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Radiographic parameters of the digit in a cohort population of Amiata donkeys

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Abstract

Background: The most common musculoskeletal conditions reported in donkeys are related to the foot. Radiographic examinations are clinically important in the diagnosis of foot abnormalities and are commonly used. However, few studies have been conducted to establish the normal radiographic appearance of a donkey's foot.

Aim: To determine the radiographic features of the front digit in healthy Amiata donkeys.

Methods: Radiographic examinations were performed on 56 forefeet of 28 Amiata donkeys. Three radiographic views of each front foot were taken: lateromedial, dorsopalmar and dorso-65°proximal/palmarodistal oblique. Seventeen angular and linear radiographic parameters and the *crena solearis* were evaluated in all forefeet, and 18 morphometric parameters were evaluated in 16 out of 56 forefeet. Statistical analysis was carried out on all the measures assessed.

Results: The radiographic appearance of the forefoot was ascertained, and data were reported as median ± standard error, minimum and maximum values. No statistical differences were obtained between the right and left forefeet.

Conclusion: The normal baseline parameters of the forefeet of Amiata donkeys were recorded and described and compared with other donkey breeds and horses. The findings highlighted that the donkey breed affects the radiographic parameters of the digit.

Keywords: Amiata, Donkey, Foot, Radiography.

Introduction

Donkeys (*Equus Asinus*) represent an important percentage of the world's equine population (Walker *et al.*, 1995) and have been close companions for humans for millennia. Donkeys contribute to the agricultural economy as working animals or for transportation (Thiemann and Poore, 2019). Donkeys are used for milk production (Carroccio *et al.*, 2000; Muraro *et al.*, 2002) and in animal-assisted therapy (Borioni *et al.*, 2012). They are important for the tourist industry and recently have become popular as pets (Thiemann and Rickards, 2013; El-Shafaey *et al.*, 2017; Salem *et al.*, 2018). The scientific literature has shown increased interest in their welfare (Rota *et al.*, 2018), in donkeys' infectious diseases (Laus *et al.*, 2015; Barrandeguy and Carossino, 2018; Sgorbini *et al.*, 2018), alternative therapies (Bonelli *et al.*, 2016a), and in specific diagnostic criteria and reference values in adults (Meucci *et al.*, 2015; Sgorbini *et al.*, 2017; Bonelli *et al.*, 2019), pregnant and lactating jennies (Crisci *et al.*, 2014; Bonelli *et al.*, 2016b; Carluccio *et al.*, 2016), and donkey foals (Sgorbini *et al.*, 2013; Veronesi *et al.*, 2014; Carluccio *et al.*, 2017).

Musculoskeletal disease has also been investigated. Up to 65% of the donkey population may be affected by hoof-related problems (Mendoza *et al.*, 2018; Thiemann and Poore, 2019). In a post-mortem study, Morrow *et al.* (2011) found that 44.8% of the donkey population investigated presented foot disorders, and 2.6% were euthanized due to irreversible damage of the foot. In most cases, foot disease was related mainly to hoof neglect and improper management (Thiemann and Poore, 2019). The most common clinical conditions reported were overlong hooves, unbalanced feet, solar abscesses, white line disease, laminitis, keratomas, and third phalange fractures (Thiemann and Rickards, 2013; Reix *et al.*, 2014; Thiemann and Poore, 2019).

In donkeys, the foot represents the same general anatomical structure as horses, but has particular morphological features related to keeping the hoof moist (Van Thielen *et al.*, 2018) and enabling the donkeys to be safe on rough ground (Thiemann and Poore, 2019). Donkeys' feet are more vertical than horses (5°–10° more upright) and the hoof capsule is cylindrical in the dorsal view compared with the conical view of the horse (Fowler, 1995; Thiemann and Rickards, 2013; Thiemann and Poore, 2019). The heels are narrower,

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giving an overall U-shape to the sole (Fowler, 1995; Thiemann and Rickards, 2013).

Although radiography is commonly used to assess the severity of foot abnormalities (Salem *et al.*, 2018), few studies have investigated the radiographic anatomy of normal donkey feet to provide univocal radiographic parameters (Collins *et al.*, 2011; El-Shafaey *et al.*, 2017). There has been a tendency to diagnose foot disease in donkeys using the same interpretation as horses (Cripps and Eustace, 1999). Since donkey feet are anatomically different from horse feet, the radiological parameters studied in horses cannot be used in donkeys (Thiemann and Poore, 2019). Moreover, there is a great variability in body size among different donkey breeds, which could cause significant variations in skeletal and hoof structures (Collins *et al.*, 2011; El-Shafaey *et al.*, 2017). This study aimed to establish the radiometric and morphometric parameters of a normal foot in Amiata donkeys in a homogeneous cohort in terms of sex, and to analyze the differences with horses.

Materials and Methods

Animals

A total of 28 Amiata female donkeys belonging to the Regional Stud Centre of Tuscany were enrolled in this study.

Donkeys were aged between 1 and 19 years (median age 16 years) and the body weight (BW) ranged between 110 and 393 kg (median 284 kg). All jennies were at pasture, not in work, and were used for reproductive purposes. Jennies were housed in collective paddocks 24 hours a day, fed hay *ad libitum* along with commercial equine feed according to NRC energy recommendations (National Research Council, 2007). All jennies were barefoot and underwent an orthopedic examination to rule out lameness and/or malformations of the hoof before enrolment in the study.

Radiographic protocol

For all donkeys, the feet were trimmed no more than a week prior to carrying out the radiographic exam (Collins *et al.*, 2011; El-Shafaey *et al.*, 2017). All feet were thoroughly cleaned prior to radiography and the donkeys were put in a stock. All subjects were sedated with xylazine (0.5 mg/kg). The dorsal hoof wall was marked with a soft metal marker positioned at the palpable limit of the hoof wall (Collins *et al.*, 2011; El-Shafaey *et al.*, 2017) in order to highlight the dorsal aspect and proximal limit of the hoof wall (Collins *et al.*, 2011).

For all feet, lateromedial (LM), dorsopalmar (DPa), and dorso65°proximal-palmarodistal oblique (DPrPaDi) views were acquired (Walker *et al.*, 1995; Butler *et al.*, 2017; El-Shafaey *et al.*, 2017). For LM and DPa views, both feet were positioned bearing the weight on a flat wooden block (4 cm high) to ensure an even weight distribution between the front limbs (Collins *et al.*, 2011). For the DPrPaDi view, the feet were positioned on a Hickman block.

All radiographs were obtained with a focal distance of 80 cm (Butler *et al.*, 2017). The radiographic beam was focused 1 cm below the coronary band for LM and DPa views (Collins *et al.*, 2011), and midway between the coronary band and the tip of the hoof for the DPrPaDi view. The X-ray beam was perpendicular to the X-ray cassette and parallel to the ground. Exposure factors were 68 Kv and 0.12 mA/s for LM view; 70 Kv and 0.12 mA/s for DP view; and 74 Kv and 0.12 mA/s for DPrPaDi view. A portable x-ray generator (GIERTH HF100 M) and an indirect digital radiographic system (Fujifilm FCR model Capsula X) were used. One experienced operator carried out all the radiographs (GP). Images were analyzed using a commercial software (Osirix DICOM Viewer, Pixmeo SARL, Switzerland), and all the radiographs were assessed by the same experienced operator (GP).

Radiological parameters

A series of 17 linear and angular, direct and derived radiometric parameters were evaluated in all 56 forefeet, for LM and DPa views (Fig. 1), according to the literature (Collins *et al.*, 2011). A detailed description is given in Table 1. These parameters evaluate the anatomical relationship between the osseous structures of the foot, define their relationship with the hoof capsule, and characterize the morphometric appearance of the distal phalanx in a normal foot (Collins *et al.*, 2011).

In addition, a total of 18 morphometric parameters were evaluated in 16 out of 56 forefeet for LM and DPa views (Fig. 2). A detailed description is given in Table 2.

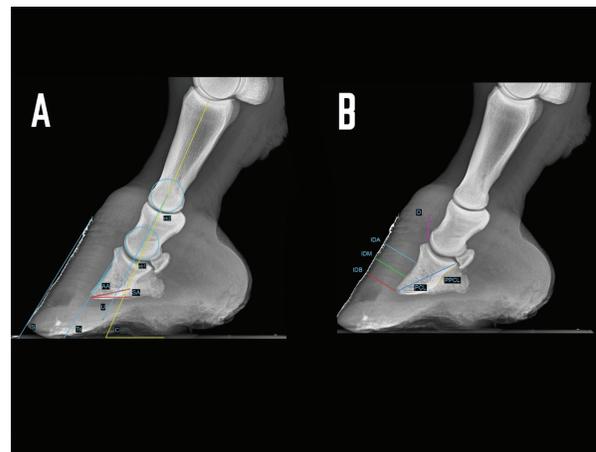


Fig. 1. LM radiographs of a normal donkey foot showing the angular (A) and linear (B) parameters established using Osirix DICOM Viewer (Pixmeo SARL, Switzerland). (A) Key: SA, angle of solar aspect of the distal phalanx. Ts, dorsal angle of the distal phalanx. AA, S, dorsal hoof wall angle. U, angle of proximal phalanx. C, angle of middle phalanx. Dorsal is to the left of image and palmar is to the right. (B) Key: IDA, integument depth (proximal site). IDM, integument depth (mid-dorsal site). IDB, integument depth (distal site). D, distal displacement of the distal phalanx. PCL, and PPCL. Dorsal is to the left of image and palmar is to the right.

Table 1. Definition of linear and angular, direct, derived radiological foot parameters.

		Angular parameters of the foot
Parameters	Anatomical definition	
1	S dorsal hoof wall angle	Angle subtended between the aspect of the hoof wall and the ground line. Direct parameter
2	Ts dorsal angle of the distal phalanx	Angle subtended between the dorsal aspect of the distal phalanx and the ground line. Direct parameter
3	C angle of middle phalanx	Angle subtended between the long axis of the middle phalanx and the ground line. Direct parameter
4	U angle of proximal phalanx	Angle subtended between the long axis of the proximal phalanx and the ground line. Direct parameter
5	SA angle of solar aspect of the distal phalanx	Angle subtended between the solar aspect of the distal phalanx and the ground line. Direct parameter
6	Paxisangle of pastern axis	Angular difference between long axis of the proximal phalanx and middle phalanx. Derived parameter. Paxis = U-C
7	HPA angle of hoof pastern axis	Angular difference between the dorsal hoof wall angle and the long axis of the proximal phalanx. Derived parameter. HPA = U-S.
8	Ang H angular deviation between the dorsal aspect of the DP and dorsum of the hoof wall	Angular difference between dorsal aspect of the distal phalanx and the dorsal hoof wall angle-derived parameter. Ang H = Ts-S.
9	Ang R phalangeal rotation angle	Angular difference between dorsal aspect of the distal phalanx and the long axis of the proximal phalanx. Derived parameter. Ang R = U-Ts.
10	Ang FDIP rotation angle	Angular difference between dorsal aspect of the distal phalanx and the long axis of the middle phalanx. Derived parameter. Ang F = C-Ts.
11	AA	Internal angle subtended between the distal palmar cortex and the dorsal aspect of the distal phalanx. Direct parameter
12	IDA integument depth of the dorsal aspect of the foot (proximal site)	Perpendicular linear distance between the dorsal aspect of the hoof wall and the dorsal surface of the distal phalanx, immediately distal to the distal limit of the extensor process. Direct parameter
13	IDB integument depth of the dorsal aspect of the foot (distal site)	Perpendicular linear distance between the dorsal aspect of the hoof wall and the dorsal surface of the distal phalanx proximal to the apex of the distal phalanx. Direct parameter
14	IDM integument depth of the dorsal aspect of the foot (mid-dorsal site)	Perpendicular linear distance between the dorsal aspect of the hoof wall and the dorsal surface of the distal phalanx at the midpoint between the IDA and IDB measurement sites. Direct parameter
15	D distal displacement of the distal phalanx	Perpendicular linear distance between the proximal limit of the hoof wall and the extensor process of the distal phalanx. Direct parameter
16	PCL	Linear distance between the apex of the distal phalanx and the articular process of the navicular joint. Direct parameter
17	PPCL	Linear distance between the point of insertion of DDFT and the articular process of the navicular joint. Direct parameter

Adapted from Collins *et al.* (2011).

Distal phalangeal rotation, if present, was measured by parameters SA, Ang H, Ang R, and Ang F. In addition to angular parameters, linear parameters were taken for the evaluation of the rotation of the phalanges. The solar margin of the third phalanx was evaluated for semi-quantitative assessment in LM and DPrPaDi views, and a grading system scale was established, according to the literature (Walker *et al.*, 1995; Butler *et al.*, 2017) (Table 3).

Statistical analysis

The distribution of the radiological parameters was evaluated using the D'Agostino and Pearson's test. Since not all radiological parameters showed a Gaussian distribution, the distribution was considered as non-Gaussian. Thus, results were reported as median \pm standard error, minimum and maximum values.

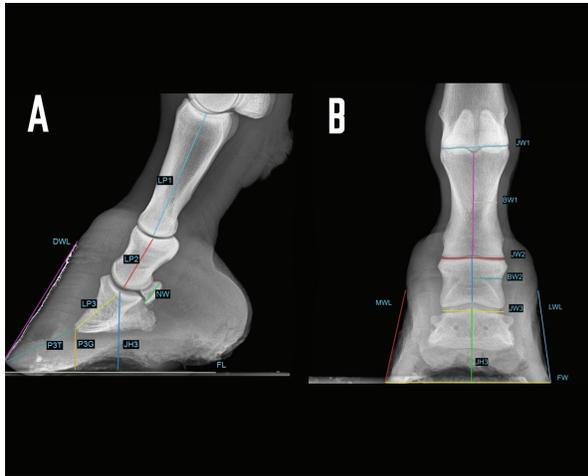


Fig. 2. LM (A) and dorsopalmar (B) radiographs of a normal donkey foot to show the morphometric parameters established using Osirix DICOM Viewer (Pixmeo SARL, Switzerland). (A) Key: LP1, length of first phalanx. LP2. LP3. JH3, height of the distal interphalangeal joint. NW, width of the navicular bone. FL. DWL. P3T. P3G. Dorsal is to the left of image and palmar is to the right. (B) Key: JW1, JW2, JW3, BW1, BW2, and JH3. Dorsopalmar radiographic view. MWL, medial wall length, LWL, FW, width of the foot. Medial is to the left of image and lateral is to the right.

The Mann–Whitney test was used for all the parameters measured to verify differences between right and left feet. Statistical significance was set at $p < 0.05$. Statistical analysis was carried out using GraphPad Prism 8.0 for Mac OS (GraphPad Software Inc., San Diego, CA).

Ethical approval

The present study was authorized by “Ethical Committee of the University of Pisa (23/19), according to the D.L.116/92 and D. Lgs. 26/14; owner written consents were obtained.

Results

Radiographs were carried out in all donkeys for a total of 56 feet. The time needed to carry out the radiographic exam ranged between 30 and 40 minutes, starting from the inoculation of the sedative. No statistical differences were found between the right and left feet for any of the parameters. The results for linear and angular parameters obtained in 56 feet are reported in Tables 4 and 5, while the data on the morphometric parameters obtained in 16 out of 56 feet are reported in Table 6. In the DPRPaDi view, the *crena solearis* of the distal phalanx appeared with a semi-circular shape, except for 3 out of 56 (5.3%) feet that presented a *crena solearis* with grade 1 and two out of 56 (3.5%) feet with grade 2.

In the LM view, periosteal-like bony proliferative changes occurred in 4 four out of 56 (7.1%) feet with grade 2 and 3 three out of 56 (5.3%) feet with grade 1.

Discussion

Donkeys have particular anatomical and, as a consequence, radiographic features of the digit (Collins *et al.*, 2011; El-Shafaey *et al.*, 2017; Thiemann and Poore, 2019), which differ from those reported for horses (Thiemann and Rickards, 2013). We assessed the radiometric and morphometric parameters of normal feet in a population of Amiata female donkeys and analyzed the differences with other donkey breeds and horses.

In our study, a wide range of both S and Ts angular parameters was found, in agreement with Collins *et al.* (2011) for European donkeys. The median values obtained for S and Ts parameters were similar, supporting the hypothesis that the hoof wall and the dorsal aspect of the distal phalanx are mostly in parallel alignment in healthy donkey feet, with a minimal difference in inclination (0.7°) (Collins *et al.*, 2011). The hypothesis of the parallel alignment was also supported by the median values of the linear parameters, IDA, IDM and IDB, which were comparable.

The distance between the dorsal hoof wall and the dorsal surface of the distal phalanx seems to vary according to the donkey breed. In fact, Collins *et al.* (2011) reported a mean IDM value of 15.6 ± 2.6 mm (s.d.) in European donkeys, while in the Mammoth breed, an IDM value of 23 ± 3 mm (s.d.) has been reported (Walker *et al.*, 1995).

We found that the Amiata breed showed an intermediate IDM value (21.2 ± 0.6 mm) between the two intervals proposed by other studies (Walker *et al.*, 1995; Collins *et al.*, 2011), in particular smaller than the Mammoth and bigger than European donkey breeds. This difference might be related to the body size. In fact, larger donkeys (i.e., Mammoth) presented higher values than smaller ones (i.e., Amiata and European), as suggested by other studies (Collins *et al.*, 2011; Smith, 2016).

In our study, the median value of the linear distance (D) was shorter than the values reported in Egyptian donkeys (25.2 ± 31.8 mm) (El-Shafaey *et al.*, 2017), but longer (10.4 ± 3.7 mm) than that reported in European donkeys (Collins *et al.*, 2011).

In our study, the foot showed a broken forward pastern axis, similar to findings previously reported for European donkey breeds ($5.1^\circ \pm 5.2^\circ$) (Collins *et al.*, 2011). Amiata donkeys presented a wide range in values related to the third phalanx rotation degree (i.e., Ang R; Ang F; SA), which is in line with the results on European donkey breeds (Collins *et al.*, 2011).

The data obtained in this study for the third phalanx angular morphometric features [i.e., palmar cortex length (PCL), proximal palmar cortex length (PPCL), apex angle (AA)] were in agreement with values

Table 2. Morphometric parameters definitions of digital bones and hoof capsule.

		Morphometric parameters of the foot
Parameters		Anatomical definition
1	LP1, Length of first phalanx	Longitudinal length of the first digital bone. Direct parameter, measured from the lateromedial radiographic view.
2	LP2	Longitudinal length of the second digital bone. Direct parameter, measured from the lateromedial radiographic view.
3	LP3	Longitudinal length of the third digital bone. Direct parameter, measured from the lateromedial radiographic view.
4	NW, Width of the Navicular bone	Width of the navicular bone. Direct parameter, measured from the lateromedial radiographic view.
5	P3G	Perpendicular linear distance between the tip of the third digital bone to the ground. Direct parameter, measured from the lateromedial radiographic view.
6	P3T	Linear distance between the tip of the third digital bone to the toe, parallel to the ground. Direct parameter, measured from the lateromedial radiographic view.
7	JH3	Perpendicular linear distance between the distal interphalangeal joint to the ground. Direct parameter, measured from the lateromedial radiographic view.
8	FL	Length of the foot. Direct parameter, measured from the lateromedial radiographic view.
9	DWL	Length of the dorsal wall of the hoof from the coronary band to the ground. Direct parameter, measured from the lateromedial radiographic view.
10	JW1	Width of the metacarpophalangeal joint. Direct parameter, measured from the dorsopalmar radiographic view.
11	JW2	Width of the proximal interphalangeal joint. Direct parameter, measured from the dorsopalmar radiographic view.
12	JW3	Width of the distal interphalangeal joint. Direct parameter, measured from the dorsopalmar radiographic view.
13	BW1	Width of the first digital bone, measured from the point of lesser width, from the sagittal bone plane to the bone cortex. Direct parameter, measured from the dorsopalmar radiographic view.
14	BW2	Width of the second digital bone, measured from the point of lesser width, from the sagittal bone plane to the bone cortex. Direct parameter, measured from the dorsopalmar radiographic view.
15	LWL	Length of the lateral wall of the hoof, from the coronary band to the ground. Direct parameter, measured from the dorsopalmar radiographic view.
16	MWL, Medial wall length	Length of the medial wall of the hoof, from the coronary band to the ground. Direct parameter, measured from the dorsopalmar radiographic view.
17	FW, Width of the foot	Width of the foot. Direct parameter, measured from the dorsopalmar radiographic view.
18	JH3 (DPv). Dorsopalmar radiographic view.	Perpendicular linear distance between the distal interphalangeal joint to the ground. Direct parameter, measured from the dorsopalmar radiographic view.

Adapted from El-Shafaey *et al.* (2017) (modified).

Table 3. Grading of the edge shape and periosteal proliferation of the distal phalanx.

	DPrPaDio view	LM view
Grade 0	Semi-circular edge of distal phalanx	Absence of periosteal proliferation
Grade 1	Mild sagittal irregular shape on the edge	Mild periosteal proliferation
Grade 2	Moderate irregular shape on the edge	Moderate periosteal proliferation
Grade 3	Marked irregular shape on the edge	Marked periosteal proliferation

Adapted from Walker *et al.* (1995) and Butler *et al.* (2017) (modified).

Table 4. Linear parameters results (expressed in mm) in all 56 healthy forefeet.

	IDA	IDB	IDM	D	PCL	PPCL
Med ± SE	19.0 ± 0.6	21.4 ± 0.7	21.2 ± 0.6	19.0 ± 0.8	43.4 ± 0.4	15.0 ± 0.8
m-M	14.0–24.0	12.0–26.0	15.0–25.0	12.0–25.0	36.0–47.0	12.0–17.0

(Med): median value; (SE): standard error; (m): minimum value; (M): maximum value.

Table 5. Angular parameters results (expressed in degree) in all 56 healthy forefeet.

	S	Ts	U	C	PAxis	HPA	AngH	AngR	AngF	SA	AA
Med±SE	57.3±0.7	58±1.0	63.8±0.9	62.2±1.0	9.0±0.9	8.1±1.1	1.4±0.8	5.3±1.5	-1.5±1.1	9.0±0.5	51.0±0.8
m-M	44.2-68.6	41.6-66.3	48.3-80.8	41.8-68.7	-3.1-17.8	-13.4-29.3	-9.2-8.3	-18.0-29.2	-18.5-19.9	2.6-16.1	21.7-57.0

(Med): median value; (SE): standard error; (m): minimum value; (M): maximum value.

Table 6. Morphometric parameters results (expressed in mm) in 16 out of 56 healthy forefeet.

	LM radiographic view									
	LP1	LP2	LP3	NW	P3G	P3T	JH3	FL	DWL	
Med ± SE	82.9 ± 1	35.3 ± 0.5	35.6 ± 0.7	16.4 ± 0.5	18.7 ± 1.1	27.5 ± 1.3	45.4 ± 1.2	127.5 ± 3.4	80.0 ± 2.7	
m-M	77.0–93.1	32.6–39.7	32.1–41.1	12.1–17.8	14.2–28.1	21.7–38.5	41.0–56.3	110.0–160.0	70.0–105.0	
	DPa radiographic view									
	JW1	JW2	JW3	BW1	BW2	LWL	MWL	FW	JH3 (DPv)	
Med±SE	46.5 ± 0.6	43.2 ± 0.7	42.2 ± 0.7	15.8 ± 0.3	20.5 ± 0.2	72.5 ± 1.1	65.0 ± 1.2	100 ± 1.3	50.1 ± 1	
m-M	44.5–51.8	40.6–50.0	39.1–47.2	13.3–18.2	19.0–22.2	60.0–80.0	65.0–75.0	90–110	45.6–59.1	

(Med): median value; (SE): standard error; (m): minimum value; (M): maximum value.

reported in European donkey breeds (Collins *et al.*, 2011).

All the linear morphometric parameters measured in the Amiata donkey population showed higher values than Egyptian donkey breeds (El-Shafaey *et al.*, 2017). The anatomical variation might be related to the body size (BW, height, and weight) of the Amiata donkey compared to Egyptian donkeys. In particular, the BW range in Amiata donkeys was higher than previously reported (El-Shafaey *et al.*, 2017).

Comparing our findings with normal foot values reported for horses, many differences were observed. In particular, in horses, the S and Ts values showed a narrow range of values (i.e., $48.2^\circ \pm 2.6^\circ$ and $47.8^\circ \pm 3^\circ$, respectively) and less variability among different breeds (Linford *et al.*, 1993), compared to our results for donkeys.

In horses, homogenous IDM values were found between different breeds (i.e., Hanoverian: 18 ± 0.7 mm; Thoroughbred: 16.3 ± 1.8 mm; other breeds: 18.4 ± 1.4 mm; ponies: 13.2 ± 1.9 mm) (Cripps and Eustace, 1999). In our donkeys, these values were generally higher, supporting the hypothesis of a thicker hoof wall and, as a consequence, a deeper location of the third phalanx within the hoof in donkeys compared to horses, as previously suggested (Collins *et al.*, 2011).

In horses, the D value, also called the founder distance, has a wider variability (–2–10 mm) (Parks and

Belknap, 2017) compared to donkey breeds. However, the D value in horses is smaller than in donkeys. The D value is relevant in the clinical evaluation of laminitis in horses and a value over 8 mm is considered diagnostic for laminitis in Thoroughbreds (Cripps and Eustace, 1999). In donkeys, the distal dislocation of the third phalanx should therefore be evaluated carefully, bearing in mind that the bone is usually located deeper in the hoof capsule (Collins *et al.*, 2011; El-Shafaey *et al.*, 2017; Thiemann and Poore, 2019).

Another difference between horses and donkeys was found in the SA value, which showed a narrow range and smaller values in horses (Parks and Belknap, 2017) compared with donkeys. The reported value for Warmblood horses is $4.0^\circ \pm 2.1^\circ$ and for ponies $6.3^\circ \pm 2.6^\circ$ (Parks and Belknap, 2017), while in the present study the value was $9.0^\circ \pm 0.5^\circ$.

It has been suggested that in horses, the SA value is useful for the diagnosis and prognosis of laminitis, and the degree of rotation is inversely related to the prognosis (Linford *et al.*, 1993). Conversely, our findings support the hypothesis that the SA value may provide limited information on the third phalanx rotation in donkeys, in agreement with previous reports (Collins *et al.*, 2011). The SA value should therefore be assessed in relation with other relevant radiographic values for the diagnosis of laminitis, such as S, Ts, Ang H, Ang R, Ang F, IDM, and D (Collins *et al.*, 2011).

In the present study, an irregular dorsal solar margin and changes in the periosteal-like bony proliferation on the mid-dorsal aspect of the distal phalanx were observed with a low prevalence (7.1% of the feet with grade 2 and 5.3% of the feet with grade 1) and were not associated with signs of lameness. Our results are in contrast with findings reported in horses and in another study conducted on donkeys (Linford *et al.*, 1993; Walker *et al.*, 1995). In Thoroughbreds, in race training, the bony proliferation on the distal phalanx is frequently seen in sound horses (88%), and seems to be related to the age of the first race (Linford *et al.*, 1993). The bony proliferation was also verified in 75% of Mammoth donkeys (Walker *et al.*, 1995). In addition, a high variability of the dorsal solar margin shape not associated with signs of lameness was observed in Mammoth donkeys (87.5%) (Walker *et al.*, 1995). These differences might be explained considering the athletic activities of horses compared to the low level of activity in our donkey population (Linford *et al.*, 1993). Finally, in donkeys, bone morphometric parameters [i.e., length of second phalanx (LP2), length of third phalanx (LP3), width of the metacarpophalangeal joint (JW1), width of the proximal interphalangeal joint (JW2), width of the distal interphalangeal joint (JW3), width of the first phalanx (BW1), and width of the second phalanx (BW2)] showed lower values than horses, while hoof capsule parameters [i.e., tip of P3 to the ground (P3G), tip of P3 to the toe (P3T), height of the distal interphalangeal joint (JH3), length of the foot (FL), length of the dorsal wall (DWL), lateral wall length (LWL), and medial wall length (MWL)] had similar values (Rocha *et al.*, 2004). As discussed previously, this anatomical variation might be related to the different body sizes between donkeys and horses. In the present study, the *crena solearis* generally presented (51 out of 56, 91%) a semi-circular shape, and was altered in 5 five out of 56 (9%) donkeys. Walker *et al.* (1995) reported a great variability in the shape of the *crena solearis* and were not able to exactly define the normal appearance; also, in horses, a variable size and appearance of the *crena* has been found (Butler *et al.*, 2017). These results would seem to confirm the relevance of differences in breed regarding hoof and bone features.

Our study highlighted the great variability in bone and hoof parameters between different donkey breeds, which also indicates the importance of obtaining parameters for each breed.

The limitations of this study concern the small number of donkeys enrolled and the inclusion of only females. As reported in the literature, the wither height and weight of female Amiata donkeys do not differ significantly from males or geldings (Casini *et al.*, 2007; Cecchi *et al.*, 2007). It is thus possible that the weight and height in Amiata donkeys might not lead to differences in morphometric hoof parameters between females and males. On the other hand, our study provided results from data only from

female donkeys and this could potentially create a bias when comparing pathological findings with reference ranges. However, a larger study group, including males and geldings, would provide more accurate data for the assessment of a normal radiographic appearance of the fore digit in Amiata donkeys.

Our data confirm that the donkey has a unique radiological anatomy, as also suggested by others (Collins *et al.*, 2011; El-Shafae *et al.*, 2017). This study contributes to the literature by developing a specific model and by collecting data on healthy feet of Amiata donkeys. Prior knowledge of these parameters is essential for the early detection of slight anatomical modifications of the digit and hoof shape (El-Shafae *et al.*, 2017; Thiemann and Poore, 2019). We also confirm that the donkey breed affects the variability in the radiographic parameters of the digit, which is in agreement with studies conducted by Walker *et al.* (1995) and Collins *et al.* (2011) on Mammoth and European donkey breeds, respectively.

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Conflict of interest

The authors declare that there is no conflict of interest.

Authors' contributions

GR, MS, and SC conceived, designed, and supervised the project. IN, BA, and GP executed the experiment. IN, BA, GP, and CP analyzed the data. All the authors interpreted the data, wrote, and critically revised the manuscript for intellectual content and approved the final version. IN and MS had full access to all the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis.

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