Radiographic characterization of ossification of the ungular cartilages in horses: 271 cases (2005–2012)

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Objective—To describe in detail the radiographic appearance of ossified ungular cartilages in horses and to evaluate the usefulness of a flexed dorsolateral-palmaromedial oblique (flexed oblique) radiographic view in evaluating the ungular cartilages.

Design—Retrospective case series.

Sample—Radiographs of 1,255 front feet of horses.

Procedures—Ossification of the ungular cartilages was graded during evaluation of radiographs on a scale from 0 to 5; feet with cartilages with an ossification grade ≥ 2 were included (386 feet [271 horses]). The shape (straight, curved outward or inward, and dorsopalmar extension of ossification) was determined. The view on which abnormalities were best identified was documented. Abnormalities of the compact bone, radiopacity, trabecular architecture, compactospongious demarcation, and presence of radiolucent lines were recorded; grouped as modeling, adaptive changes, or both; compared with ossification grade, separate centers of ossification, mediolateral symmetry of ossification, shape, cartilage (medial or lateral), and foot (left or right); and tested for significant associations.

Results—Fractures (n = 35) were most common in feet with cartilages with an ossification grade of 4 (18) or 5 (17) and were best identified in flexed oblique images, compared with more commonly recommended images. Multivariable logistic regression showed a significant positive association of ossification grade with modeling or adaptive changes; feet with cartilages with an ossification grade of 4 (OR, 11.59; 95% CI, 6.52 to 20.60) or 5 (OR, 72.90; 95% CI, 25.32 to 209.90) were more likely than those with an ossification grade of 2 or 3 to have modeling or adaptive changes. Abnormally shaped cartilages were more likely to have modeling or adaptive changes, compared with normally shaped cartilages (OR, 4.90; 95% CI, 1.94 to 12.42).

Conclusions and Clinical Relevance—Extensive ossification and the presence of inward or outward curvature as well as palmar curvature or a bulbous shape were significant risk factors for modelling and adaptive changes. Flexed oblique images provided clinically useful information, including detection of abnormal shape and fractures, that may not be evident on other currently recommended images. Such images are recommended for complete radiographic appraisal of ossified ungular cartilages of the foot in horses. (*J Am Vet Med Assoc* 2015;247:801–811)

The ungular cartilages of the foot in horses are attached distally to the palmar processes of the distal phalanx and extend both proximally and in dorsal and palmar (plantar) directions. Ossification originates from the base at the attachment to the distal phalanx and extends a variable distance proximally. There may be 1 or more additional separate centers of ossification, which may be completely isolated. Alternatively, a separate center of ossification may fuse with the proximal aspect of the ossified cartilage or remain separate with a radiolucent line at the junction between them.[1] Radiographic differentiation of the junction between a separate center of ossification and the distal ossified cartilage versus fracture of an ossified cartilage may be difficult.[1–3]

The clinical importance of ossification of the ungular cartilages of the foot (colloquially known as sidebone) is controversial. Ossification is commonly more extensive in the lateral than the medial cartilage.[1,4,5] Although sidebone was historically considered a potential problem in working draft horses,[6] in riding horses it has been thought to be of no clinical importance.[1] However, there is increasing evidence suggesting that higher ossification grades (grade 3 plus a separate center of ossification, grade 4, and grade 5 [on a scale from 0 to 5]), called "possibly significant ossification" by Ruohoniemi et al,[7] and mediolateral asymmetry of ossification may be predisposing factors for and contribute to foot-related pain.[2,4,7,8] Although grading of ossification of the ungular cartilages has been well documented,[5,9] to our knowledge, there have been no reports of studies fully describing variations in the radiographic appearance of ossified ungular cartilages. Ossified ungular cartilages may be important if they are subject to altered biomechanical forces and therefore are predisposed to modeling, adaptive changes, or both, which may be a precursor to fracture.[10,11] Changes

Abbreviation	
CI	Confidence interval

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in the compact bone, compactospongious demarcation, clarity of trabecular pattern of spongious bone, and radiopacity are radiographic indicators of modeling or adaptive changes.[10]

It has been suggested that ossification of the ungular cartilages is best assessed on dorsopalmar radiographic images.[1,12] Currently, published systems for grading ossification of ungular cartilages[5,9] use dorsopalmar images to determine the proximodistal extent of ossification. However, the additional use of dorsoproximal-palmarodistal oblique and flexed dorsolateral-palmaromedial oblique and flexed dorsomedial-palmarolateral oblique images (flexed oblique images) was valuable for detection of a fracture of an ossified ungular cartilage.[13,14]

The objectives of the study reported here were to further characterize the radiographic appearance of ossified ungular cartilages in horses and to verify the usefulness of flexed oblique images for describing variants. Our hypotheses were that radiographic evidence of modeling and adaptive changes to ossified ungular cartilages would be more common in either extensively or asymmetrically ossified cartilages and also more common in lateral cartilages than medial cartilages. Further, we hypothesized that additional information could be obtained from a flexed oblique radiographic view, compared with currently recommended views.[15]

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Materials and Methods

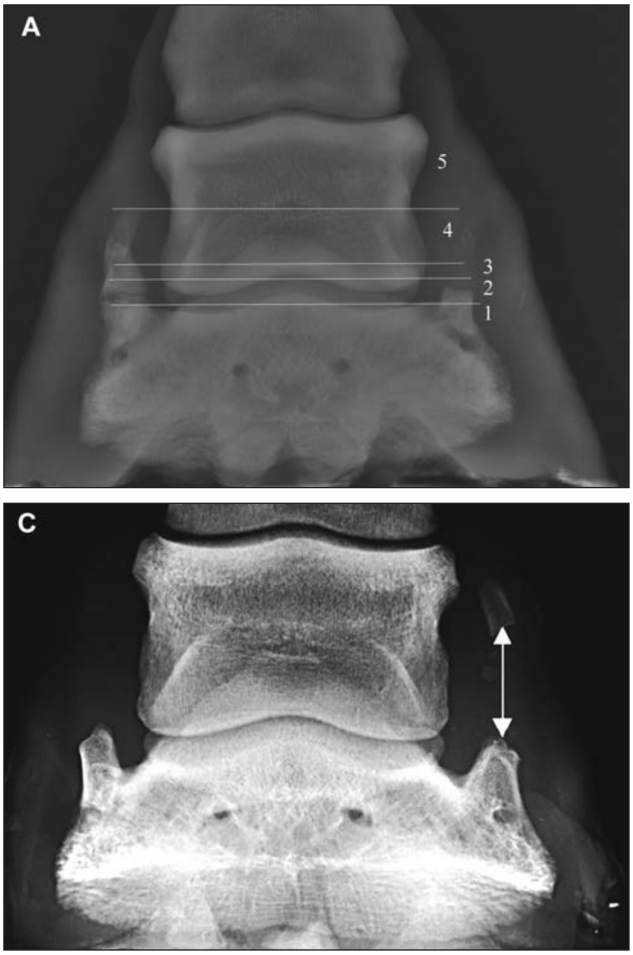
Case selection criteria—All front foot radiographs of horses acquired at the Animal Health Trust between January 2005 and December 2012 were retrospectively reviewed. Radiography was performed following diagnostic local analgesia confirming the presence of foot pain. Horses with unilateral foot pain only underwent radiographic examination of the affected foot. Breed, age, sex, and use were recorded for each horse. In addition, horses also underwent MRI, nuclear scintigraphic examination, or both of the front feet (bilaterally). Nuclear scintigraphy was performed in horses that did not undergo MRI. Horses were assigned into 2 groups on the basis of whether they were or were not examined with MRI, and a final diagnosis was recorded for both groups. Horses included in the study were categorized as having foot pain likely to be associated with an injured ossified cartilage by the presence of increased radiopharmaceutical uptake, abnormalities on MRI, or both and by the exclusion of other potential causes on the basis of results of diagnostic analgesia and imaging (MRI and nuclear scintigraphy). The study was approved by the Ethical Review Committee of the Animal Health Trust.

Radiographic examination—All horses underwent comprehensive computed digital radiographic examination (66 kV and 16 mAs) of the affected feet, including weight-bearing dorsopalmar, lateromedial, flexed dorsomedial-palmarolateral oblique and flexed dorsolateral-palmaromedial oblique (referred to as flexed oblique; **Figure 1**), dorsoproximal-palmarodistal oblique (upright pedal), and palmaroproximal-palmarodistal oblique views.[3] All images were acquired with a horizontal x-ray beam.

Radiographic assessment and validation—Ossification of the ungular cartilages was graded on the basis of results of evaluation of weight-bearing dorsopalmar radiographic images with the following grading system[9]: 0 = no ossification, 1 = ossification up to the level of the medial or lateral margin of the distal interphalangeal joint, 2 = ossification up to the level of the midsagittal aspect of the distal interphalangeal joint, 3 = ossification up to the most proximal aspect of the distal sesamoid (navicular) bone (excluding proximal enthesiophytes), 4 = ossification up to the midpoint of the middle phalanx (based on the most proximal aspect of the joint surface), and 5 = ossification proximal to the midpoint of the middle phalanx (**Figure 2**). Feet of all horses with 1 or both ungular cartilages assigned an ossification grade ≥ 2 were included. Feet with an ossification grade < 2 were excluded from analysis because the extent of ossification was judged as unlikely to be clinically important. Fifty sets of foot radiographs fulfilling the inclusion criteria were randomly selected by use of a random number generator and assessed subjectively by one of the authors, an equine veterinarian undergoing specialty diagnostic imaging training (LEJ). Descriptive systems considering each variant observed were developed in agreement with the other author, a highly experienced equine veterinarian (SJD). An additional 10 sets of radiographs were randomly selected; ossification of ungular cartilages was graded by both authors with complete agreement and then graded in a blinded fashion (horse identification was removed) and described 10 times each in a random order by one author (LEJ) to determine repeatability of the grading and classification systems. The coefficient of variance was < 2%.

The ossification grade of each ungular cartilage was determined from the dorsopalmar images. The

Figure 1—Photograph demonstrating the technique for acquiring a flexed dorsolateral-palmaromedial oblique (flexed oblique) image of the foot of a horse. The toe is supported in a v-shaped groove in a block, with the interphalangeal joints flexed.



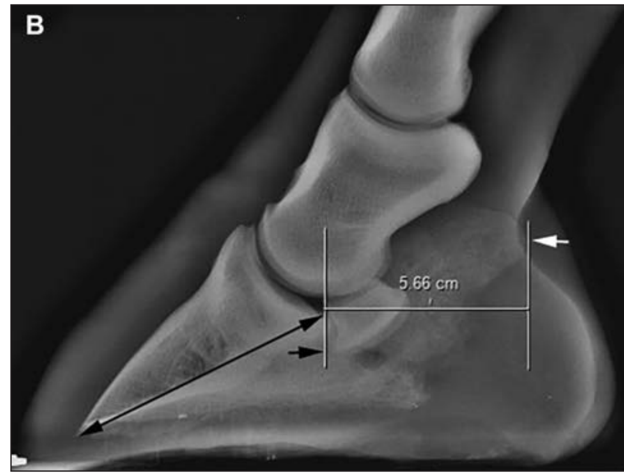


Figure 2—Radiographic images demonstrating the grading system[5] and measurements obtained for evaluation of the radiographic appearance of ossified ungular cartilages in horses evaluated for foot pain between 2005 and 2012. A—Dorsopalmar radiographic image illustrating the grading system for the proximodistal extent of ossification of the ungular cartilages. Ossification of the ungular cartilages was graded on the basis of results of evaluation of weight-bearing dorsopalmar radiographic images with the following grading system: 0 = no ossification, 1 = ossification up to the level of the medial or lateral margin of the distal interphalangeal joint, 2 = ossification up to the level of the midsagittal aspect of the distal interphalangeal joint, 3 = ossification up to the most proximal aspect of the distal sesamoid (navicular) bone (excluding proximal enthesiophytes), 4 = ossification up to the midpoint of the middle phalanx (based on the most proximal aspect of the joint surface), and 5 = ossification proximal to the midpoint of the middle phalanx. B—Lateromedial radiographic image of a foot. To measure palmar extension of an ossified ungular cartilage, a vertical line was drawn digitally at the most dorsodistal aspect of the dorsal compact bone of the distal sesamoid bone (black arrow) and at the most palmar aspect of the ossified ungular cartilage (white arrow). A horizontal line was drawn between the 2 vertical lines to measure palmar extension of the ungular cartilage, which was identified as the lateral cartilage on orthogonal images. The dorsopalmar length of the distal phalanx was also measured (double-headed black arrow), and palmar extension was expressed as a ratio to account for variable magnification. C—Dorsopalmar radiographic image of a foot to illustrate the measurement of junction height. Lateral is to the right. There is grade 2 ossification of the lateral ungular cartilage, which also has a proximally located separate center of ossification. A vertical line between the separate center of ossification and ossification at the base of the cartilage was drawn digitally to measure the junction height (double-headed arrow).

presence of higher ossification grades (meeting the criteria of "possibly significant ossification" described by Ruohoniemei et al[7] [grade 3 plus a separate center of ossification, grade 4, and grade 5]) was recorded. The width of ossification was measured digitally from the dorsopalmar image, both at the base and halfway up the ossified portion of the cartilage (mid), and expressed as a ratio to the width of the distal phalanx (measured digitally at the widest point) to account for variable magnification. The dorsopalmar extent of ossification of the largest lateral and medial cartilages was measured on the lateromedial image. A vertical line was drawn at the most dorsodistal aspect of the dorsal compact bone of the distal sesamoid bone and at the most palmar aspect of the ossified cartilages (Figure 2). The horizontal distance between these 2 vertical lines was measured and expressed as a ratio to the dorsopalmar length of the distal phalanx. Medial versus lateral cartilage identification was impossible in the lateromedial image without the use of additional images. Repeatability of the measurement techniques was confirmed by analysis of 10 sets of 10 images 10 times, with a coefficient of variance of < 2%. The presence, height (in the dorsopalmar image), junction height (distance between separate centers of ossification and ossification from the base), presence of modeling at the junction, and changes in opacity and trabecular (spongious) architecture of separate centers of ossification were recorded. Radiolucent lines, their location and orientation, and a description of their margins were also recorded. They were classified as being consistent with a fracture (ie, because of the presence of a sharp irregular contour and associated modeling or adjacent increased opacity or both) or unknown (ie, impossible to differentiate between a fracture and modeling at the junction between a separate center of ossification and ossification at the base of the cartilage). The ability to identify separate centers of ossification and radiolucent lines was compared among images (flexed lateromedial, dorsopalmar, dorsolateral-palmaromedial oblique, flexed dorsomedial-palmarolateral oblique, and flexed dorsoproximal-palmarodistal oblique flexed); whether the separate center of ossification or radiolucent line was visible in each image as well as the images in which it was subjectively best appreciated were recorded.

The site and severity of irregularities of the compact bone and increases in radiopacity (none, mild, moderate, or severe), alteration to the clarity of the trabecular pattern (normal, reduced, or absent), and compacto-

Figure 3—Radiographic images showing abnormalities of ossified ungular cartilages in horses evaluated for foot pain between 2005 and 2012. A—Dorsopalmar radiographic image of a foot. Lateral is to the right. There is grade 4 ossification of both the medial and lateral ungular cartilages. The lateral ungular cartilage is markedly thickened. Both medial and lateral ungular cartilages have diffuse areas of increased radiopacity, which is more evident in the lateral cartilage and extends into the junction with the distal phalanx. The medial ungular cartilage curves outward and the lateral cartilage is straight. B—Flexed oblique image of the same foot as in panel A. There is an ill-defined radiolucent line traversing the lateral ungular cartilage (arrows) with mild callus formation at the compact bone.

spongious demarcation (normal, poorly defined, or absent) were recorded. The shape of the ossified ungular cartilages was assessed **(Figures 3–5)** in both dorsopalmar (straight, outwardly curved, or inwardly curved) and flexed oblique images (straight, bulbous shape, or palmar curvature). Mediolateral symmetry of ossification of the ungular cartilages was recorded (for the purposes of this assessment, ungular cartilages with an ossification grade < 2 were included, assuming that ossification of 1 ungular cartilage in the foot had an ossification grade ≥ 2). Mediolateral imbalance of the distal phalanx (> 2° angle between the horizontal and a line drawn at a tangent to the distal border of the distal phalanx) was determined from dorsopalmar images.

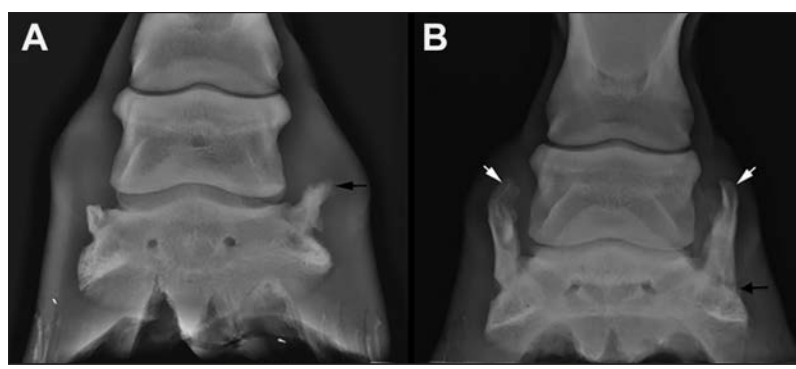


Figure 4—Dorsopalmar radiographic images of 2 feet from 2 horses illustrating abnormalities of ossified ungular cartilages. Lateral is to the right. A—There is grade 3 ossification of the lateral ungular cartilage, which curves outward (black arrow). Note also the irregular compact bone, lack of compactospongious demarcation, increased radiopacity, and absence of the normal trabecular pattern proximally. B—There is grade 5 ossification of both medial and lateral ungular cartilages, which both curve inward proximally (white arrows). Note also the decreased compactospongious demarcation, areas of increased radiopacity, and reduced clarity of trabecular pattern. There is also an ill-defined radiolucent line at the base of the lateral cartilage (black arrow). This was confirmed to be a fracture on a flexed oblique image.

Statistical analysis—For statistical analysis, abnormalities of the compact bone, radiopacity, trabecular architecture, compactospongious demarcation, and presence of radiolucent lines were grouped together as modeling, adaptive changes, or both, against which the following variables were tested for associations: ossification grade, symmetry of ossification, mediolateral balance, separate centers of ossification, shape, cartilage (medial vs lateral), and foot (left vs right).

Statistical analyses were performed with a commercial software program.[a] Data were described as mean ± SD if continuous and normally distributed and as a proportion (%) for categorical data. A Mann-Whitney *U* test was used to assess the distribution of palmar extension in fractured and nonfractured cartilages and of cartilage width ratio (base and mid) in cartilages with and cartilages without modeling or adaptive changes or both. χ^2 Analysis was performed on all of the variables to test for associations with modeling or adaptive changes or both. Values of $P \leq 0.05$ were considered significant.

Univariable logistic regression was performed to screen for associations between all recorded variables and modeling or adaptive changes or both as a binary outcome. Variables with a value of $P < 0.25$ were included in a multivariable logistic regression model, which was built in a stepwise, backward elimination procedure. Variables remained in the model if they significantly ($P \leq 0.05$) improved the fit or if removal resulted in substantial change (> 25%) to the effect of other variables. Interaction terms for all variables retained in the final model were assessed. Goodness-of-fit was assessed by means of the Hosmer-Lemeshow test and the area under the receiver operating characteristic curve.

Results

Of the 1,255 foot radiographs examined, 386 feet (271 horses) met the study inclusion criteria. Exclusion of cartilages with an ossification grade < 2 resulted in 345 lateral cartilages and 274 medial cartilages being assessed (619 total). Both front feet were included in 115 horses, right front only in 92, and left front only in 64. The mean ± SD age of the horses was 9 ± 1.2 years (median, 8 years; range, 3 to 24 years), and geldings predominated (n = 176) over mares (91) and stallions (3). Horses were used for general purpose riding (including unaffiliated competition; n = 108), eventing (74), dressage (50), show jumping (27), and other disciplines (11). Breed categories included Thoroughbred (n = 17), Thoroughbred cross (49), warmblood (88), Cob-type (77), and other (39).

Descriptive statistics for regularity of the compact bone, opacity, compactospongious demarcation, and clarity of trabecular pattern were summarized **(Table 1)**.

Radiolucent lines—Radiolucent lines were evident in 42 ossified cartilages in 36 horses, of which 35 (83.3%) were identified as fractures. For 7, it was impossible to differentiate between a nonunion fracture and trauma[2,7,8,14] to the junction between separate centers of ossification (these were characterized by a radiolucent gap with modeling of the opposing ends, which were flared, and irregular new bone formation). Fractures were present in 18 medial (12 at the base and 6 midcartilage) and 17 lateral (6 at the base and 11 midcartilage) ossified ungular cartilages in 30 horses. For fractures, there was a significant (P = 0.02) association between foot and affected cartilage: 15 of 23 (62.5%) fractures in the right forefoot were identified in the lateral cartilage, and 9 of 12 (75%) fractures in the left forefoot were identified in the medial cartilage. There was also a significant ($P < 0.001$) association between the presence of other modeling, adaptive changes, or both and fractures. In 5 ossified cartilages, the fracture was oriented from distal to proximal and obliquely outward, 7 from distal to proximal and obliquely inward, 3 mediolateral, and 2 mixed (several directional changes). The fracture orientation of the remaining 14 ossified cartilages was not

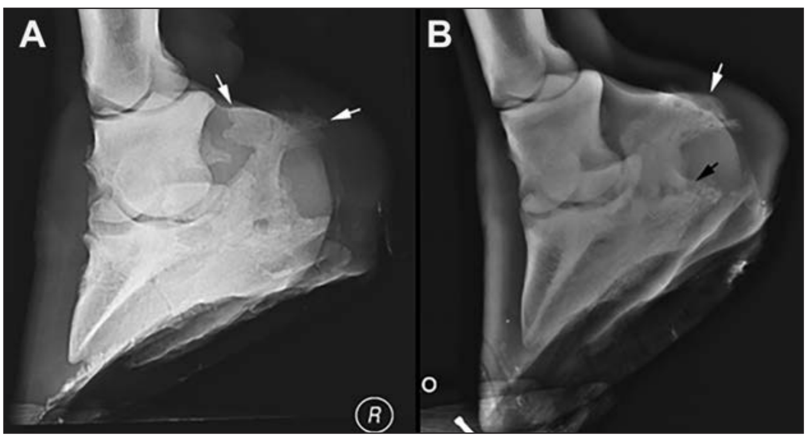


Figure 5—Radiographic images showing abnormalities of ossified ungular cartilages in horses with foot pain. A—Flexed oblique radiographic image of a foot. There is extensive ossification of the lateral ungular cartilage, which has a bulbous shape (arrows). Note also the periarticular modeling of the dorsoproximal aspect of the distal phalanx. There was no response to intra-articular analgesia of the distal interphalangeal joint. B—Flexed oblique radiographic image of a foot. There is marked ossification of the medial ungular cartilage, which extends in a palmar direction proximally (white arrow). Note also the irregular radiolucent line at the junction of the ossified ungular cartilage and the distal phalanx (black arrow).

Table 1—Radiographic characteristics of ungular cartilages of 271 horses (386 feet) with lameness evaluated for foot pain at the Animal Health Trust between January 2005 and December 2012.

Radiographic variable	Lateral ungular cartilage	Medial ungular cartilage	Grade[9] 2	Grade[9] 3	Grade[9] 4	Grade[9] 5	Symmetric ossification	Asymmetric ossification
Compact bone								
Smooth	291 (84.3)	244 (89.1)	342 (98.3)	90 (93.8)	91 (72.2)	13 (26.5)	460 (87.1)	75 (82.4)
Mildly irregular	35 (10.1)	23 (8.4)	6 (1.7)	6 (6.3)	23 (18.3)	23 (46.9)	46 (8.7)	12 (13.2)
Moderately irregular	18 (5.2)	6 (2.2)	0 (0)	0 (0)	11 (8.7)	13 (26.5)	20 (3.8)	4 (4.4)
Severely irregular	1 (< 1)	1 (< 1)	0 (0)	0 (0)	1 (< 1)	0 (0)	2 (< 1)	0 (0)
Opacity								
Normal	262 (75.9)	228 (83.2)	328 (94.3)	80 (83.3)	77 (61.1)	6 (10.9)	430 (81.4)	60 (65.9)
Mildly increased	56 (16.2)	36 (13.1)	19 (5.5)	15 (15.6)	33 (26.2)	24 (43.6)	71 (13.4)	21 (23.1)
Moderately increased	26 (7.5)	10 (3.6)	1 (< 1)	1 (1)	16 (12.7)	19 (34.5)	27 (5.1)	9 (9.9)
Severely increased	1 (< 1)	0 (0)	0 (0)	0 (0)	0 (0)	6 (10.9)	0 (0)	1 (1.1)
Compactospongious demarcation								
Normal	274 (79.4)	234 (85.4)	332 (95.4)	86 (89.6)	81 (64.3)	9 (18.4)	445 (84.3)	63 (69.2)
Poor	46 (13.3)	29 (10.6)	15 (4.3)	10 (10.4)	27 (21.4)	23 (46.9)	55 (10.4)	20 (22.0)
Absent	25 (7.2)	11 (4.0)	1 (< 1)	0 (0)	18 (14.3)	17 (34.7)	28 (5.3)	8 (8.8)
Clarity of trabecular pattern								
Normal	271 (78.6)	231 (84.3)	331 (95.1)	79 (84.9)	78 (61.9)	11 (22.4)	438 (83.0)	64 (70.3)
Reduced	53 (15.4)	30 (10.9)	16 (4.6)	14 (15.1)	31 (24.6)	22 (44.9)	64 (12.1)	19 (20.9)
Absent	21 (6.1)	13 (4.7)	1 (< 1)	0 (0)	17 (13.5)	16 (32.7)	26 (4.9)	8 (8.8)

Data represent number (%) of ungular cartilages. Ossification of ungular cartilages was graded on the basis of results of evaluation of weight-bearing dorsopalmar radiographic images with the following grading system: 0 = no ossification, 1 = ossification up to the level of the medial or lateral margin of the distal interphalangeal joint, 2 = ossification up to the level of the midsagittal aspect of the distal interphalangeal joint, 3 = ossification up to the most proximal aspect of the distal sesamoid (navicular) bone (excluding proximal enthesiophytes), 4 = ossification up to the midpoint of the middle phalanx (based on the most proximal aspect of the joint surface), and 5 = ossification proximal to the midpoint of the middle phalanx.

described because the fracture could not be identified in the dorsopalmar image.

Fractures were more commonly identified in extensively ossified cartilages (13/35 [37.1%] for grade 5; 16/35 [45.7%] for grade 4), compared with less ossification (3/35 [8.6%] for grade 3; 3/35 [8.6%] for grade 2). Ossification grade was significantly ($P < 0.001$) associated with fracture. Eighteen of 35 (51.4%) fractures occurred in feet with asymmetric ossification of the ungular cartilages; however, 39 of 57 (68.4%) feet with asymmetric ossification of the ungular cartilages did not have a fracture. Mediolateral imbalance of the distal phalanx was present in 14 of 35 (40.0%) feet with ossified ungular cartilages and a fracture, compared with 61 of 601 (10.1%) without a fracture. Thus, ossification grade; the presence of modeling, adaptive changes, or both; and mediolateral imbalance of the distal phalanx were associated with a fracture of the distal phalanx.

Radiographic view and detection of radiolucent lines—All 42 radiolucent lines could be identified in the appropriate flexed oblique image (Figure 3). Eleven of 42 (26.2%) radiolucent lines could only be seen in a flexed oblique image. Subjectively, 39 of 42 (92.9%) radiolucent lines could be best seen (either alone or equally with other images) in a flexed oblique image, and 32 of 42 (76.2%) were best seen in a flexed oblique image alone.

Twenty-one of 42 (50.0%) radiolucent lines were identified in the dorsopalmar image, 19 of 42 (45.2%) in the dorsoproximal-palmarodistal oblique image, and 16 of 42 (38.1%) in the lateromedial image, although in the latter, it was impossible to determine whether it was of the medial or lateral ungular cartilage without the use of other images. Only 6 of 42 (14.3%) radiolucent lines were best seen (alone or equally with other images) in a dorsopalmar image and 3 of 42 (7.1%) in a dorsoproximal-palmarodistal oblique image. Because all radiolucent lines were seen on the flexed oblique view and because of small sample size (n = 42), statistical analysis of image was purely descriptive. Fractures were detected on 17 of 35 (48.6%) dorsopalmar images, 12 of 35 (34.3%) lateromedial images, and 14 of 35 (40.0%) dorsoproximal-palmarodistal oblique images. Thus, the flexed oblique images were required for complete assessment of ossified ungular cartilages.

Ossification grade—The most frequent ossification grade was 2 for both medial and lateral cartilages (348/619 [56.2%]). Ossification grade was the same medially and laterally in 137 feet, greatest in the lateral cartilage of 181 feet, and greatest in the medial cartilage of 68 feet. Cartilages had higher ossification grades (meeting the criteria of "possibly significant ossification" as described by Ruohoniemi et al[7] [grade 3 plus a separate center of ossification, grades 4, and grade 5]) in 118 feet, including 102 (86.4%) in the lateral cartilage, 76 (64.4%) in the medial cartilage, and 30 (25.4%) in both medial and lateral cartilages. Only 3 cartilages (3 horses) had grade 3 ossification in both medial and lateral cartilages with a separate center of ossification, of which none had modeling or adaptive changes; the remaining cartilages had an ossification grade of 4 or 5. Modeling, adaptive changes, or both were present in 147 cartilages, of which 105 (71.4%) had an ossification grade of 4 or 5. There was a significant ($P < 0.001$) positive association of ossification grade with modeling, adaptive changes, or both and between lateral cartilages and the presence of modeling, adaptive changes, or both on univariable analysis (**Table 2**). Fifty-seven of 386 feet (32 horses) had a difference in ossification grades ≥ 2 between the medial and lateral ungular cartilages. Of these, 42 of 57 (73.7%) feet met the criteria of "possibly significant ossification" as described by Ruohoniemi et al[7] for 1 or both cartilages. Mediolateral imbalance of the distal phalanx was present in 22 of these 57 (38.6%) feet, compared with only 53 of 329 (16.1%) feet with symmetric ossification of the ungular

Table 2—Results of univariable logistic regression for variables investigated for their association with modeling or adaptive changes in 619 ungular cartilages of 271 horses.

Variable	Frequency (%)	OR	95% CI	Wald *P* value
Ossification grade[9] (n = 619)				
2	348 (56.2)	1.00		< 0.001
3	96 (15.5)	3.90	2.03–7.51	
4	126 (20.4)	13.91	8.00–24.23	
5	49 (7.9)	130.40	46.99–361.91	
Symmetry of ossification (n = 619)				
Symmetric	528 (85.3)	1.00		< 0.001
Asymmetric	91 (14.7)	2.19	1.37–3.52	
Separate center of ossification (n = 619)				
Absent	586 (94.7)	1.00		0.001
Present	33 (5.3)	4.19	2.29–7.69	
Shape (dorsopalmar [n = 619])				
Straight	587 (94.8)	1.00		< 0.001
Curved outward or inward	32 (5.2)	27.53	9.47–80.00	
Shape (oblique [n = 619])				
Not curved	588 (95.0)	1.00		< 0.001
Bulbous shape or palmar curve	31 (5.0)	36.78	11.00–123.05	
Cartilage (n = 619)				
Lateral	345 (55.7)	1.00		0.020
Medial	274 (44.3)	1.56	1.07–2.29	
Foot (n = 619)				
Left	285 (46.0)	1.00		0.232
Right	334 (54.0)	1.25	0.87–1.82	

cartilages. In these 57 feet, 91 cartilages had an ossification grade ≥ 2, of which 34 (37.4%) had modeling or adaptive changes. A difference in ossification grade of the medial and lateral ungular cartilages of a foot was associated with modeling or adaptive changes or both ($P = 0.001$); feet with a difference in ossification grade ≥ 2 were significantly ($P < 0.001$) more likely to have evidence of modeling or adaptive changes or both of an ossified cartilage, compared with feet with symmetrically ossified cartilages (OR, 2.19; 95% CI, 1.37 to 3.52).

Width ratios of ossification at both the cartilage base and midway of the length of ossification were summarized **(Tables 3 and 4)**. Median cartilage width ratio at the base and midway were both significantly ($P < 0.001$) greater in cartilages with modeling or adaptive changes, compared with cartilages with no modeling or adaptive changes.

Thus, ossification grade was positively associated with modeling, adaptive change, or both. A difference in ossification grades within a foot ≥ 2 was also associated with modeling or adaptive changes or both.

Separate centers of ossification—Separate centers of ossification were identified in 33 ossified ungular cartilages of 29 feet (25 horses), most commonly in the lateral cartilage (25/29 [86.2%]). Four of 29 (13.8%) feet had separate centers of ossification in both medial and lateral cartilages; no feet had a separate center of ossification in the medial cartilage alone. Two of 29 (6.9%) feet had more than 1 separate center of ossification in the same cartilage (both lateral). The junctions between separate centers of ossification and the ossified cartilage were well demarcated in all; however, 7 of 33 (21.2%) had modeling of the junction. Eleven of 33 (33.3%) separate centers of ossification had increased opacity adjacent to the junction (7 mild and 4 moderate). The flexed oblique view was the only image for accurate assessment of the junction between separate centers of ossification and ossification from the base of the cartilage for 22 of 33 (66.7%) cartilages. For 9 of 33 (27.3%) cartilages, the junction between a separate center of ossification and ossification from the base of the cartilage was equally evident on a flexed oblique image and 1 other view **(Figure 6)**. The weight-bearing dorsopalmar image generally provided less information, and the presence of a gap easily seen on a flexed oblique image was not discernible in 23 of 33 (69.7%) cartilages. The dorsopalmar image was the only image for accurate assessment of the junction in 1 of 33 (3.0%) cartilages. Thus, the flexed oblique view was the only image for accurate assessment of the junction between separate centers of ossification and ossification from the base of the cartilage in most.

Shape—Twenty-one ossified ungular cartilages (6 medial and 15 lateral) curved inward (17 horses), 11 (4 medial and 7 lateral) curved outward (8 horses), and 587 were straight (255 horses; horses could have 1 curved ungular cartilage and the remainder straight; Figure 4). Radiolucent lines were present in 5 of 21 (23.8%) inwardly curved cartilages (4 were fractures) and 4 of 11 outwardly curved cartilages (3 were fractures), compared with 33 of 587 (5.6%) straight cartilages. Modeling, adaptive changes, or both were identified in 9 of 11 outwardly curved cartilages, 19 of 21 (90.5%) inwardly curved cartilages, and 119 of 587 (20.3%) straight cartilages. The presence of either an inward or outward curve was significantly ($P < 0.001$) associated with evidence of modeling or adaptive changes or both.

Extensive ossification (grade 4 or 5) that curved in a palmar direction proximally was identified in 31 ungular cartilages (Figure 5). A bulbous shape, defined as the proximal aspect of ossification extending in both

Table 3—Median width ratio of ungular cartilages with radiographic evidence of modeling or adaptive changes, compared with the ratio of ungular cartilages with no radiographic evidence of modeling or adaptive changes.

	Base			Midway		
Variable	**Median width ratio**	**Interquartile range**	**Wald *P* value**	**Median width ratio**	**Interquartile range**	**Wald *P* value**
Cartilages with modeling or adaptive changes (n = 147)	13.2	11.6–15.3	< 0.001	10.1	8.9–12.1	< 0.001
Cartilages without modeling or adaptive changes (n = 472)	10.9	9.6–12.2		8.4	7.4–9.4	

Table 4—Width ratio at the base of 386 ossified ungular cartilages (271 horses) and midway up the extent of ossification in medial versus lateral ungular cartilages.

Variable	Base	Midway
Width ratio greater in lateral than medial cartilages (n = 386)	254 (65.8)	228 (59.1)
Width ratio greater in medial than lateral cartilages (n = 386)	64 (16.6)	71 (18.4)
Width ratio equal in lateral and medial cartilages (n = 386)	68 (17.6)	87 (22.5)

Data represent number (%) of ungular cartilages.

Cartilages were considered to be of equal width if there was a difference of < 1 between the ratio of ungular cartilage to distal phalanx width for medial and lateral cartilages.

palmar and dorsal directions, was identified in 13 ungular cartilages (10 lateral and 3 medial; 9 horses). Palmar curvature was identified in 18 cartilages (11 lateral and 7 medial; 16 horses).

Modeling, adaptive changes, or both were present in 28 of 31 (90.3%) cartilages with pronounced palmar ossification. Pronounced palmar ossification could be appreciated in all lateromedial and flexed oblique images but not in dorsopalmar images. For 22 of 31 (71.0%) cartilages with pronounced palmar ossification, a flexed oblique image was necessary to determine whether it was medial or lateral. In the 9 feet that did not require the use of a flexed oblique image, this was due to marked asymmetry of ossification, 7 of which had a difference in ossification grades ≥ 2. For all 13 feet with a bulbous shape of the ossified cartilage, the proximal ossification in a dorsal direction could only be identified in a flexed oblique image. For all 31 cartilages, the flexed oblique image was superior to all the other images for identification of palmar curvature or a bulbous shape. Although palmar curvature could be determined as medial or lateral on 100% of flexed oblique images, it could be determined on only 29.0% of lateromedial, dorsopalmar, and dorsoproximal-palmarodistal oblique images combined. The presence of either palmar curvature or a bulbous shape was significantly positively associated with modeling or adaptive changes in univariable analysis (Table 2).

Palmar extension was greater in the lateral cartilage of 283 of 386 (73.3%) feet, greater in the medial cartilage of 97 of 386 (25.1%) feet, and symmetric in 6 of 386 (1.6%) feet. The mean ± SD ratio of distal phalanx length to palmar extension for lateral and medial cartilages was 38.5 ± 12.2 and 35.7 ± 10.1, respectively. Cartilages with a radiolucent line indicative of a fracture had a mean ± SD ratio of 50.4 ± 19.3, whereas cartilages without a fracture had a mean ± SD ratio of 35.5 ± 10.0. Median cartilage length was significantly ($P <$ 0.001) greater in fractured cartilages (median, 47.4 cm; interquartile range, 35.7 to 64.7 cm), compared with nonfractured cartilages (median, 34.4 cm; interquartile range, 30.2 to 40.1 cm). Thus, inward or outward curvature of an ossified cartilage or dorsal or palmar extension was associated with modeling, adaptive changes, or both.

Multivariable linear regression model—There was a significant ($P <$ 0.001) positive association of ossification grade with modeling or adaptive changes (**Table 5**). Because of the small sample, inward or outward curvature data were combined for inclusion in the multivariable model, as was palmar curve or a bulbous shape. The presence of any of these abnormal shapes was a significant ($P =$ 0.001) risk factor for modeling, adaptive changes, or both. Cartilage (medial or lateral) was included as a variable in the final multivariable linear regression model because it substantially improved the goodness of fit. Removal of outlying individual observations with large residual values had little effect on coefficients; therefore, all observations were retained in the final model.

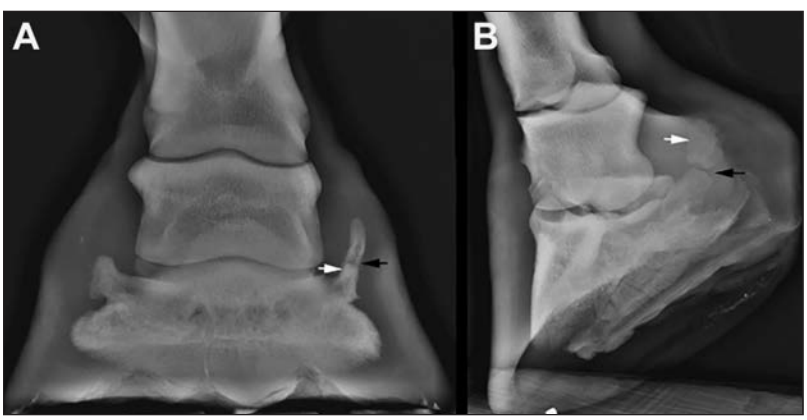


Figure 6—Radiographic images showing abnormalities of ossified ungular cartilages in horses. A—Dorsopalmar radiographic image of a foot. Lateral is to the right. There is grade 4 ossification of the lateral ungular cartilage, which has a poorly defined radiolucent line (black arrow) midway up the ossified cartilage with increased radiopacity distal to the line (white arrow). The radiolucent line cannot be identified definitively as either a separate center of ossification or a fracture. B—Flexed oblique image of the same foot. The radiolucent line is clearly seen (black arrow), and the margins are smoothly demarcated, indicating that it is consistent with the junction between a separate center of ossification (white arrow) and ossification from the base of the cartilage.

Table 5—Final multivariable logistic regression model of risk factors for modeling or adaptive changes or both in 619 ungular cartilages of 271 horses.

Variable	Frequency (%)	OR	95% CI	Wald *P* value
Ossification grade (n = 619)				< 0.001
2	348 (56.2)	1.00		
3	96 (15.5)	3.64	1.88–7.07	
4	126 (20.4)	11.59	6.52–20.60	
5	49 (7.9)	72.90*	25.32–209.90	
Shape (n = 619)				0.001
Straight (not curved)	572 (92.4)	1.00		
Abnormal	47 (7.6)	4.90	1.94–12.42	
Cartilage (n = 619)				0.09
Lateral	345 (55.7)	1.00		
Medial	274 (44.3)	1.51	0.93–2.44	

The Hosmer-Lemeshow statistic for this model was 1.18 ($P =$ 0.95), and the area under the receiver operating characteristic curve was 0.86 (95% CI, 0.82 to 0.89).

*Forty-four of 49 (89.8%) cartilages with an ossification grade of 5 had modeling or adaptive changes or both, producing the high OR.

Although extensive ossification and modeling or adaptive changes were more commonly identified in lateral than medial cartilages, when tested in the final multivariable model, the association between cartilage and evidence of modeling or adaptive changes was not a significant (P = 0.09) risk factor (Table 5).

Clinical relevance—Trauma to an ossified cartilage was diagnosed as being the probable primary source of foot pain in 11 of 131 (8.4%) horses that did not undergo MRI but underwent nuclear scintigraphy in addition to radiography, on the basis of the presence of increased radiopharmaceutical uptake. Magnetic resonance imaging was performed in 139 horses. Thirty-one (22.3%) horses had injuries associated with ossification of the ungular cartilages, including feet with increased signal intensity in fat-suppressed images in the ipsilateral aspect of the distal phalanx adjacent to the distal attachment of the ungular cartilage. Eighteen of 31 (58.1%) horses had an injury of an ossified cartilage as the primary cause of foot pain. Four of 18 horses had an ossified cartilage fracture identified on MRI that was not detected radiographically; all 4 feet had modeling or adaptive changes or both seen radiographically. Eleven of 18 horses had evidence of trauma of an ossified cartilage, characterized by increased signal intensity in fat-suppressed images. Three of 18 horses with a radiolucent line that could not be identified as either fracture or modeling between 2 adjacent separate centers of ossification had a fracture diagnosis confirmed on the basis of results of MRI. Of the 42 horses (11 based on scintigraphy and 31 based on MRI) with injury to an ossified ungular cartilage identified as a contributing factor to lameness, 27 (64.3%) had cartilages with an ossification grade of 4 or 5. However, 32 of 131 (24.4%) horses that underwent MRI had grade 4 or 5 ossification of an ungular cartilage, but the final diagnosis was related to other lesions.

Discussion

In the present study that evaluated front foot radiographs of 271 horses (386 feet) acquired at the Animal Health Trust between January 2005 and December 2012, we demonstrated a significant association between extensively ossified ungular cartilages and modeling, adaptive changes, or both, in agreement with our hypothesis. Contrary to our hypothesis, even though asymmetries of ossification and cartilage (medial vs lateral) were significantly associated with modeling or adaptive changes in the univariable analysis, they were not significant risk factors when analyzed in the final multivariable model, although retaining medial versus lateral cartilage in the final model improved the fit. Flexed oblique images provided substantial additional diagnostic information, compared with conventional images. Furthermore, for an ossified ungular cartilage, an inward or outward curvature as well as a palmar curve or bulbous shape were significant risk factors for modeling or adaptive changes.

In horses, the ungular cartilages are believed to contribute to the dissipation of energy from concussion.[16] The reason for ossification has been debated, with suggestions of genetic factors, mediolateral foot imbalance, concussion, and conformation having a role.[5,17] Ossification results in stiffening of the ungular cartilages. Forces may be transmitted differently through the rigid structure, compared with unossified cartilages. Thus, ossified cartilages may be less able to dissipate energy, which may predispose to further modeling or adaptive changes.[10,18] Increased radiopacity is consistent with increased tissue density, which may be a result of fatigue and remodeling[10] or possibly the forces that initially cause ossification. With increased density, the ossified cartilage may then have an increased propensity for fracture.[11] In the present study, injury to an ossified cartilage was identified as a source of foot pain contributing to lameness in 42 of 170 horses. An association between ossification of the ungular cartilages and injury to the collateral ligaments of the distal interphalangeal joint[8,9,19] and the distal phalanx has also been identified.[8,9,18]

Extensive ossification (grade 4 or 5) was a significant risk factor for the presence of modeling or adaptive changes in this study. An association between extensive ossification and fractures and injuries of the junction between separate centers of ossification has been previously demonstrated,[8,13] but to our knowledge, this was the first description of an association with modeling or adaptive changes.

The term "possibly significant ossification" was adopted to describe a degree of ossification that may be of clinical importance.[7] In the present study, only 3 cartilages (in 3 horses) had an ossification grade of 3 with a separate center of ossification, none of which had modeling or adaptive changes, suggesting that they may be an incidental finding. Most (71.4%) modeling or adaptive changes were seen in cartilages with an ossification grade ≥ 4. We prefer to avoid the term "possibly significant ossification."

In agreement with previous studies,[1,4,5,8] the lateral cartilage was more commonly extensively ossified than the medial cartilage. Injury to an ossified cartilage has previously been noted to be more common in the lateral cartilage.[8] Although cartilage was significantly associated with modeling or adaptive changes in univariable analysis, it was not identified as a significant risk factor in the multivariable model. In agreement with a previous study,[20] separate centers of ossification were more common in the lateral cartilage, but their presence was not significantly associated with modeling or adaptive changes.

The front feet may land laterally first[21,22]; the center of pressure starts at the lateral heel of the hoof before moving dorsally and medially toward the center of the hoof.[23] Greater forces may be transmitted through the lateral aspect of the foot than the medial at landing. This could support the concussion theory for ossification, in that extensive ossification is frequently greater in lateral cartilages. However, it is difficult to relate concussion, or poor conformation or farriery, to ossification seen in young horses that have never been in training; the number of years in work did not affect the incidence of extensive ossification in Finnhorses.[5]

Mediolateral imbalance of the distal phalanx was associated with asymmetric ossification in the present study, although there is no evidence for a causal relationship. However, it is conceivable that imbalance causing unequal distribution of concussive forces may

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increase the risk of modeling or adaptive changes in an ossified cartilage. Marked asymmetry of ossification has been linked with injury or fracture of the cartilage base[24] and was more frequent in fractured cartilages than nonfractured cartilages in this study.

In agreement with a previous study,[13] fractures were found in lateral and medial cartilages with similar frequency. Radiographic,[13] MRI,[17] and scintigraphic[25] studies have previously identified the base of the ossified cartilage as a predilection site for fracture or bone trauma, in agreement with our findings for medial cartilages. Most (29/35 [82.9%]) fractures were identified in extensively ossified cartilages, which appears to be a predisposing factor for injury. Radiolucent lines were best identified in flexed oblique images, without which 26% of radiolucent lines in this study would not have been identified. However, in 4 feet in 4 horses, a fracture not discernible radiographically was detected on MRI. We have no plausible explanation for the difference in mediolateral distribution of fractures in the left and right feet.

To our knowledge, there have been no previous radiographic descriptions of variation in the shape of ossification of the ungular cartilages. However, in an MRI and CT study[26] of the ungular cartilages of 6 Finnhorses, some variation in shape was observed. It was noted that the cartilages remained unossified palmarly.[26] To our knowledge, a bulbous shape of ossification has not previously been described. This could only be identified in a flexed oblique image. For ossified ungular cartilages, inward or outward curvature as well as palmar curvature or a bulbous shape were associated with modeling or adaptive changes and may be the result of this rather than a cause. Nonetheless, whatever the sequence of events, these feet with ossified cartilage had a significant risk of fracture. Therefore, when these cartilage shapes are identified, we suggest that it is important to assess the cartilages thoroughly. Because of small numbers, abnormal shapes were combined for statistical analysis in this study. A larger study is required to determine the risk of modeling or adaptive changes for each individual shape.

Flexed oblique images were superior to lateromedial, dorsopalmar, and dorsoproximal-palmarodistal oblique images for identification of a fracture in the present study. Without a flexed oblique image, a fracture of an ossified cartilage could be missed. In addition, unless marked asymmetry is present, a flexed oblique view is required to differentiate which cartilage (medial vs lateral) has pronounced palmar ossification.

The horses in this study were from a referral population and were therefore not necessarily representative of the general equine population. Increased radiopharmaceutical uptake is not a definitive indication of pain that causes lameness. However, with respect to the ungular cartilages, in those horses having undergone both scintigraphy and MRI, there is excellent correlation between increased radiopharmaceutical uptake and lesions identified on MRI.[2,8] We believe it is reasonable to suggest that in this anatomic location, increased radiopharmaceutical uptake may be of clinical importance. Not all horses underwent MRI, and injury diagnosis was not compared with the gold standard of postmortem examination. No horse was defined as likely to have pain that caused lameness on the basis of radiographic abnormalities alone; there had to be supporting evidence from results of scintigraphy, MRI, or both. Thus, the contribution to pain and lameness associated with extensively ossified ungular cartilages may be underestimated. However, the primary purpose of this study was to describe radiographic variants of the ungular cartilages.

The results of this study indicated that extensive ossification and the presence of inward or outward curvature as well as palmar curvature or a bulbous shape were significant risk factors for modeling and adaptive changes. Radiolucent lines consistent with fracture were most commonly identified in extensively ossified cartilages and those with abnormal shape. Flexed oblique images provided useful information, including abnormal shape and fracture, that may not have been gained from other currently recommended radiographic views and should therefore be considered essential for thorough and complete radiographic appraisal of ossified ungular cartilages of the foot in horses.

a. IBM SPSS Statistics for Windows, version 21.0, SPSS Inc, Chicago, Ill.

References

1. Verschooten F, Van Waerebeek B, Verbeeck J. The ossification of cartilages of the distal phalanx in the horse: an anatomical, experimental, radiographic and clinical study. *J Equine Vet Sci* 1996;16:291–305.
2. Dyson S, Nagy A. Injuries associated with the cartilages of the foot. *Equine Vet Educ* 2011;23:581–593.
3. Butler J, Colles C, Dyson S, et al. Foot, pastern and fetlock. In: *Clinical radiology of the horse*. 3rd ed. Oxford, England: Wiley-Blackwell, 2008;53–188.
4. Down S, Dyson S, Murray R. Ossification of the cartilages of the foot. *Equine Vet Educ* 2007;19:51–56.
5. Ruohoniemi M, Laukkanen H, Ojala M. Radiographic evaluation of ossification of the collateral cartilages of the third phalanx in Finnhorses. *Equine Vet J* 1993;25:453–455.
6. O'Connor J. The feet. In: Dollar JAW, O'Connor JJ, eds. *Dollar's veterinary surgery*. 3rd ed. Madison, Wis: A Eger, 1944;907–969.
7. Ruohoniemi M, Raekallio M, Tulamo RM, et al. Relationship between ossification of the cartilages of the foot and conformation and radiographic measurements of the front feet in Finnhorses. *Equine Vet J* 1997;29:44–48.
8. Dyson SJ, Murray R. Injuries associated with ossification of the cartilage of the foot, in *Proceedings*. 56th Annu Conv Am Assoc Equine Pract 2010;152–165.
9. Dyson S, Brown V, Collins S, et al. Is there an association between ossification of the cartilages of the foot and collateral desmopathy of the distal interphalangeal joint or distal phalanx injury? *Equine Vet J* 2010;42:504–511.
10. Frost HM. Structural adaptations to mechanical usage (SATMU): 1. Redefining Wolff's law: the bone modelling problem. *Anat Rec* 1990;226:403–413.
11. Secombe CJ, Firth EC, Perkins NR, et al. Pathophysiology and diagnosis of third carpal bone disease in horses: a review. *N Z Vet J* 2002;50:2–8.
12. Colles CM. Interpreting radiographs 1: the foot. *Equine Vet J* 1983;15:297–303.
13. Dakin SG, Robson KE, Dyson SJ. Fractures of ossified cartilages of the foot: 10 cases. *Equine Vet Educ* 2006;18:120–138.
14. Ruohoniemi M, Mäkelä O, Eskonen T. Clinical significance of ossification of the cartilages of the front feet based on nuclear bone scintigraphy, radiography and lameness examinations in 21 Finnhorses. *Equine Vet J* 2004;36:143–148.

15. Riedesel E. The equine phalanges. In: Thrall D, ed, *Textbook of veterinary radiology*. 6th ed. St Louis: Elsevier, 2013;429–456.
16. Bowker RM, Van Wulfen K, Springer SE, et al. Functional anatomy of the cartilage of the distal phalanx and digital cushion in the equine foot and a hemodynamic flow hypothesis of energy dissipation. *Am J Vet Res* 1998;59:961–968.
17. Stashak TS. Ossification of the collateral cartilages of the distal phalanx (sidebones). In: Stashak TS, ed. *Adams' lameness in horses*. 5th ed. Philadelphia: Lippincott Williams & Wilkins Publications, 2002;715–717.
18. Selberg K, Werpy N. Fractures of the distal phalanx and associated soft tissue and osseous abnormalities in 22 horses with ossified sclerotic ungual cartilages diagnosed with magnetic resonance imaging. *Vet Radiol Ultrasound* 2011;52:394–401.
19. Mair TS, Sherlock CE. Collateral desmitis of the distal interphalangeal joint in conjunction with concurrent ossification of the cartilages of the foot in none horses. *Equine Vet Educ* 2008;20:485–492.
20. Holm AW, Bjornstad G, Ruohoniemi M. Ossification of the cartilages in the front feet of young Norwegian coldblood horses. *Equine Vet J* 2000;32:156–160.
21. Balch O, Clayton H, Lanovaz J. Effects of increasing hoof length on limb kinematics of trotting horses, in *Proceedings*. 40th Annu Conv Am Assoc Equine Pract 1994;43–44.
22. Thomason JJ, Biewener AA, Bertram JE. Surface strain on the equine hoof wall In vivo: implications for the material design and functional morphology of the wall. *J Exp Biol* 1992;166:145–168.
23. Chateau H, Holden L, Robin D, et al. Biomechanical analysis of hoof landing and stride parameters in harness trotter horses running on different tracks of a sand beach (from wet to dry) and on an asphalt road. *Equine Vet J Suppl* 2010;(38):488–495.
24. Dyson SJ, Murray R. Lameness and diagnostic imaging in the sports horse: recent advances related to the digit, in *Proceedings*. 53rd Annu Conv Am Assoc Equine Pract 2007;262–275.
25. Nagy A, Dyson SJ, Murray RM. Scintigraphic examination of the cartilages of the foot. *Equine Vet J* 2007;39:250–256.
26. Ruohoniemi M, Karkkainen M, Tervahartiala P. Evaluation of the variably ossified collateral cartilages of the distal phalanx and adjacent anatomic structures in the Finnhorse with computed tomography and magnetic resonance imaging. *Vet Radiol Ultrasound* 1997;38:344–351.