Bone stress injuries and fatigue fractures of the pelvis in endurance horses

Massimo Puccetti, Francesca Beccati, Jean-Marie Denoix

Received: 25 February 2021 | Accepted: 29 October 2021
DOI: 10.1111/evj.13536

Equine Veterinary Journal WILEY

ORIGINAL ARTICLE

Bone stress injuries and fatigue fractures of the pelvis in endurance horses

Massimo Puccetti[1] | Francesca Beccati[2] | Jean-Marie Denoix[3]

[1]Dubai Equine Hospital, Zabeel, Dubai, UAE

[2]Department of Veterinary Medicine, Sport Horse Research Centre, University of Perugia, Perugia, Italy

[3]CIRALE-EnvA NEV, Unité INRAE-EnvA, Goustranville, France

Correspondence
Francesca Beccati, Department of Veterinary Medicine, Sport Horse Research Centre, University of Perugia, Perugia, Italy.
Email: francesca.beccati@unipg.it

Funding information
The study was not supported by a grant or other funding sources

Summary

Background: Bone stress injuries and fatigue fractures of the pelvis are reported in only a small number of endurance horses.

Objectives: To describe bone stress injuries and fatigue fracture of the pelvis in endurance horses trained and competing on the deep sand surfaces.

Study design: Retrospective case series.

Methods: Medical records of horses used for endurance and diagnosed with bone stress injuries and/or fatigue fractures of the pelvis by ultrasound were reviewed. The bone stress injuries and fatigue fractures were classified as affecting the iliac wing, the iliac shaft, the tuber ischiadicum, the rest of the ischium or the pubis and subdivided into four fracture configurations: isolated iliac fracture, isolated fracture of the floor of the pelvis, isolated tuber ischiadicum fracture and multiple fractures. Descriptive statistics were performed overall and on fracture configurations for age, sex, breed, level of activity, affected limbs, previous injuries, development of the injury, seasons in the UAE, physical and dynamic findings and outcome. For each fracture configuration and the outcome, multivariable logistic regression models were developed after univariable logistic regression and collinearity analyses. Significance was set at $P \le .05$.

Results: Sixty endurance horses were included; 48% (95% CI: 36%-61%) had isolated iliac fracture, 17% (7%-26%) isolated fracture of the floor of the pelvis, 15% (6%-24%) isolated tuber ischiadicum fracture and 20% (10%-30%) had multiple fractures. Breed (OR, 4.42; 95%CI, 1.02-19.57) was significantly associated with isolated iliac fracture and asymmetry of bone landmarks (OR, 7.42; 95% CI, 1.47-37.45) with isolated tuber ischiadicum fracture. Degree of lameness (OR, 3.08; 95% CI, 1.07-8.9) and trotting on three tracks (OR, 8.62; 95% CI, 1.43-51.9) were significantly associated with the diagnosis of isolated fracture of the floor of the pelvis.

Main limitations: Data acquired in a single country.

Conclusions: Bone stress injuries and fatigue fractures of the pelvis can affect endurance horses trained and competing on deep sand. Isolated bone stress injuries and/or fatigue fractures of the ileum were the commonest followed by multiple pelvic bones involvement. The presence of lameness and trotting on three tracks suggest the presence of bone stress injuries and/or fatigue fractures of the floor of the pelvis; asymmetry of bony landmarks is more commonly detected in horses with bone stress injuries and/or fatigue fractures of the tuber ischiadicum.

KEYWORDS
deep sand, horse, lameness, stress fracture, stress-related bone injury

1 | INTRODUCTION

Fractures of the equine pelvis usually have a low incidence but their recognition has increased recently with the improvement of the diagnostic procedures.[1-5] They can develop as the consequence of trauma but also as the result of repetitive load induced by the athletic activity, especially in racehorses, so they can be considered as a stress or fatigue fracture.[2,4-6] Adaptive bone remodelling to exercise is normal but if the amount or intensity of exercise exceeds the bone capacity to remodel, non-adaptive remodelling (ie, stress reaction) of the bone can occur, leading to subchondral or cortical bone damage in long bones or injury of the compact and spongious bones in flat bones.[7-11] Ultrasonography is very sensitive to any alteration of the bone surface.[4] A bone stress injury can progress to fatigue fracture due to accumulated bone microdamage induced by repetitive loading with disturbance of remodelling, weakening of the bone and a resulting fracture.[7-11]

Bone stress injuries and fatigue fractures are extensively reported in racehorses, especially in Thoroughbreds, at predilection sites,[12,13] where the most common location of fatigue fracture of the pelvis is the iliac wing and to a lesser extent the tuber coxae, the iliac shaft, pubis and ischium.[2-6,12,14,15] These pelvic fatigue fractures are rarely reported in Standardbred horses.[4,16] Bone stress injuries and fatigue fractures were previously documented in endurance horses affecting the appendicular skeleton.[17-19]

Bone stress injuries and/or fatigue fractures of the pelvis in endurance horses are reported in the literature in only a small number of horses.[17] The aim of this study was to report these lesions in a larger number of endurance horses trained and competing on the deep sand surfaces in the United Arab Emirates (UAE). A second aim was to present their clinical, diagnostic imaging characteristics and outcomes. It was hypothesised that, like Thoroughbred, fatigue fracture of the iliac wing would be the most common pelvic injury and that the number of competitive seasons and previous injuries in other anatomical locations would affect the development of some bone stress injuries and/or fatigue fractures of the pelvis.

2 | MATERIALS AND METHODS

2.1 | Inclusion criteria

The medical records of all horses used for endurance discipline trained and competing in the UAE and diagnosed with bone stress injuries and/or fatigue fractures of the pelvis by one specific veterinarian (MP) between January 2012 and March 2020 were reviewed. Cases with fractures as a result of trauma were excluded from this study and only fatigue fractures were included. The final diagnoses were obtained based on the results of physical and dynamic examinations, ultrasonographic findings and the absence of traumatic events in the history. A flowchart outlining the case inclusion is available in Figure S1.

2.2 | Cases details and diagnostic procedures

All horses were examined in the field by one observer (MP) as primary responsible veterinarian or as a second opinion vet called by the colleagues in charge of different stables. Physical and dynamic examinations consisted of inspection, palpation, walk on the circle and on a straight line and trot, if appropriate, in a straight line. The grade of lameness was assigned using the modified American Association of Equine Practitioners grading scale from 0 to 5, as described by Ross (2011).[20]

Ultrasonographic examination of the pelvis was performed by one observer (MP) with transcutaneous and transrectal approaches in all horses as previously described.[21,22] The ultrasound machine (M-Turbo® and Edge II, Fujifilm Sonosite) used was equipped with a multifrequency 3-5.5 MHz curvilinear transducer for the transcutaneous approach and with a 7.5-10 MHz transrectal linear transducer for the transrectal examination. A bone stress injury was considered when any alteration of the normal hyperechogenic bone surface was identified including mainly thickening induced by osteolysis and incompletely ossified proliferation as well as thickening of the periosteum; identification of a fatigue fracture was based on clinical manifestation and the presence of suggestive ultrasonographic findings including mainly the presence of callus formation and interruption of the bone surface.

To better describe and classify the ultrasonographic findings, the images were retrospectively reviewed simultaneously by 2 observers (MP, FB) and bone stress injuries and/or fatigue fractures were classified by consensus as affecting the iliac wing (incomplete, complete, complete and displaced, acute or chronic [only for incomplete and complete] and located at the sacroiliac junction or between iliac wing and the iliac shaft) (Figure 1); the sacral wing (Figure 1); the iliac shaft (incomplete or complete displaced; acute or chronic) (Figure 2); the tuber ischiadicum: (incomplete or complete) (Figure 3); the ischium (table and/or ramus) (Figure 4) and the cranial ramus of the pubis (cranial fragmentation or fatigue fracture or both) (Figure 5).

Iliac wing and shaft fractures were classified as previously described,[6,15] as well as tuber ischiadicum fracture.[4] The fatigue fractures were considered acute when there was a localised interruption of the bony hyperechogenic surface and associated subperiosteal or soft tissue haematoma, compared with chronic which was characterised by irregularity of the bone surface and thickening of the periosteum with or without changes to the surrounding soft tissues.[23] Cranial fragmentation of the pubis was considered when there was a bone irregularity at the dorsal and cranial aspects of

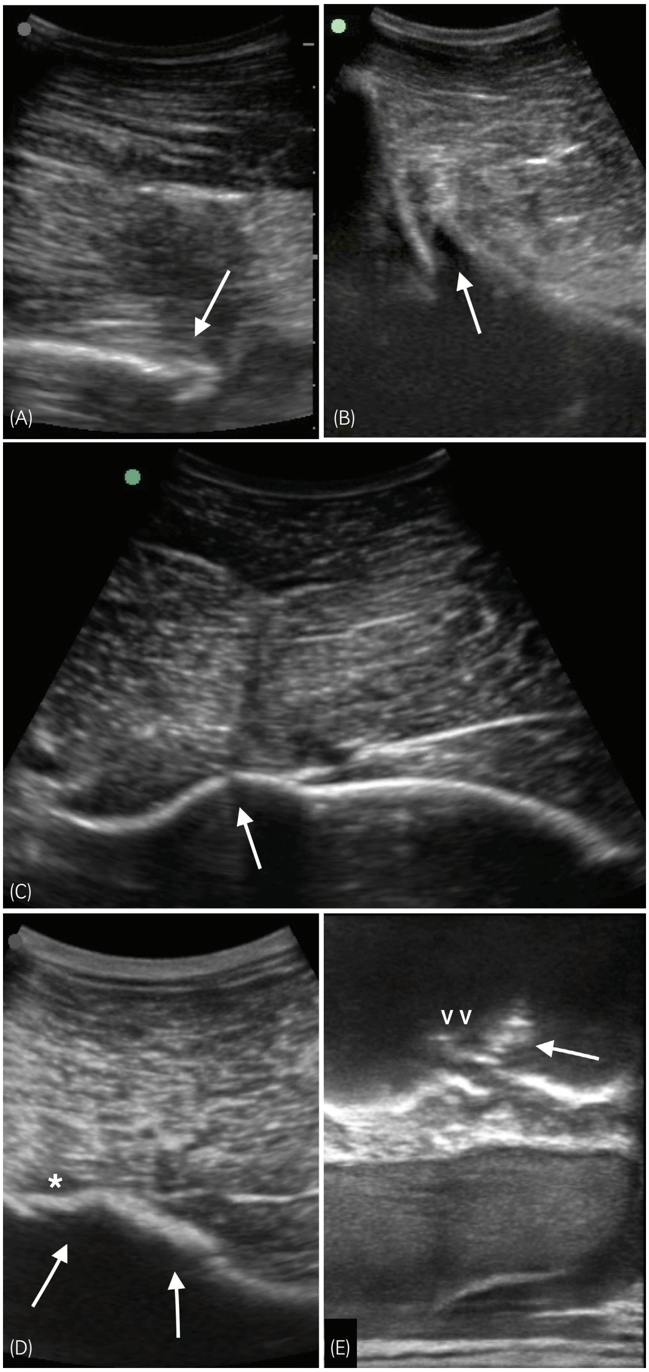

FIGURE 1 Ultrasonographic images of the iliac wing. Cranial and medial is to the left. A, Craniocaudal ultrasonographic image of the iliac wing obtained with a transcutaneous approach. Note the localised irregular bone surface consistent with acute incomplete fatigue fracture of the caudal margin of the ilium (arrow). B, Lateromedial ultrasonographic image of the iliac wing obtained with a transcutaneous approach. Note the complete and displaced fracture of the iliac wing with the lateral part displaced proximally (arrow). C, Lateromedial ultrasonographic image of the caudal part of the iliac wing at the beginning of the iliac shaft obtained with a transcutaneous approach. Note the abnormal convex shape of the bony hyperechogenic line consistent with remodelled chronic fracture (arrow). D, Lateromedial ultrasonographic image of the caudal part of the iliac wing obtained with a transcutaneous approach. Note the irregular and thickened bone surface (arrows) and periosteum (asterisk) representing a chronic fatigue fracture of the iliac wing. E, Ultrasonographic image of the sacroiliac joint obtained with a transrectal approach of the horse showed in (D). Note the irregular bone surface (open arrows) and echoes going deep into the ilium (arrow) representing the fracture

the pubis including the insertion surface of the rectus abdominis and pectineus muscles. Details of the final diagnosis for each fracture configuration were recorded.

On the basis of the final diagnosis, bone stress injuries or fatigue fractures were classified into four fracture configurations: isolated iliac fracture which included wings and shafts, isolated fracture of the floor of the pelvis including pubis and ramus or table of the ischium, isolated tuber ischiadicum fracture and multiple pelvic fractures (including more than one isolated fracture).

The following variables were recorded from the medical records for each horse and included the complaint about examination, age, sex, breed, level of activity, unilateral or bilateral lesion and side of the pelvis, history of previous injuries not related to the pelvis, detection of the lesion during training or competition, number of seasons spent in training and competition in the UAE, findings at physical examination such as asymmetry of the bone landmarks of the pelvis,[24] atrophy of the croup muscles or painful reaction at pressure over the tuber sacrale,[24] presence of lameness at walk, grade of lameness at a trot for horses able to trot and other changes in the locomotor pattern at trots such as choppy gait and tendency to trot on three tracks and outcome.

The level of activity was extrapolated from the history of the horse and it was considered as a novice (90-119 km competition at free speed), intermediate (120-139 km competitions at free speed) and elite (140-160 km competitions [free speed]) and referred to the longest distance competition the horse has participated in the last 6 months or the category for which it was trained as reported by the trainer.

A successful outcome was defined as returning to training at the same level (or higher) as before the injury; the outcome was assessed by follow-up examinations of the horses (n = 54) and by telephone interview with the referring veterinarian (n = 6). When appropriate, horses were treated conservatively with four weeks of box rest with or without hand walking, depending on the severity of the lameness and gait alteration. Then, an ascending-controlled exercise programmed for a minimum of 3 months was established, depending on the initial injury and progression of the clinical and ultrasonographic findings. The length of the follow-up ranged from 3 months to 5 years.

2.3 | Data analyses

Statistical analysis was performed using a dedicated statistical software package (JASP, Version 0.14.1, University of Amsterdam). Continuous and ordinal data were summarised by mean and standard deviation or by the median and range, as appropriate. Categorical

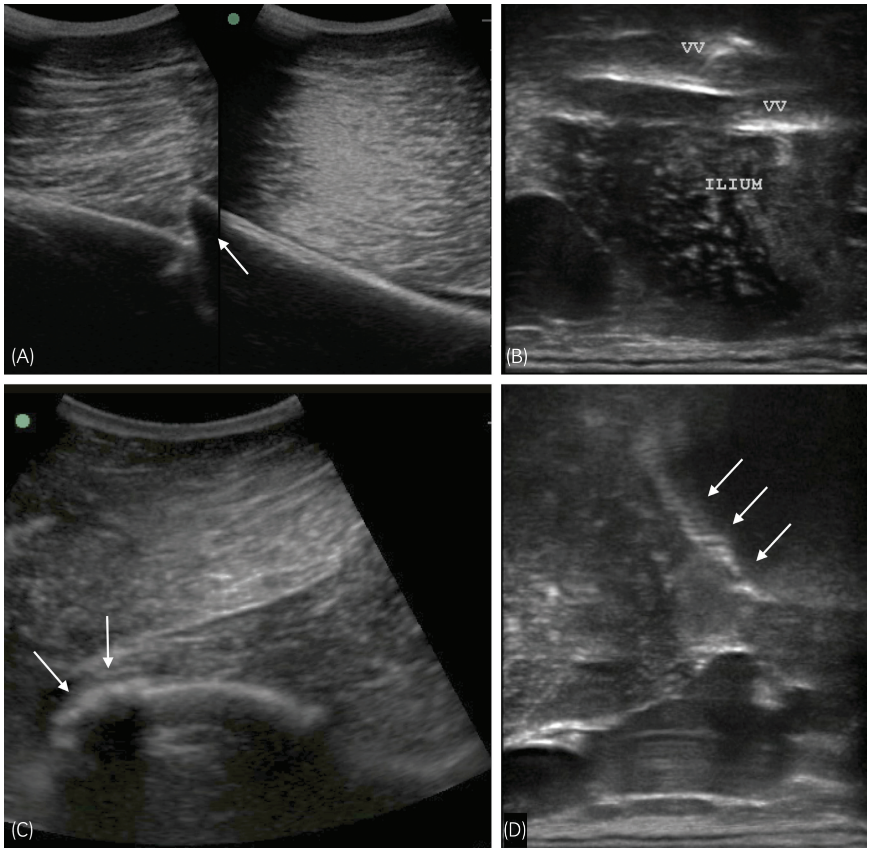

FIGURE 2 Ultrasonographic images of the iliac shaft. Cranial and medial is to the left. A, Longitudinal ultrasonographic image of the iliac shaft obtained with a transcutaneous approach. Note the complete and displaced fracture of the iliac shaft with the caudal part displaced proximally and cranially (arrow). B, Ultrasonographic image of the iliac shaft obtained with a transrectal approach of the horse showed in (A). Note the displaced bone segments of the ilium (open arrows) indicating the fracture. C, Transverse ultrasonographic image of the iliac shaft obtained with a transcutaneous approach. Note the irregular and thickened bone surface (arrows) representing a chronic fatigue fracture of the iliac shaft. D, Ultrasonographic image of the iliac shaft obtained with a transrectal approach of the horse shown in (C). Note the irregular bone surface (arrows) confirming the chronic fatigue fracture

variables were presented as frequencies and percentages with a 95% confidence interval (CI), when appropriate. Descriptive statistics of the study group were performed overall and stratified by fracture configurations including age, sex, breed, level of activity (novice, intermediate or elite), affected side/s of the pelvis, any previous injuries not related to the pelvis, time of the injury in training or competition, seasons spent in training and competition in the UAE as two or less versus three or more for statistical purpose and to stratify horses with few or more experience on training, physical examination including any asymmetry of the bony landmarks of the pelvis, whether atrophy of the croup muscles was present, any painful reaction at pressure over the tuber sacrale, lameness at walk or not, grade of lameness at a trot, presence of choppy gait, tendency to trot on three tracks and outcome as successful, retired or euthanised.

The continuous variable (age) was assessed for homoscedasticity using the Shapiro-Wilk's test for normality; the Levene's test for homogeneity of the variance and ordinal data (lameness grade) was presented as median and range; subsequent tests were applied as appropriate. Horses with multiple fractures were not included in the inferential statistical analysis, as simultaneous involvement of the different bones can represent a confounding factor.

Univariable logistic regression analyses were performed to identify the relationship between the dependent variable of fracture configurations and potential explanatory variables of age, sex, breed, level of activity of the horse, previous injuries, time of the lesion, season, asymmetry of bone landmarks, atrophy of croup muscles, painful reaction at palpation of the tuber sacrale, lameness at walk, grade of lameness, choppy gait, reduction of the cranial phase of the step, trot on three ways. Additionally, univariable logistic regression analysis was performed to identify the relationship between the dependent variable of outcome (successful vs unsuccessful) and potential explanatory variable including those of previous univariable logistic analyses plus side of the pelvis involved (unilateral vs bilateral) and fracture configurations.

On the basis of the φ or Cramer V coefficient, variables were considered highly correlated (significant) when the coefficient was >0.5; to avoid collinearity in the models, a limited number of highly correlated variables were included in the multivariable models on the basis of those that were more clinically significant.

For each fracture configuration and outcome multivariable logistic regression model, variables that had a P-value < .2 in the univariable analyses were considered for inclusion in the models. Variables were retained in each model by stepwise backwards elimination of non-significant variables; variables were retained in the model if they significantly reduced the residual deviance of the model (likelihood ratio statistic). The sensitivity and specificity and McFadden R^2 values were calculated. McFadden $R^2 > 0.2$ was considered indicative of a good fit of the model. Significance was set at $P \leq .05$.

2.4 | Power

Sample size calculation to assess the convenience sample of endurance horses with bone stress injuries and/or fatigue fractures of the pelvis (sample size for frequency in a population—random sample)

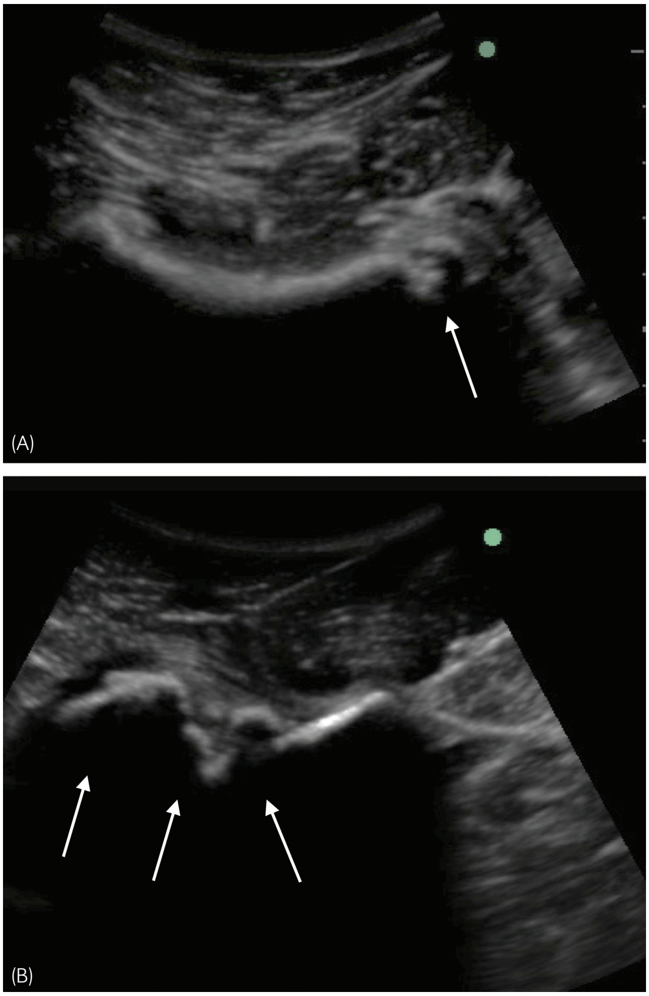

FIGURE 3 Ultrasonographic images of the tuber ischiadicum obtained with a transcutaneous approach. The Medial is to the left. A, Note the irregular bone surface at the most lateral aspect of the tuber ischiadicum with some echoes going deep into the bone (arrow) representing an incomplete fracture at the insertion of the semitendinosus muscle. B, Note the extensive irregularity of the bony surface of the tuber ischiadicum with multiple bone fragments and abnormal shape (arrows) created by a complete comminute fracture

revealed that to provide the study with 80% of power with a 95% of confidence and precision of 0.065, a sample size of 59 horses is required, assuming a prevalence of 7.3% on 997 endurance horses trained and competing in UAE between January 2015 and March 2021, which was based on the review of medical records held by MP.

3 | RESULTS

3.1 | Animals

Sixty endurance horses were included in this study, stabled in different training centres and trained by different trainers. Of these, 34 (57%; 95% confidence interval 44%-69%) were Anglo-Arabian and 26 (43%; 31%-56%) were pure Arab, with 40 (67%; 55%-78%) females and 20 (33%; 21%-45%) geldings. The median age was 8 years, ranging from 5 to 16 years. Twenty-four (40%; 28%-52%) of 60 were trained and/or competed at an elite level, 19 at novice level and 17 at an intermediate level.

Thirty-one (52%; 45%-72%) cases had previous musculoskeletal injuries in a different site, 22 (37%; 28%-55%) did not and for seven cases this information was not available. In 35 (58%; 46%-71%) cases, bone stress injury or fatigue fracture were recognised after a training session and in 25 (42%: 29%-54%) during or just after the competition. Forty (67%; 61%-84%) cases developed bone stress injury or fatigue fracture during the first (n = 29; 48%; 35%-60%) or second (n = 11) seasons of training and competition in the UAE, and 15 during the third (n = 12) or fourth (n = 3) seasons. In five cases, the number of seasons was unknown.

Of the reasons for examination, 18 were due to consistent lameness, 10 due to poor engagement and propulsion, seven for intermittent lameness, four for the tendency to trot or canter on three-ways, three for reluctance to walk or trot, one due to weight loss, one due to a strange pattern of canter and 16 due to elimination from competition for irregular gait and/or metabolic disorder.

3.2 | Clinical findings

At clinical examination, 24 (40%; 28%-52%) cases showed asymmetry of the bony landmarks of the pelvis (Figure S2), 18 had atrophy of the gluteal muscles (Figure S3) and 15 showed a painful reaction at pressure over the tuber sacrale. Twenty-four (40%; 28%-52%) cases were lame at walk with a reduction of the cranial phase of the step detected in 12 horses, 18 cases had a choppy gait and in 19 a tendency to trot on three tracks was observed. The median grade of lameness was 3, ranging from 0 to 4 of 5.[20]

3.3 | Ultrasonographic diagnoses and outcome

The total number of each bone stress injuries and/or fatigue fractures of the pelvis was 103 (Table 1). In 27 (45%; 32%-57%) of 60 cases, bone stress injuries and/or fatigue fractures at the same site or at the different sites were bilateral, in 18 cases affected, the left side of the pelvis and in 15 the right side.

There were 25 (42%; 29%-54%) injuries only of the iliac wing of which 15 were bilateral and 10 unilateral, nine unilateral injuries of the tuber ischiadicum, six unilateral injuries of the pubis, two injuries of the iliac shaft with one bilateral and one unilateral and one bilateral injury of the ischium. The remaining 17 cases had several different bones affected including three cases of bilateral iliac wing and unilateral pubis, two cases of unilateral iliac wing and pubis with one on the same side and one on the contralateral side, two cases of bilateral iliac wing and unilateral sacral wing, two cases of unilateral iliac wing and iliac shaft on the same side,

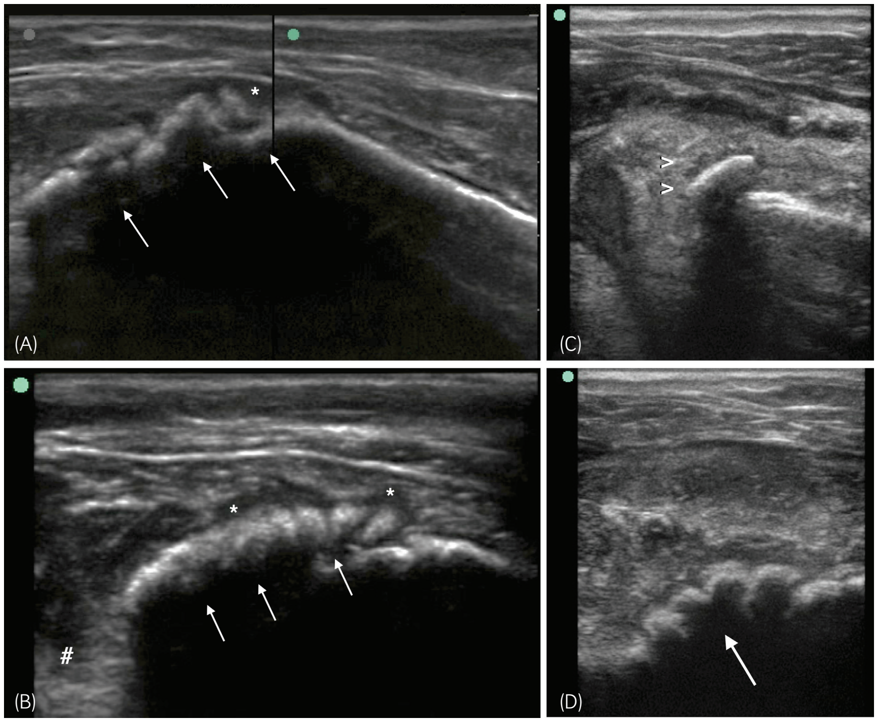

FIGURE 4 Ultrasonographic images of the ischium obtained with a transrectal approach. Cranial is to the left. A and B, Note the irregular bone surface of the cranial part of the table of the ischium (arrows) and the periosteal thickening (asterisk) close to the obturator foramen (hashtag) representing a bone stress injury and callus formation; the image shown in (B) is more medial compared to the image shown in (A). C and D, Ultrasonographic images of the table (C) and lateral ramus (D) of the ischium in the same horse. Note the bone fragment at the level of the lateral branch (open white arrows-C) and the irregularity and thickening of the bone surface (arrow-D)

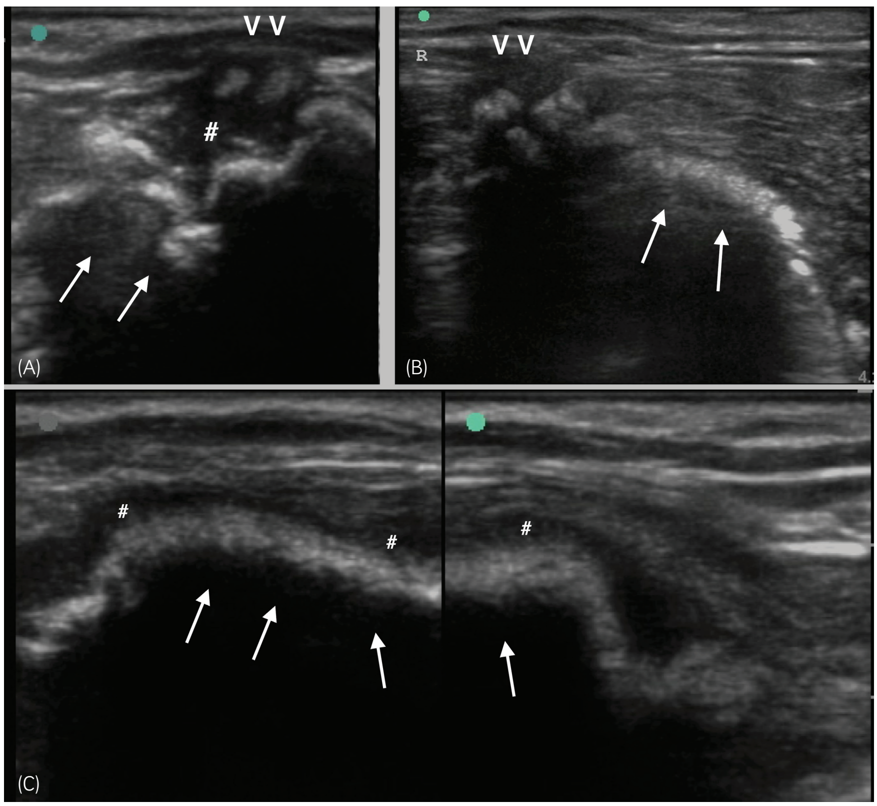

FIGURE 5 Ultrasonographic images of the cranial ramus of the pubis obtained with a transrectal approach. Cranial is to the left. A, Note the irregular bone surface at the cranial aspect of the ramus (arrows), the periosteal thickening (hashtag) and the callus formation (open arrowheads) representing cranial fragmentation of the pubis. B, Note the callus formation at the cranial aspect (open arrowheads) and the abnormal thickening and reduced echogenicity of the bone surface (arrows) indicating a cranial fragmentation and chronic fatigue fracture. C, Reconstructed image showing the cranial ramus of the pubis. Note the abnormal shape of the bone, the thickening and reduced echogenicity of the bone surface (arrows) and the periosteal thickening (hashtag), representing a bone stress injury or fatigue fracture

one case of bilateral iliac wing and ischium, one case of unilateral iliac wing and unilateral ischium on the contralateral side, one case of unilateral iliac wing and unilateral tuber ischiadicum on the same side, two cases of unilateral pubis and unilateral ramus of the ischium with one on the same side and one on the contralateral side, one case of bilateral ischium and unilateral pubis, one case of unilateral pubis and tuber ischiadicum on the same side, and finally one case of unilateral iliac wing, unilateral pubis and bilateral ischium.

In 4 of 58 fatigue fractures of the iliac wing, the injury was identified close to the junction between the iliac wing and iliac shaft and in the remaining 54 were at the level of the sacroiliac joint (Figure 1). In

TABLE 1 Details of bone stress injuries or fatigue fracture detected alone or in combination in 60 endurance horses of the study

	Bone stress injury or fatigue fracture (n = 103; % on total; 95% CI)[a]				
	Incomplete		Complete		
Bone affected	Acute	Chronic	Acute	Chronic	Complete and displaced
Iliac wing (n = 58) 56%; CI: 46%-66%	9 (9%; CI: 3%-14%)	26 (25%; CI: 16%-33%)	7 (7%; CI: 2%-11%)	5 (5%; CI: 1%-9%)	11 (10%; CI: 5-16)
Iliac shaft (n = 5) 5%; CI: 0.7%-9%	4 (4%; CI: 0.1%-7%)				1 (1%; CI: 0%-3%)
Tuber ischiadicum (n = 11) 11%; CI: 5%-16%	6 (6%; CI: 1%-10%)		5 (5%; CI: 1%-9%)		
Ischium (n = 11)[b] 11; CI: 5%-16%				11 (10%; CI: 5-16)	
Pubis (n = 16) 15%; CI: 8%-22%		4 (4%; CI: 0.1%-7%)[c]		12 (12%; CI: 5%-18%)[d]	
Sacrum (n = 2) 2%; CI: 0%-5%			2 (2%; CI: 0%-5%)		

Abbreviation: CI, confidence interval.

[a]Total number of bone stress injuries or fatigue fracture of the pelvis detected alone or in combination.

[b]Bone stress injuries/fatigue fracture of the ramus/table of the ischium.

[c]Bone stress injuries classified as cranial fragmentation.

[d]Including fatigue fracture with or without cranial fragmentation.

TABLE 2 Details of the bone stress injuries or fatigue fracture detected in each fracture configuration of the endurance horses of the study

Fracture configuration	Horses (n = 60; % of total; 95% CI)[a]
Isolated iliac fracture	29 (48%; CI: 36%-61%)
Iliac wing	25 (42%; 29%-54%)
Iliac wing and shaft	2 (3%; 0%-7%)
Iliac shaft	2 (3%; 0%-7%)
Isolated fracture of the floor of the pelvis	10 (17%; CI: 7%-26%)
Pubis	6 (10%; 2%-17%)
Pubis and ischium[b]	3 (5%; 0%-10%)
Ischium[b]	1 (2%; 0%-5%)
Isolated tuber ischiadicum fracture	9 (15%; CI: 6%-24%)
Tuber ischiadicum	9 (15%; 6%-24%)
Multiple fracture	12 (20%; CI: 10%-30%)
Iliac wing and pubis	5 (8%; 1%-15%)
Iliac wing and ischium[b]	2 (3%; 0%-7%)
Iliac wing and sacrum	2 (3%; 0%-7%)
Iliac wing and tuber ischiadicum	1 (2%; 0%-5%)
Pubis and tuber ischiadicum	1 (2%; 0%-5%)
Iliac wing, pubis and ischium[b]	1 (2%; 0%-5%)

[a]Total number of horses.

[b]Bone stress injuries/fatigue fracture of the ramus/table of the ischium.

19 of 20 cases with bilateral injuries of the iliac wing, the injuries were of the same severity on both sides with 11 incomplete, four complete and four complete and displaced and in one case the fatigue fracture was incomplete on one side and complete on the other side. The bilateral injuries of the iliac shaft were incomplete on both sides.

Twenty-nine (48%; 36%-61%) cases had isolated iliac fracture, 10 isolated fractures of the floor of the pelvis, 9 isolated tuber ischiadicum fracture and, the remaining 12 had multiple fractures. Details of the bone stress injuries and/or fatigue fractures in each fracture configurations are presented in Table 2.

TABLE 3 Results of multivariable logistic regression analyses for the fracture configurations and outcome

Risk factor	Isolated iliac fracture	No isolated iliac fracture	β-coefficient	Standard error β	Logistic odds ratio	Odds ratio 95% CI	Wald *P*-value
Sex							
Gelding	12 (25%)	4 (8%)	Ref	Ref	Ref	Ref	
Female	17 (35%)	15 (32%)	−1.41	0.83	0.24	0.04-1.24	.09
Breed							
Arab	9 (19%)	10 (21%)	Ref	Ref	Ref	Ref	
Anglo Arabian	20 (41%)	9 (19%)	1.48	0.76	4.42	1.02-19.57	.05
	Area under the curve = 0.67; Sensitivity = 0.91; Specificity = 0.38; R^2 McFadden = 0.21						

	Isolated fracture of the floor of the pelvis	No isolated fracture of the floor of the pelvis	β-coefficient	Standard error β	Logistic odds ratio	Odds ratio 95% CI	Wald *P*-value
Degree of lameness (median; range)	3; 1-3	2; 0-4	1.13	0.54	3.08	1.07-8.9	.04
Trot on three tracks							
Not present	4 (8%)	31 (64%)	Ref	Ref	Ref	Ref	
Present	6 (13%)	7 (15%)	2.15	0.92	8.62	1.43-51.9	.02
	Area under the curve = 0.81; Sensitivity = 0.40; Specificity = 0.97; R^2 McFadden = 0.25						

	Isolated tuber ischiadicum fracture	No isolated tuber ischiadicum fracture	β-coefficient	Standard error β	Logistic odds ratio	Odds ratio 95% CI	Wald *P*-value
Asymmetry bony landmarks							
Not present	3 (6%)	26 (54%)	Ref	Ref	Ref	Ref	
Present	6 (13%)	13 (27%)	2.00	0.82	7.42	1.47-37.45	.01
	Area under the curve = 0.72; Sensitivity = 0; Specificity = 1; R^2 McFadden = 0.14						

	Successful outcome	Unsuccessful outcome	β-coefficient	Standard error β	Logistic odds ratio	Odds ratio 95% CI	Wald *P*-value
Asymmetry bony landmarks							
Not present	20 (47%)	6 (14%)	Ref	Ref	Ref	Ref	
Present	9 (21%)	8 (18%)	1.60	1.05	5.00	0.64-39.05	.12
Fracture configuration							
Isolated iliac fracture	13 (30%)	12 (28%)	Ref	Ref	Ref	Ref	
Isolated fracture floor pelvis	7 (16%)	2 (5%)	−0.34	0.99	0.71	0.10-5.03	.74
Isolated tuber ischiadicum fracture	9 (21%)	0 (0%)	−18.84	2061.37	8.35^{e-5}	0-∞	.99
	Area under the curve = 0.77; Sensitivity = 0.4; Specificity = 0.93; R^2 McFadden = 0.26						

Abbreviation: CI, confidence interval.

Overall, 37 (62%; 56%-81%) cases returned successfully to competition, 12 were retired for reasons not related to the pelvic injury, three were retired because of the fracture, two were submitted to euthanasia because of the severity of the lesion, and six cases are still in rehabilitation. The two euthanised horses suffered a bilateral displaced fracture of the iliac wings and bilateral dislocation of the sacroiliac joints. The three horses retired from athletic activity suffered a unilateral complete displaced fracture of the iliac wing.

3.4 | Logistic regression models

Results of the univariable logistic regression models for fracture configurations and outcome are presented in Tables S1 and S2, respectively. Previous injuries and season were highly correlated ($\varphi = 0.61$; $P < .001$); therefore, only one was included depending on the best McFadden R^2 value obtained for the multivariable models.

The significant variable of the multivariable model for the development of isolated iliac fracture was the breed, and Anglo Arabians were more likely to develop this fracture configuration compared to Arab (Table 3). The significant variables of the multivariable model for the development of isolated fracture of the floor of the pelvis were grade of lameness and trot on three tracks (Table 3). The significant variable of the multivariable model for the development of isolated tuber ischiadicum fracture was asymmetry of bony landmarks (Table 3). Finally, variables that remained in the final multivariable analysis for the outcome were asymmetry of bony landmarks and fracture configurations; however, none were significant (Table 3).

4 | DISCUSSION

This study demonstrated that bone stress injuries and/or fatigue fractures of the pelvis can develop in endurance horses trained and competing on deep sand. Bone stress injuries and/or fatigue fractures of the pelvis represented 7.3% of the musculoskeletal lesions detected in 997 endurance horses in the UAE during a 6-year period (unpublished data). The site of the pelvis in which they were diagnosed was similar to that reported in Thoroughbred racehorses.[2,3,6] Bone stress injuries and/or fatigue fractures are often recognised in human sports activities, especially in runners and long-distance runners.[10,11] Microdamage formation as a consequence of repetitive mechanical loading is threshold-dependent and related to the number of bone strain cycles, strain magnitude and strain rate.[9-11] Microdamage is a natural phenomenon targeting remodelling of the bone but if insufficient time is given to adapt, then more damage may form before healing.[7,9-11]

For these reasons, bone stress injuries and/or fatigue fractures are considered overuse injury and it is unsurprising that they are recognised in endurance horses, who are subject to high amounts of repetitive loading necessary to reach an adequate level of metabolic and musculoskeletal training in terms of adaptation, as previously reported.[17,25] However, this is the first study to describe bone stress injuries and/or fatigue fractures of the pelvis in a large number of endurance horses. They were found in the predilection sites described in Thoroughbreds, where according to data on racehorses and the authors' hypothesis, the most common isolated fatigue fracture involved the iliac wing and were detected at the level of the sacroiliac joint. In approximately 50% of horses with injury of the iliac wing, the fatigue fracture was bilateral, as is also reported in Thoroughbred racehorses.[14,15,26] Interestingly, AA horses were 4.4 times as likely to have isolated iliac fracture compared to Arab; fatigue fractures of the pelvis are uncommon in Arabian racehorses competing in North America but are being recognised more frequently in the Middle East.[27] Influence of conformation and training/racing track surface merits further investigations.

The second-most common bone stress injury and/or fatigue fracture affects the pubis, a site that is not commonly recognised in Thoroughbred racehorses.[4,15,16,28,29] The ramus or table of the ischium and the tuber ischiadicum, was the third-most common; no acetabular fractures were identified. Contrary to the tuber ischiadicum fatigue fracture characterised by steps between bone stumps, haematoma and echoes going deep into the bone, ultrasonographic findings of the bone stress injury or fatigue fracture of the pubis and the ramus/table of the ischium were represented by irregularity and thickening of the bone surface, hypoechogenic periosteal thickening and increased echogenicity and swelling of the soft tissues.[30,31] In this study, some injuries of the pubis were classified as 'cranial fragmentation' based on the recognition of irregular bone surface at the insertion of the rectus abdominis and/or pectineus muscles, which can represent a bone stress injury due to the tensile action of pectineus and/or rectus abdominis muscles (enthesopathy). However, the periosteal bone over this fragmentation was thickened and soft tissues surrounding the area were hyperechogenic. Based on these ultrasonographic findings, calcified bone callus formation cannot be excluded.[30,31] Interestingly, in two cases, the initial ultrasonographic examination was unremarkable and ultrasonographic changes became clear at the second examination after 10 days. Ultrasonography cannot assess changes deeper to the bone surface such as bone marrow oedema, which is the feature of the early stage of stress fractures[30]; nuclear scintigraphy has a high sensitivity to diagnose fatigue fracture of the pelvis.[1,2,6,15] However, radiopharmaceutical accumulation in the urinary bladder and attenuation of gamma-radiation by the thick overlying musculature make scintigraphic examination unreliable for detection of fatigue fracture of the floor of the pelvis.[1,2] Radiography of the pelvis under general anaesthesia is described but there are several risks associated with it; however, tuber ischiadicum can be assessed radiographically on the standing horse but in our opinion ultrasound examination of this area is easy and sensitive and avoids radiation exposure.

A complete ultrasound evaluation using both transcutaneous and transrectal approaches should be performed in horses showing lameness or poor performance, in which the distal limb was excluded as the source of the problem based on physical, dynamic and diagnostic imaging investigation. Fractures of the ilium and tuber ischiadicum are best diagnosed using an external transcutaneous approach; the diagnosis of bone stress injury or fatigue fracture close to the sacroiliac joint and involving the floor of the pelvis requires a transrectal approach.

In human athletes, it was demonstrated that instability at the level of the sacroiliac joint due to trauma or chronic stress may lead to secondary bone stress injury at the level of the pubis or vice versa.[32-34] In human sports medicine, there are two distinct cortical fatigue fractures, tensile or compressive, depending on the location and the direction of the stresses.[9,10] The bone stress injuries and fatigue fractures of the iliac wing are considered due to chronic tensile stress on the caudal iliac border associated with bending at the sacroiliac articulation, as demonstrated by the consistent orientation of the fracture line perpendicular to the caudomedial border.[14] Biomechanical strains exerted by strong pelvic muscles and associated ligamentous structures on the different flat bones such as the ischium and pubis may play a role in the development of multiple fractures; it has been previously reported that tensile and compressive forces acting on the coxal bone affect its architecture and its mechanostructure influence the location of the pelvic fracture.[4,35-37] However, anatomical differences in bone morphology, the direction of forces and mechanics of bipedal versus quadrupedal locomotion between humans and horses must be considered.

These bone stress injuries and/or fatigue fractures of the pelvis were only diagnosed in endurance horses trained and competing in the UAE. A retrospective study that investigated orthopaedic injuries during 10 years of observation in 235 endurance horses trained in Italy and competing in Europe failed to identify bone stress injuries and/or fatigue fractures of the pelvis.[38] Some training factors may explain these data. Endurance horses in the UAE are generally trained at canter at 18 to 20 km/h for variable amounts of time (from 45 minutes up to 4 hours) per day and several days per week, depending on the level of activity of the horse and trainer's preferences. Training is made on the deep dry sand of approximately 10 cm of depth, typical of the desert environment. This kind of training and training surface may affect the development of bone stress injuries and/or fatigue fractures of the pelvis. In Thoroughbreds, synthetic surfaces were demonstrated acting as a risk factor for the development of pelvic and tibial stress fractures and the type of training or competition surface are recognised as having a role in stress fracture.[39-41] Some studies in human sports medicine and Standardbred horses demonstrated that training in soft, compliant surfaces like deep sand, results in decreased impact forces and loading rate but muscle activation is emphasised.[42-45] In human sports medicine, there is an increase in concentric muscle activity in propulsive muscles and consequently a higher energy cost of soft sand running compared to firm surfaces.[43,44] This was not extensively investigated in horses, but it was demonstrated that the overall loading of the forelimb in horses is reduced and more progressive on deep sand compared to firm sand but the propulsive muscular effort is increased as the consequence of the poor damping effect of the deep sand.[44,45] From these data, it is possible that dry sand increased the energy cost of locomotion, probably resulting in a higher heart rate at a lower speed, allowing training of the cardiorespiratory system without reaching the maximal speed when horses compete on the wet sand.[46] Training on deep sand may have a protective effect for some injuries as a consequence of the decreased impact forces on the distal limbs, but it may act as a risk factor for some others due to the increased muscular effort. This concept is widely recognised in human sports medicine and the need for training adaptation to sand has been highlighted.[47]

As previously reported, muscles play an essential role in fatigue fractures because the most important forces are created by muscle contraction and the bone adapt to the strength of the muscles, so increasing muscle activity in athletes increases muscle strength and bone strength. However, muscles adapt faster and in a larger proportion than bone and favour the development of fatigue fracture, especially in some conditions such as a sudden increase in training or changes of running surfaces. The theory of the bone-muscles unit helps to explain the occurrence of a fatigue fracture in non-loadbearing bones.[11]

A predisposition of females for pelvis fractures has been previously reported in some studies because of sex-related differences in bone shape.[4,28,48] According to other studies, females (67%) were overrepresented in this study based on data available on the FEI database, where over the study period, geldings and males (n = 328) were overrepresented in the UAE compared to females (n = 132).[49]

In contrast with our second hypothesis, the number of seasons did not affect the type of pelvic injury. Overall, 48% of bone stress injuries and/or fatigue fractures developed during the first season in the UAE, which may suggest the role of changes in training technique or surface in their development. Endurance horses in the UAE are commonly bought in other countries such as Europe, South America, Australia and South Africa, with different training techniques and ground surfaces available for training and competition. Also, in contrast with our second hypothesis, previous injuries sustained in other sites than the pelvis did not significantly affect the type of pelvic injuries.

Horses with asymmetry of bone landmarks were more likely to have bone-stress injuries and/or fatigue fractures of the tuber ischiadicum compared to horses without. This type of pelvic injury could be related to a high number of cyclical loading for long distances prolonged over time that result in the development of an acute (incomplete or complete) fatigue fracture without atrophy of the semitendinosus/semimembranosus muscles. Horses with injuries of the iliac wing and floor of the pelvis sometimes showed atrophy of the muscles of the croup but this variable was not significant neither in the univariable nor in the multivariable models; however, muscles that origin and insert on the floor of the pelvis cannot be evaluated clinically. Finally, horses with isolated bone stress injuries and/or fatigue fractures of the pubis and ramus or table of the ischium more commonly did not show asymmetries of the bony landmarks of the pelvis but were 8.62 times as likely to trot on three tracks. These fractures generally remain in a reasonable alignment and the tendency to move with the hindlimbs tracking on one side of the forelimb may reflect a biomechanical adjustment to reduce the stress of adductor muscles in this area. For every increased grade of lameness, the odds of having bone-stress injuries and/or fatigue fractures of the floor of the pelvis increased by 208%.

In agreement with other studies on Thoroughbred racehorses, overall, the prognosis can be considered good with 62% of these horses returning successfully to competition. None of the investigated variables was found to significantly affect the outcome, but this needs further investigation. A low number of horses were retired from athletic activity because of pelvic injury or suffered catastrophic fractures that needed euthanasia. This highlights the importance of investigating this area to prevent the development of catastrophic injuries. Some of these horses were eliminated for metabolic reasons during competition as often they commonly were reluctant to move and the heart rate did not recover normally. These signs at the vet gate are often confused with metabolic problems such as myopathies, as reported for Thoroughbred racehorses after the end of the race.[2]

The main limitation of this study is related to the detection of pelvic injuries in horses trained and competing in a single country and, to our knowledge, they have not been reported in the literature in other countries.[38] However, this study highlights the importance of investigating the pelvis as a source of lameness and poor performance in endurance horses. Still images were evaluated retrospectively by 2 of the authors; however, they were used only for classification purposes as still images do not allow having all the information that was acquired during the real-time evaluation.

Additional studies are needed to confirm or reject pelvic bone stress injuries and/or fatigue fractures as affecting primarily horses trained and competing on deep sand. In addition, the data available for these horses did not allow investigation of trainers' preferences such as days per week of training, speed of training and distance. Thus, longitudinal prospective studies are advisable to investigate risk factors for pelvic fracture configuration and outcome.

5 | CONCLUSION

Bone stress injuries and/or fatigue fractures can affect endurance horses trained on deep sand and competing at a relatively high speed. Isolated iliac fractures were the commonest followed by multiple pelvic bones involvement, isolated fracture of the floor of the pelvis (pubis and table or ramus of the ischium) and tuber ischiadicum. The presence of lameness and trot on three tracks suggest the presence of bone stress injury or fatigue fracture of the floor of the pelvis; asymmetry of bony landmarks is more commonly detected in horses with bone stress injury or fatigue fracture of the tuber ischiadicum. Return to athletic activity after rest and rehabilitation can be considered good.

ETHICAL ANIMAL RESEARCH

Research ethics committee oversight not required by this journal: retrospective analysis of clinical data.

INFORMED CONSENT

Explicit owner-informed consent for the inclusion of animals in this study was not stated.

ACKNOWLEDGEMENTS

Authors would like to acknowledge the referring veterinarians in the United Arab Emirates, Dr Maximo Cabal, Dr Laura Paiz, Dr Marco Giagnori, Dr Erik Siccardi and Dr Alberic Thery.

CONFLICT OF INTERESTS

No competing interests have been declared.

AUTHOR CONTRIBUTIONS

M. Puccetti contributed to the conception of the study and data acquisition. M. Puccetti and J-M. Denoix contributed to the interpretation of the ultrasonographic images. M. Puccetti and F. Beccati contributed to study design. F. Beccati contributed to the data analysis. All the authors participated in data interpretation and drafting and/or revising the manuscript and gave final approval of the submitted manuscript.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1111/evj.13536.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Francesca Beccati https://orcid.org/0000-0002-3126-2738

REFERENCES

1. Davenport-Goodall CLM, Ross MW. Scintigraphic abnormalities of the pelvic region in horses examined because of lameness or poor performance: 128 cases (1993–2000). J Am Vet Med Assoc. 2004;224:88–95.
2. Powell S. Investigation of pelvic problems in horses. In Practice. 2011;33:518–24.
3. Ramzam PHL. The pelvis. In: Ramzam PHL, editor. The racehorses: a veterinary manual. Boca Raton: CRC Press, 2014; p. 168–78.
4. Moiroud CH, Coudry V, Denoix JM. Distribution of pelvic fractures in racing and non-racing sport horses: a retrospective study of 86 cases examined in a referral centre. Vet Comp Orth Traumatol. 2019;32:215–21.
5. Ducharme NG, Nixon AJ. Fractures of the pelvis. In: Nixon AJ, editor. Equine fracture repair. 2nd ed. Philadelphia: Wiley Blackwell; 2020. p. 723–33.
6. Pilsworth RC, Shepherd MC, Herinckx BMB, Holmes MA. Fracture of the wing of the ileum, adjacent to the sacroiliac joint, in Thoroughbred racehorses. Equine Vet J. 1994;26:94–9.
7. Riggs CM. Fractures—a preventable hazard of racing Thoroughbred? Vet J. 2002;163:19–29.
8. Bahrens SB, Deren ME, Matson A, Fadale PD, Monchik KO. Stress fractures of the pelvis and legs in athletes: a review. Sports Health. 2013;5:165–74.
9. Kaeding CC, Miller T. Classification of stress fractures. In: Miller TL, Kaeding CC, editors. Stress fractures in athletes: diagnosis and management. London: Springer; 2015. p. 51–62.
10. Saunier J, Chapurlat R. Stress fracture in athletes. Joint Bone Spine. 2018;85:307–10.
11. Breathnach O, Splinder KP, Wasserstein DN. Pathophysiology and epidemiology of stress fractures. In: Miller TL, Kaeding CC, editors. Stress fractures in athletes. London: Springer; 2020. p. 29–39.
12. Davidson EJ, Ross MW. Clinical recognition of stress-related bone injury in racehorses. Clin Tech Equine Pract. 2003;2:296–311.
13. Ely ER, Avella CS, Price JS, Smith RKW, Wood JLN, Verheyen KLP. Descriptive epidemiology of fracture, tendon and suspensory

ligament injuries in national hunt racehorses in training. Equine Vet J. 2009;41:372–8.
14. Haussler KK, Stover SS. Stress fractures of the vertebral lamina and pelvis in Thoroughbred racehorses. Equine Vet J. 1998;5:374–81.
15. Hennessy SE, Muurlink MA, Anderson GA, Puksmann TN, Whitton RC. Effect of displaced versus non-displaced pelvic fractures on long-term racing performance in 31 Thororughbred racehorses. Aust Vet J. 2013;91:246–50.
16. Bertuglia A, Bullone M, Rossotto F, Gasparini M. Epidemiology of musculoskeletal injuries in a population of harness Standardbred racehorses in training. BMC Vet Res. 2014;10:11.
17. Misheff MM, Alexander GR, Hirst GR. Management of fractures in endurance horses. Equine Vet Educ. 2010;22:623–30.
18. Dyson S, Nagy A, Murray R. Clinical and diagnostic imaging findings in horses with subchondral bone trauma of the sagittal groove of the proximal phalanx. Vet Rad Ultrasound. 2011;52:596–604.
19. Beccati F, Cerocchi A, Conte M, Pilati N, Pepe M. Computed tomographic diagnosis of incomplete palmar cortical (fatigue) fracture of the third metacarpal bone in two young adult endurance horses. Equine Vet Educ. 2019;31:e17–e22.
20. Ross MW. Movement. In: Ross MW, Dyson SJ, editors. Diagnosis and management of lameness in the horse, 2nd ed. Philadelphia: Elsevier Saunders; 2011. p. 64–80.
21. Walker WT, Werpy NM, Goodrich LR. Procedure for the transrectal and transcutaneous ultrasonographic diagnosis of pelvic fractures in the horse. J Equine Vet Sci. 2012;32:222–30.
22. Tallaj A, Coudry V, Denoix JM. Transrectal ultrasonographic examination of the sacroiliac joints of the horse: techniques and normal images. Equine Vet Educ. 2019;31:666–71.
23. Bianchi S. Ultrasound and bone: a pictorial review. J Ultrasound. 2020;23:227–57.
24. Denoix JM. Approche sémiologique des régions lombo-sacrale et sacro-iliaque chez le Cheval. Prat Vét Équine. 1992;24:23–38.
25. Robert C. Veterinary aspect of training and racing endurance horses. In: Hinchcliff KW, Kaneps A, Geor R, editors. Equine sport medicine and surgery, 2nd ed. Philadelphia: Saunders Elsevier; 2013. p. 1083–106.
26. Hornof WJ, Stover SM, Koblik PD, Arthur RM. Oblique views of the ileum and the scintigraphic appearance of stress fractures of the ileum. Equine Vet J. 1996;28:355–8.
27. Dalglish RA, Rick MC. Lameness in the Arabian racehorses: middle east and North America. In: Ross MW, Dyson SJ, editors. Diagnosis and management of lameness in the horse, 2nd ed. Philadelphia: Elsevier Saunders; 2011. p. 1062–75.
28. Rutkowski JA, Richardson DW. A retrospective study of 100 pelvic fractures in horses. Equine Vet J. 1989;21:256–9.
29. Stover SM, Ardans AA, Read DH, Johnson BJ, Barr BC, Daft BM, et al. Patterns of stress fractures associated with complete bone fractures in racehorses. Proc Am Assoc Equine Practnrs. 1993;39:131–2.
30. Fukushima Y, Ray J, Kraus E, Syrop IP, Fredericson M. A review and proposed rationale for the use of ultrasonography as a diagnostic modality in the identification of bone stress injuries. J Ultrasound Med. 2018;37:2297–307.
31. Moraux A, Gitto S, Bianchi S. Ultrasound of the normal and pathologic periosteum. J Ultrasound Med. 2019;38:775–84.
32. Major NM, Helms CA. Pelvic stress injuries: the relationship between osteitis pubis (symphysis pubic stress injury) and sacroiliac abnormalities in athletes. Skeletal Radiol. 1997;26:71–717.
33. Miller C, Major N, Toth A. Pelvic stress injuries in athlete: management and prevention. Sports Med. 2003;33:1002–12.
34. Douglas SR, Troy KL, Tenforde AS. Radiographic pattern to recognize overuse injury in runners: the ipsilateral pubic ramus and sacral bone stress injury. PM&R. 2020;12(12):1279–1280. https://doi.org/10.1002/pmrj.12436
35. Barone R. Cintura e arto pelvici – Cintura pelvica. In: Barone R, editor. Anatomia comparata dei mammiferi domestici. Vol.1—parte I Osteologia, 3rd ed. Bologna: Edagricole; 2006; p. 541–578.
36. Bressou C, Pavaux C, Vladutiu O. Mécano-structure et fracture du bassin chez le cheval. Revue Méd Vét. 1979;130:543–66.
37. Denoix JM. Aspects fonctionnels des régions lombo-sacrales et sacro-iliaque du Cheval. Prat Vét Équine. 1992;24:13–21.
38. Paris A, Beccati F, Pepe M. Type, prevalence, and risk factors for development of orthopaedics injuries in endurance horses during training and competition. J Am Vet Med Assoc. 2021;258:1109–18. https://doi.org/10.2460/javma.258.10.1109
39. Verheyen KLP, Newton JR, Price JS, Wood JLN. A case-control study of factors associated with pelvic and tibial stress fractures in Thoroughbred racehorses in training in the UK. Prev Vet Med. 2006;74:21–35.
40. MacKinnon MC, Bonder D, Boston RC, Ross MW. Analysis of stress fractures associated with lameness in Thoroughbred flat racehorses training on different track surfaces undergoing nuclear scintigraphic examination. Equine Vet J. 2015;47:296–301.
41. Maeda Y, Hanada M, Oikawa M. Epidemiology of racing injuries in Thoroughbred racehorses with special reference to bone fractures: Japanese experience from 1980s to 2000s. J Equine Sci. 2016;27:81–97.
42. Barrett RS, Neal RJ, Roberts LJ. The dynamic loading response of surfaces encountered in beach running. J Sci Med Sport. 1997;1:1–11.
43. Pinnington HC, Dawson B. The energy cost of running on grass compared to soft dry beach sand. J Sci Med Sport. 2001;4:416–30.
44. Chateau H, Holden L, Robin D, Falala S, Pourcelot P, Estoup P, et al. Biomechanical analysis of hoof landing and stride parameters in harness trotters horses running on different tracks on sand beach (from wet to dry) and on an asphalt road. Equine Vet J. 2010;42(suppl 38):488–95.
45. Crevier-Denoix N, Robin D, Pourcelot P, Falala S, Holden L, Estoup P, et al. Ground reaction force and kinematic analysis of limb loading on two different beach sand tracks in harness trotters. Equine Vet J. 2010;42(suppl 38):544–51.
46. Nagy A, Dyson SJ, Murray JK. A veterinary review of endurance riding as an international competitive sport. Vet J. 2012;194:288–93.
47. Binnie MJ, Dawson B, Pinnington H, Landers G, Peeling P. Sand training: a review of current research and practical applications. J. Sports Sci. 2014;32(1):8–15.
48. Carrier TK, Estberg L, Stover SM. Association between long periods without high-speed workouts and risk of complete humeral or pelvic fracture in Thoroughbred racehorses: 54 cases (1991–1994). J Am Vet Med Assoc. 1998;15:1582–7.
49. Federation Equestre Internationale database. Federation Equestre Internationale; 2020 [cited 2000 Dec 15]. Available from https://data.fei.org/Horse/Search.aspx

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Puccetti M, Beccati F, Denoix J-M. Bone stress injuries and fatigue fractures of the pelvis in endurance horses. Equine Vet J. 2022;54:1064–1075. https://doi.org/10.1111/evj.13536