical structures such as joints, ligaments, and hooves also playing a role in locomotion. Furthermore, the presence of digital lesions and lameness is significantly influenced by infectious agents.

Another interesting finding was the observed difference in the length and the breadth of the proximal and distal ends and the smallest breadth of the diaphysis of the first and second phalanges and of the length of the digits between fore and hind limbs. The distinct functions of the fore limbs and hind limbs in cursorial quadrupeds suggest a potential correlation with the distribution of body weight across the limbs during locomotion. In sheep, for instance, approximately 30% of the body weight is allocated to each fore limb and 20% to each hind limb [33]. A similar phenomenon was observed in another study [34], where 31.34% of the body weight was found to be distributed between the forelimb and 18.79% between the hind limb in sheep. The direct relationship between these length differences and the prevalence of digital lesions and lameness remains uncertain and requires further investigation. Some studies have indicated a higher prevalence of lameness in the fore limb [35,36], while others have found it to be more prevalent in the hind limb [31,37,38].

The indexes have been demonstrated to be of significant value in facilitating comprehension of the morphology and functionality of the bones. The disparities observed between the fore and hind limbs in both species are indicative of the previously mentioned body weight distribution. Furthermore, from an archaeological perspective, the indexes are also useful for the differentiation of the bones between the different species. The metapodial index has been proposed as a means of differentiating between sheep and goats [39]. The results of the present study suggest that the index of the third phalanx can also be used for the differentiation between sheep and goats. Apart from the differentiation between species, the indexes seem to be useful for the differentiation between the fore and hind limb phalanges, but not for the third phalange of goats.

From an archaeological perspective, the prediction equations also proved to be of significant value. The results obtained from the analysis indicate that the most useful parameter for the prediction of the length of the first and second phalanges in sheep is the length of the first phalanx of the fourth fore digit. In goats, the equivalent parameter is the first phalanx of the fourth hind digit.

5. Conclusions

The findings of the present study suggest the presence of substantial disparities in the lengths and the breadths of the phalanges between the third and the fourth digits as well as between the fore and the hind limb. Furthermore, the indexes calculated were found to be effective in differentiating the third phalanx between sheep and goats as well as in distinguishing between the fore and hind digits. The length of the first phalanx of the fourth fore digit for sheep and the length of the first phalanx of the fourth hind digit for goats were identified as the most useful parameters for the prediction of the lengths of the first and second phalanges.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ruminants5020013/s1. Table S1: Bone measurements obtained for sheep, Table S2: Bone measurements obtained for goat.

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