Effect of track surface firmness on the development of musculoskeletal injuries in French Trotters during four months of harness race training

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OBJECTIVE
To evaluate the effect of track surface firmness on the development of musculoskeletal injuries in French Trotters during 4 months of race training.

ANIMALS
12 healthy 3-year-old French Trotters.

PROCEDURES
Horses were paired on the basis of sex and body mass. Horses within each pair were randomly assigned to either a hard-track or soft-track group. The counterclockwise training protocol was the same for both groups. Surface firmness of each track was monitored throughout the training period. Radiography, ultrasonography, MRI, and scintigraphy were performed on all 4 limbs of each horse before and after 2 and 4 months of training. Lesions were described, and lesion severity was classified with a 5-point system, where 0 = no lesions and 4 = severe lesion.

RESULTS
86 lesions were identified, of which 46 (53.5%) were classified as potentially clinically relevant (grade, ≥ 2). Of the 18 moderate and severe lesions, 15 were identified in horses of the hard-track group, and 10 of those were in forelimbs. Moderate to severe tendinopathy of the superficial digital flexor tendon of the forelimb developed in 3 of the 6 horses of the hard-track group but none of the horses of the soft-track group. Metatarsal condyle injuries were more frequent in horses of the hard-track group than horses of the soft-track group. Severe lesions were identified only in left limbs.

CONCLUSIONS AND CLINICAL RELEVANCE
Results indicated that track surface firmness is a risk factor for musculoskeletal injuries in horses trained for harness racing. (*Am J Vet Res* 2017;78:xxx–xxx)

Musculoskeletal injuries are the most frequent cause of wastage in race and sport horses, and the type and condition of the surface used for racing and training affect the occurrence and nature of injuries.[1–7] The incidence of severe or catastrophic injuries in Thoroughbred racehorses that race on turf surfaces increases as the firmness of the surface increases.[8–11] However, to our knowledge, the effect of surface firmness on the occurrence and type of injures in racehorses has not been investigated for surfaces other than turf that are used for the racing and training of horses. Moreover, most studies[1–11] regarding the effect of surface on racehorse injuries were retrospective in nature. In fact, we are aware of only 2 prospective studies that were conducted to investigate the effect of track surface on the remodeling response of proximal sesamoid bones[12] and third metacarpal bones[13] of 2-year-old Thoroughbred racehorses during training.

Epidemiology of exercise-related musculoskeletal injuries in Thoroughbred racehorses has been intensively studied,[14–16] but only 1 study[17] has been performed to investigate the epidemiology and incidence rates of exercise-related injuries in Standardbreds involved in harness racing. Injuries to both the forelimbs and hind limbs were assessed in that study,[17] and the most frequently observed injuries were to the suspensory ligaments, followed by the SDFT. Damage to those 2 structures accounted for 38.3% of all injuries reported.[17] Unfortunately, bone lesions in the horses of that study[17] were not evaluated with MRI, and track surface was not evaluated as a risk factor for musculoskeletal injuries because all horses trained at the same racetrack.

Exercise-related musculoskeletal injuries are directly linked to the loading pattern of anatomic struc-

ABBREVIATIONS

FSE	Fast spin echo
GRE	Gradient echo
POD	Plantar or palmar osteochondral disease
SDFT	Superficial digital flexor tendon
STIR	Short tau inversion recovery
T1	T1-weighted
T2	T2-weighted

tures, which is determined by the external loads applied to the limbs (ie, ground reaction forces) during exercise. Ground reaction forces, particularly the loading rate, applied to the limbs are affected by track surface characteristics.[18–22] In a preliminary study[23] involving 1 Standardbred racehorse at training speed, the forces and decelerations associated with impact shock in both the forelimbs and hind limbs were positively associated with the firmness of the track surface (sand).

The objective of the study reported here was to evaluate the effect of track surface firmness on the development of musculoskeletal injuries in French Trotters during 4 months of training. The hypothesis was that the number and severity of musculoskeletal lesions in both the forelimbs and hind limbs of horses trained on a hard sand track would be greater than those of horses trained on a soft sand track.

Materials and Methods

Animals

All study procedures were reviewed and approved by the Animal Care and Ethics Committee of the Ecole Nationale Vétérinaire d'Alfort. The study was conducted during the summers of 2012 and 2013, and the same selection and study protocols were used each summer. During each of the 2 summers, 6 horses owned by and maintained for research purposes at the Centre for Imaging and Research in Equine Locomotor Disorders were enrolled in the study. All study horses were 3-year-old French Trotters that had been in race training for 6 to 10 months prior to evaluation for study eligibility. To be included in the study, horses had to have a normal conformation and be healthy as determined on the basis of results of a physical examination, be able to maintain a symmetric trot on a track at a minimum speed of 40 km/h (1.5 min/km), and not have any clinically relevant limb abnormalities as determined by diagnostic imaging, which included ultrasonographic examination of the SDFT of both forelimbs and suspensory ligament (scanned from the proximal insertion to the body and distal branches) of all 4 limbs, radiographic examination (dorsopalmar-plantar and lateromedial views) of the metacarpophalangeal and metatarsophalangeal (4 fetlock) joints and both tarsal (hock) joints, and MRI examination of all 4 fetlock joints. Horses with any clinically relevant abnormalities on physical examination or diagnostic imaging or that could not maintain a symmetric trot at the minimum speed were excluded from the study.

Immediately after study enrollment, horses were paired into 3 pairs on the basis of sex and body mass. Each pair was housed in a small paddock (15×20 m^2) and allowed an approximately 3-month (median, 2.8 months; range, 2.5 to 4 months) period without training prior to initiation of the study protocol. Immediately before initiation of the study protocol, each horse within a pair was randomly assigned by drawing lots to 1 of 2 treatment groups (hard track or soft track [control]).

Tracks

Both sand tracks used in the study were located at the same private training center. The physical characteristics of each track were evaluated by a private firm[a] that specializes in evaluating sports and recreational surfaces. The soft track was composed of a soft 8-cm cushion of 0/4-mm sand resting on top of 7 cm of the same sand, which was compacted, on a silty-clay foundation. The hard track was composed of a hard 8-cm cushion of very compact stabilized material (0/5-mm sand with a high proportion of fines) resting on top of 12 cm of wind-blown sand on a clinker foundation. The surface of the soft track was regularly watered, whereas the surface of the hard track was never watered during the training period. Both tracks were maintained with a leveling bar or drag to minimize or avoid surface irregularities. The firmness of both tracks was tested approximately 2 times/mo throughout the training period. For each track during each measurement session, an impact soil tester[b] (drop height, 0.45 m; weight, 2.25 kg) was applied 5 times to 4 systematically selected sites along each track, and the peak deceleration was recorded for each impact.

Training protocol

Horses in both treatment groups were trained by the same professional trainer for 4 months and were trained exclusively on the assigned track. Horses were trained 3 times/wk throughout the 4-month (16-week) training period, except for week 9 during which horses underwent midprotocol clinical and imaging examinations and were trained only twice. Horses were maintained in paddocks when they were not being trained. The training protocol was the same for both treatment groups and consisted of the horse in harness pulling a sulky while circling the assigned track in a counterclockwise direction at a gradually increasing speed (ie, workload or intensity). Each training session consisted of a 5,000-m warm-up period followed by a 5,000-m work period. For each horse during each training session (day), the distance and speed prescribed by the protocol **(Appendix 1)** were strictly adhered to and monitored by use of an electronic device[c] with a global positioning system that is commonly used in the training of racehorses. The trainer maintained a detailed record of each training session for each horse, which included comments regarding the behavior and comfort of the horse, and was instructed to immediately report any sign of discomfort for any horse. Training was immediately modified or discontinued for any horse that developed a clinical problem so that it could receive appropriate treatment.

Physical and diagnostic imaging examinations

Each horse underwent a physical examination, which included a lameness examination, and diagnostic imaging at the Centre for Imaging and Research in

Equine Locomotor Disorders before initiation, during week 9, and at the completion of the 4-month training protocol. All physical examinations were performed by the same experienced equine clinician (J-MD). Horses were assessed for lameness at a walk and trot on a hard surface and treadmill and assigned a lameness score by use of the 5-point scale developed by the American Association of Equine Practitioners.[24] Each horse's response to 1-minute digital (forelimb) and global (hind limb) flexion tests was also subjectively graded.

Diagnostic imaging (radiography, scintigraphy, ultrasonography, and MRI) of the forelimbs and hind limbs of each horse was performed during each examination. Depending on the modality and anatomic location, complementary views or sequences were performed when further documentation of a lesion was required.

Radiography

For radiographic examination, horses were sedated with detomidine hydrochloride[d] (0.01 mg/kg, IV) and butorphanol tartrate[e] (5 mg, IV) and imaged while standing. Radiographs were obtained by use of a digital radiography system that included a ceiling-mounted x-ray machine[f] and flat-panel detector[g] with exposure settings of 68 to 79 kV and 5 to 12.5 mAs, depending on the projection and region radiographed. A minimum of 22 images were acquired during each examination and included dorsopalmar 55° on-block and lateromedial projections of both forefeet; dorsopalmar or dorsoplantar and lateromedial projections of all 4 fetlock joints; dorsopalmar, lateromedial, and flexed proximodistal projections of the third carpal bone; and dorsoplantar and lateromedial projections of both hock joints.

Scintigraphy

For scintigraphic examination, each horse was trotted for 15 minutes as a warm-up and then administered ^{99m}technetium-decarboxypropane diphosphonate[h] (1 GBq/100kg, IV). Immediately thereafter, the distal portion of all 4 limbs was bandaged to prevent isotope contamination of the urine before the acquisition of bone-phase images. Furosemide[i] (0.5 mg/kg, IV) was administered 1.5 hours after the radiotracer, and bone-phase images were obtained 3 hours later with the horse in a standing position. Immediately prior to image acquisition, horses were sedated with morphine chlorhydrate[j] (40 mg, IV) and detomidine (0.01 mg/kg, IV); some horses were administered additional doses of detomidine (1 mg, IV) as necessary to achieve adequate sedation for imaging.

Bone-phase images were acquired as described.[25] Eighteen images were acquired for each horse including dorsal and lateral views of both metacarpophalangeal regions and carpi, solar views of the forefeet, lateral views of both humeri and stifle joints, and plantar and lateral views of both metatarsophalangeal regions and hock joints. Additionally, sixty 2-second dynamic images with a 128×128 matrix size were acquired by use of a nuclear γ camera[k] equipped with a low-energy, high-resolution collimator. Those images were evaluated with a customized motion-correction software program developed with a commercially available matrix computation program[l] to calculate a static image of 120 seconds' duration. All images had > 150,000 counts except the solar projections, which had > 50,000 counts. While each limb was imaged, stand-alone leaded protection was used to protect the other 3 limbs from γ radiation.

Ultrasonography

All ultrasonographic examinations were performed by the same investigator (J-MD) with an ultrasound machine[m] and multiple transducers (7.5- to 13-MHz linear probes, 3- to 7.5-MHz convex probes, and a 7.5-MHz microconvex probe), which were selected on the basis of the area being scanned. Twenty areas were routinely imaged, including the SDFTs of both forelimbs; proximal third (including insertion), body, and branches of the suspensory ligament of all 4 limbs; palmar or plantar proximal recesses of all 4 fetlock joints; digital tendon sheaths of all 4 limbs; articular cartilage of the metacarpal condyle and distal radius of both forelimbs; and articular cartilage of the femoral trochlea of both hind limbs. Any physical deformation identified was also imaged by ultrasonography.

MRI

Magnetic resonance imaging was performed with horses in a standing position following sedation with detomidine (0.01 mg/kg, IV) and butorphanol (4 to 5 mg, IV). Some horses were administered additional doses of the sedatives (1 mg of detomidine with or without 1 mg of butorphanol, IV) as necessary to achieve adequate sedation for image acquisition.

A 0.27-T equine MRI system[n] was used to acquire images of all 4 fetlock joints of all 12 horses and both forefeet of the 6 horses evaluated in 2013. The following sequences were acquired for each fetlock joint: T1 GRE in the transverse and sagittal planes, STIR FSE in the transverse and sagittal planes, and T2 FSE with motion correction in the transverse plane. The following sequences were acquired for the forefeet of the 6 horses evaluated in 2013: T1 3-D GRE in the transverse plane, high-resolution T1 3-D GRE in the frontal plane, STIR FSE in the sagittal plane, T2 FSE in the transverse plane, and high-resolution T2 3-D GRE out of phase. The technical parameters used to acquire each image sequence were summarized **(Appendix 2)**.

Diagnostic image assessment

Radiographic and ultrasonographic images were reviewed by 1 equine clinician (J-MD) who was experienced in the diagnosis of musculoskeletal lesions of French Trotters, and scintigraphic and MRI sequences were collegially reviewed by 2 experienced clinicians (J-MD and FA) on a commercially available diagnostic image viewer.[o] Clinicians were unaware of (blind to) the treatment group (hard track or soft track) to which each horse was assigned during image review.

A 5-point grading system was developed for evaluation of lesion severity during review of ultrasonographic **(Appendix 3)** and MRI **(Appendix 4)** images. In both systems, 0 = clinically normal (no lesions observed), 1 = discrete lesions that are not clinically relevant (ie, subclinical lesions), 2 = mild lesions of discrete or mild clinical relevance, 3 = moderate lesions of mild to moderate clinical relevance, and 4 = severe lesions of moderate to severe clinical relevance. Horses with grade 1 and grade 2 musculoskeletal lesions continued the prescribed training protocol, whereas the training protocol for horses with grade 4 lesions was modified (ie, workload lessened) or discontinued. For horses with grade 3 lesions, the training protocol was or was not modified on the basis of each horse's apparent tolerance of the training. For example, the training protocol for a horse with a grade 3 lesion that was clinically lame (eg, grade 2 lameness[24]) was discontinued if the lameness did not improve during the warm-up period.

Statistical methods

Peak deceleration data obtained from the impact soil tester were used to measure the surface firmness of each track; the greater the peak deceleration, the firmer the track surface. Each track underwent a total of 15 test sessions during the summers of 2012 and 2013. The data for all 4 selected sites were pooled for each track, and the mean peak deceleration was calculated on the basis of impact order during a given test session (1 through 5) and collectively. Thus, the mean for each impact-order category represented 60 impacts (15 test sessions X 4 sites), and the mean for each track represented 300 impacts (15 test sessions X 4 sites X 5 impacts at each site).

Only musculoskeletal lesions that were first observed or became more severe during the 4-month training protocol were included in the analyses. Rare grade 1 (subclinical) musculoskeletal lesions present prior to initiation of the training protocol that remained stable or improved during the training period were not considered. Data analyses were largely based on the grades assigned to diagnostic images acquired at completion of the training protocol, and lesions with a grade ≥ 2 (ie, clinically relevant lesions) were considered most likely to be associated with track surface firmness.

The number and grade of musculoskeletal lesions for each anatomic area evaluated and horse were tabulated. Because the number of horses in each treatment group (hard track and soft track) was small (n = 6), the Mann-Whitney test was used to compare medians between the 2 treatment groups. Comparisons between forelimbs and hind limbs and between left and right limbs were performed with a mixed linear regression model, with a random effect for horse to account for repeated measures within individual animals. All analyses were performed with a commercial software program,[p] and values of $P \leq 0.05$ were considered significant.

Results

The study population consisted of 8 mares and 4 geldings with a mean ± SD body mass of 471 ± 49 kg. The mean peak deceleration as determined by the impact soil tester was significantly greater for

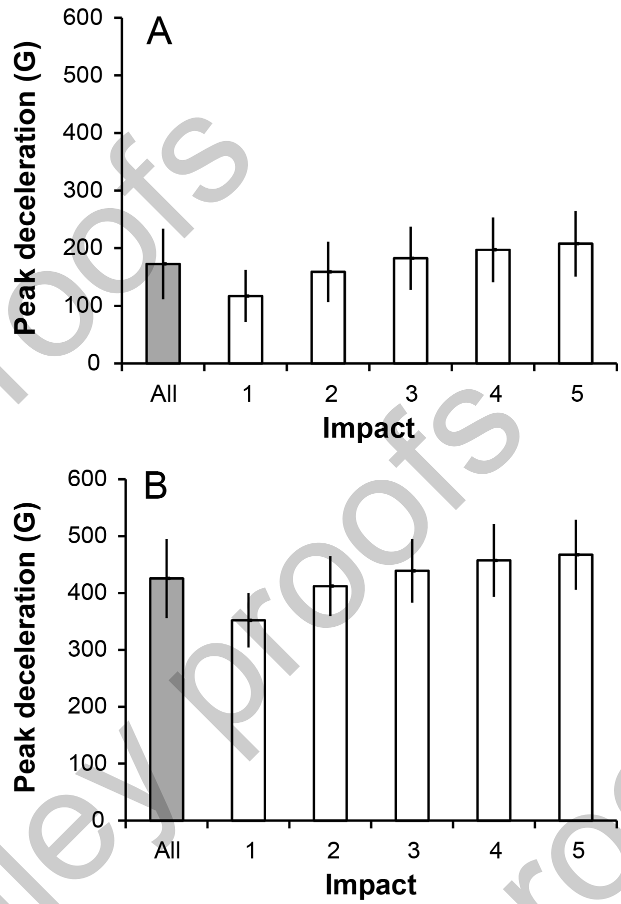

Figure 1—Mean ± SD peak deceleration as determined by use of an impact soil tester for the surface of 2 sand racetracks designed to have either a soft (A) or hard (B) surface on which twelve 3-year-old French Trotters (6 horses/track) underwent harness race training for 4 months during the summers of 2012 and 2013 to evaluate the effect of track surface firmness on the development of musculoskeletal injuries. Peak deceleration increases as the firmness of the tested surface increases. The firmness of both tracks was tested approximately 2 times/mo throughout the study period, which resulted in a total of 15 measurement sessions for each track. During each measurement session, the soil tester (drop height, 0.45 m; weight, 2.25 kg) was applied 5 times to each of 4 systematically selected sites on each track, and the peak deceleration was recorded for each impact. For each track, the data for all 4 test sites were pooled, and the mean peak deceleration was calculated on the basis of impact order during the measurement session (1 through 5) and collectively. Thus, the mean for each impact-order category represented 60 impacts (15 test sessions X 4 sites), and the mean for each track represented 300 impacts (15 test sessions X 4 sites X 5 impacts at each site).

Table 1—Description and number of musculoskeletal lesions identified in the forelimbs and hind limbs for twelve 3-year-old French Trotters after a 4-month training period on a sand track with a soft (n = 6) or hard (6) surface.

				Soft surface		Hard surface		
Limb	**Anatomic area**	**Lesion description**	**Grade**	**Left limb**	**Right limb**	**Left limb**	**Right limb**	**Total**
Forelimb	Foot	Abnormal MRI signals of the distal interphalangeal joint cartilage	1	1	0	1	0	**2**
			2	1	0	0	0	**1**
		Bone marrow edema–type lesions observed on MRI sequences or IRU on the distal phalanx or distal sesamoid bone	2	1	0	2	4	**7**
			3	0	0	2	0	**2**
	Metacarpophalangeal joint	Bone densification or bone marrow edema–type lesions of the third metacarpal condyle	1	0	1	0	2	**3**
			2	2	1	2	1	**6**
		Synovitis of the fetlock joint	1	1	1	1	1	**4**
		Chronic synovitis	1	0	0	0	1	**1**
		Tenosynovitis of a digital sheath	1	1	0	0	0	**1**
	Metacarpus	Tendinopathy of the SDFT	1	1	1	1	0	**3**
			2	1	0	0	0	**1**
			3	0	0	0	3	**3**
			4	0	0	3	0	**3**
		Desmopathy of the suspensory ligament branches	1	1	1	1	1	**4**
			2	0	0	0	1	**1**
			3	0	0	0	1	**1**
		Peritendonitis of the SDFT	1	0	1	1	0	**2**
	Carpus	IRU on the radial carpal or third carpal bone	1	2	1	0	0	**3**
		IRU on the distal epiphysis of the radius	2	0	0	1	0	**1**
		Remodeling of the radial carpal bone	2	0	0	0	1	**1**
		and synovitis of the middle carpal joint	4	0	0	1	0	**1**
Total forelimb lesions by grade			**1**	**7**	**6**	**5**	**5**	**23**
			2	**5**	**1**	**5**	**7**	**18**
			3	**0**	**0**	**2**	**4**	**6**
			4	**0**	**0**	**4**	**0**	**4**
Hind limb	Foot	IRU on the distal phalanx or distal sesamoid bone	1	0	1	0	0	**1**
	Metatarsophalangeal joint	Bone densification or bone marrow edema–type lesions on the third metatarsal condyle	1	1	1	0	1	**2**
			2	0	0	1	2	**3**
			3	1	0	1	2	**4**
			4	0	0	1	0	**1**
		Bone marrow edema–type lesions on the proximal phalanx	3	0	1	0	0	**1**
			4	1	0	0	0	**1**
		Synovitis of the fetlock joint	1	1	1	0	1	**3**
		Tenosynovitis of a digital sheath	1	1	1	1	1	**4**
	Metatarsus	Tendinopathy of the SDFT	4	0	0	1	0	**1**
		Desmopathy of the proximal insertion of the suspensory ligament	2	0	1	0	1	**2**
		Desmopathy of the suspensory ligament branches	1	2	1	1	1	**5**
		Exostoses on the second metatarsal bone	1	0	1	0	0	**1**
	Other	IRU of the central and third tarsal bones	2	1	0	0	0	**1**
		IRU of the hock joint	2	1	0	1	0	**2**
		IRU of the patella	2	0	1	0	0	**1**
		IRU of the tibial condyle	2	0	0	1	0	**1**
Total hind limb lesions by grade			**1**	**5**	**6**	**2**	**4**	**17**
			2	**2**	**2**	**3**	**3**	**10**
			3	**1**	**1**	**1**	**2**	**5**
			4	**1**	**0**	**2**	**0**	**3**

Each lesion was assigned a grade of 1 to 4, where 1 = discrete lesion that is not clinically relevant (ie, subclinical lesion), 2 = mild lesion of discrete or mild clinical relevance, 3 = moderate lesion of mild to moderate clinical relevance, and 4 = severe lesion of moderate to severe clinical relevance.

the hard track, compared with that for the soft track **(Figure 1)**, which confirmed that the surface of the hard track was significantly firmer than the surface of the soft track.

Eighty-six musculoskeletal lesions were identified in the study horses. The type, number, and severity of lesions within each limb for horses of each treatment group were summarized **(Table 1)**. Forty-six (53%) lesions had the potential to be clinically relevant (grade, ≥ 2), of which 11 (24%) and 7 (15%) were assigned a lesion grade of 3 (moderately severe lesion) and 4 (severe lesion), respectively. The mean number of lesions per horse by lesion grade within each limb was summarized **(Figure 2)**. Overall, the mean number of forelimb lesions per horse (4.3) did not differ significantly ($P = 0.10$) from the mean number of hind limb lesions per horse (2.9). The mean number of left-limb (forelimb and hind limb) lesions per horse was greater than the mean number of right-limb lesions per horse, but that difference was not significant for any lesion grade except grade 4; the mean number of grade 4 left-limb lesions per horse (0.6) was significantly ($P = 0.01$) greater than the mean number of grade 4 right-limb lesions per horse (0). The mean number of grade 3 and grade 4 lesions per horse for the hard-track group (2.5) was significantly ($P = 0.04$) greater than that for the soft-track group (0.5). The mean number of grade 3 and grade 4 forelimb lesions per horse for the hard-track group (1.7) was significantly ($P = 0.05$) greater than that for

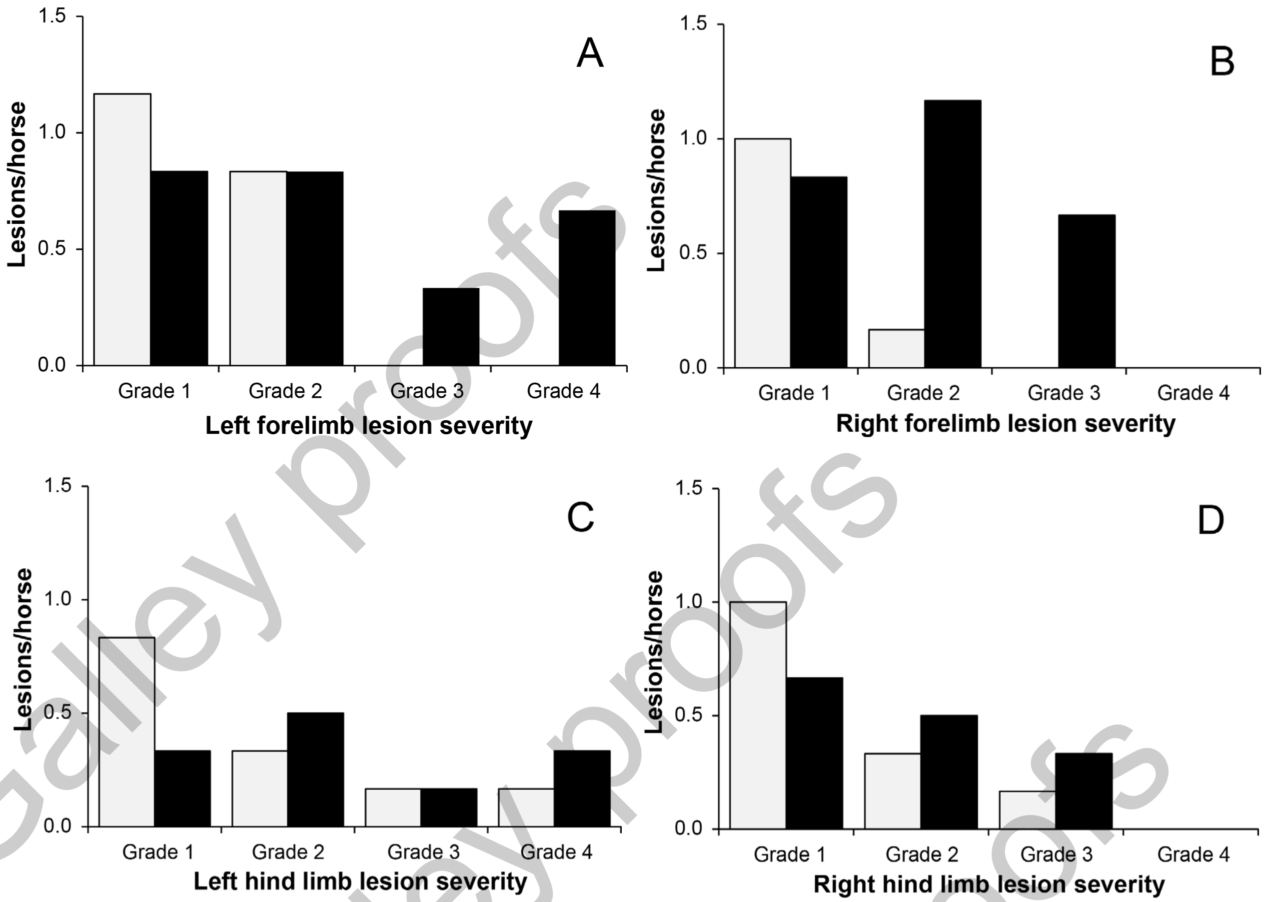

Figure 2—Mean number of lesions per horse categorized by lesion severity in the left (A) and right (B) forelimbs and left (C) and right (D) hind limbs of twelve 3-year-old French Trotters after 4 months of race training on a sand track with a soft (white bars; n = 6 horses) or hard (black bars; 6) surface. For each horse, all 4 limbs were imaged by use of radiography, scintigraphy, ultrasonography, and MRI, and the severity of each lesion identified was assigned a grade of 1 to 4, where 1 = discrete lesions that were not clinically relevant (ie, subclinical lesions), 2 = mild lesions of discrete or mild clinical relevance, 3 = moderate lesions of mild to moderate clinical relevance, and 4 = severe lesions of moderate to severe clinical relevance.

the soft-track group (0); however, the mean number of grade 3 and grade 4 hind limb lesions per horse did not differ significantly (*P* = 0.45) between the hard-track (0.8) and soft-track (0.5) groups. Likewise, the number of grade 3 and grade 4 left-limb lesions per horse for the hard-track group (1.5) was significantly (*P* = 0.04) greater than that for the soft-track (0.3) group, but the number of grade 3 and grade 4 right-limb lesions per horse did not differ significantly (*P* = 0.11) between the hard-track (1.0) and soft-track (0.2) groups.

The most common types of lesions observed were bone alterations in the distal condyles of the third metacarpal or metatarsal bones (n = 21 [soft-track group, 8; hard-track group, 13]), bone alterations in the distal phalanx or distal sesamoid bones (10 [soft-track group, 2; hard track group, 8]), and tendinopathy of the SDFT (11 [soft-track group, 3; hard-track group, 8]). The bone alterations identified in the distal condyles of the third metacarpal and metatarsal bones, distal phalanx, and distal sesamoid bones were not evident on radiographic images and were detectable only on MRI or scintigraphic images. Bone alterations consisted of spongious bone densification and bone marrow edema–type lesions. On MRI images, bone densification was characterized by focal areas of hypointense bone on T1 GRE and T2 FSE sequences and isointense bone on STIR sequences. Bone marrow edema–type lesions were characterized by areas of hyperintense bone on STIR MRI sequences and abnormally increased radiopharmaceutical uptake on scintigraphic images as described.[26,27]

Of the 21 bone lesions detected on the distal condyles of the third metacarpal or metatarsal bones, 7, 9, 4, and 1 were assigned lesion grades of 1, 2, 3, and 4, respectively (Table 1). Among the 14 lesions with grades ≥ 2, 6 and 8 involved the distal condyles of the third metacarpal and third metatarsal bones, respectively. Bone lesions on the distal condyles of the third metatarsal bones tended to be more severe **(Figure 3)** than those in the third metacarpal bones **(Figure 4)** in both treatment groups. In fact, the mean number of grade 3 and grade 4 lesions in the distal condyle of the third metatarsal bone per horse (0.4) was significantly greater (*P* = 0.05) than the mean number of grade 3 and grade 4 lesions in the distal condyle

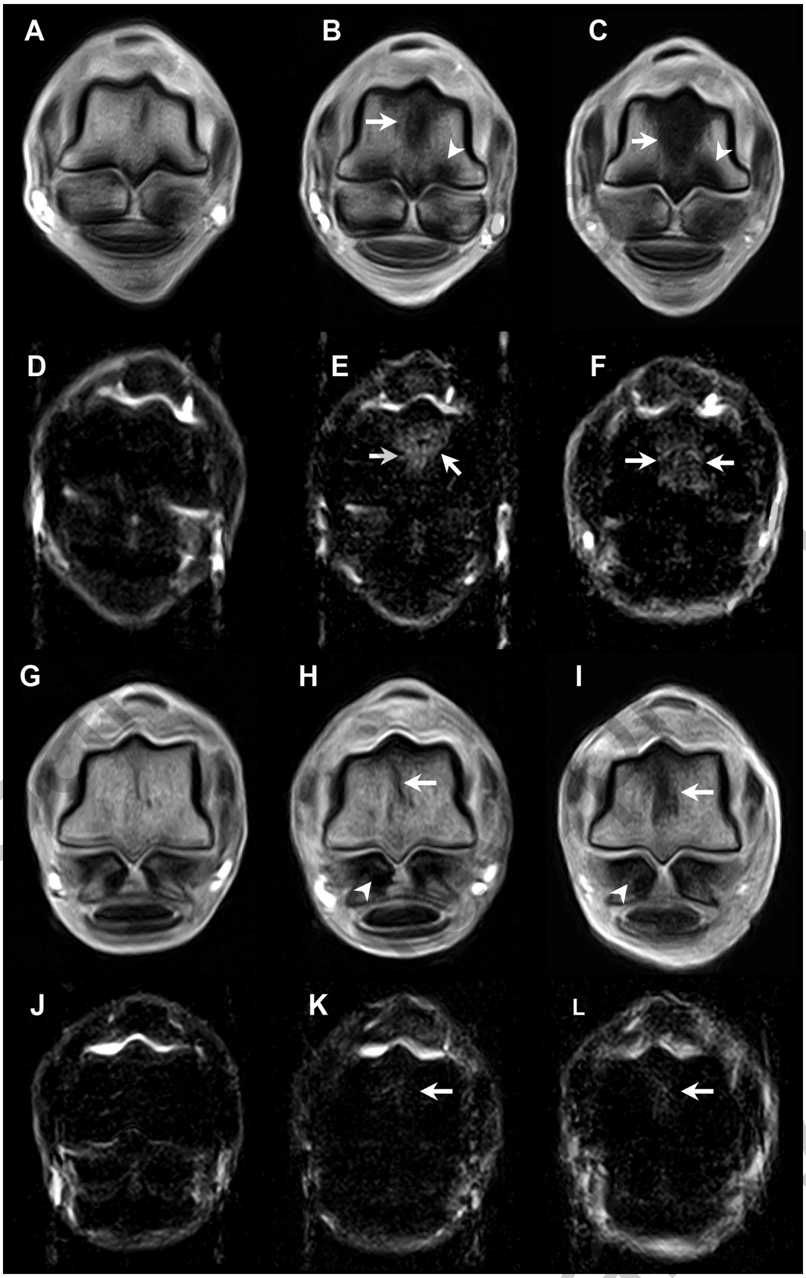

Figure 3—T1-weighted GRE (A, B, C, G, H, and I) and STIR FSE (D, E, F, J, K, and L) MRI images of the metatarsophalangeal joint of the left (A through F) and right (G through L) hind limbs obtained in the transverse plane at the level of the distal aspect of the third metatarsal bone for a 3-year-old French Trotter before (A, D, G, and J) and after 2 (B, E, H, and K) and 4 (C, F, I, and L) months of race training on a sand track with a hard surface (hard-track group), which depict the progressive development of bone marrow edema–type lesions and bone densification in the distal condyles of both the left and right third metatarsal bones. The bone marrow edema–type lesions (arrows) were characterized by focal areas of hypointense bone on the T1 GRE images and hyperintense bone on the STIR FSE images, whereas bone densification (arrowheads) was characterized by areas of hypointense bone on the T1 GRE images and isointense bone on the STIR FSE images. After 4 months of training, the lesions were classified as severe (grade 4 lesions; C and F) in the left hind limb and moderate (grade 3 lesions; I and L) in the right hind limb. Notice the bone marrow edema–type lesions developed on the dorsal aspect and bone densification developed on the plantarolateral aspect of the distal condyle of the third metatarsal bone of the left hind limb (B, C, E, and F), whereas in the right hind limb, the bone marrow edema–type lesion developed at the sagittal aspect of the distal condyle of the third metatarsal bone, and bone densification developed on the axial surface of the lateral proximal sesamoid bone (H, I, K, and L). In all panels, dorsal is to the top; medial is to the left in panels A through F and to the right in panels G through L. ***See*** Figure 2 for remainder of key.

of the third metacarpal bone per horse (0). Also, the mean number of clinically relevant (grades 2 to 4) bone lesions in the distal condyle of the third metatarsal bone per horse for the hard-track group (1.2) was significantly (P = 0.05) greater than that for the soft-track group (0.2).

Of the 10 bone lesions detected in the distal phalanx or distal sesamoid bones, 1, 7, and 2 were assigned lesion grades of 1, 2, and 3, respectively. All 7 grade 2 and 2 grade 3 **(Figure 5)** lesions were detected in the forefeet, and all but one of those lesions were in horses assigned to the hard-track group.

Of the 11 SDFT tendinopathy lesions, 3, 1, 3, and 4 were assigned lesion grades of 1, 2, 3, and 4, respectively (Table 1). All 7 grade 3 and grade 4 lesions were identified in horses of the hard-track group and were localized to the dorsal or dorsolateral aspect of the SDFT **(Figure 6)**. Moreover, all 4 grade 4 lesions were identified in a left SDFT (forelimb, n = 3; hind limb, 1), whereas all 3 grade 3 lesions were identified in the SDFT of the right forelimb. Three of the 6 horses of the hard-track group developed bilateral tendinopathy of the SDFT. In 2 of those horses, subtle lesions associated with tendinopathy of the SDFT were detectable on diagnostic images at 2 months after initiation of the training protocol; however, the horses did not develop clinical lameness until 3 and 3.5 months after initiation of the training protocol. The training program for those horses was modified as soon as they became noticeably lame, and they underwent alternating periods of rest and light jogging until the end of the scheduled 4-month training period.

Discussion

In the present study, twelve 3-year-old French Trotters underwent a 4-month period of harness race training on a sand track with either a hard or soft surface to assess the effect of track firmness on the development of musculoskeletal injuries. The 12 horses were paired on the basis of sex and body mass, and the horses within each pair were randomly assigned to either the hard-track or soft-track group. The training protocol was the same for all horses in terms of distance and speed.

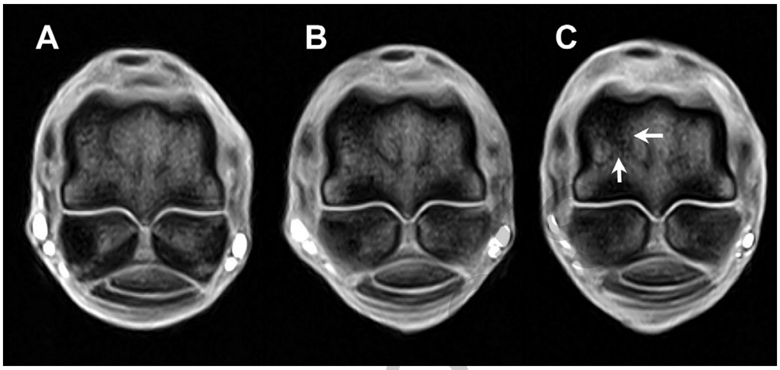

Figure 4—T1-weighted GRE MRI images of the metacarpophalangeal joint of the left forelimb obtained in the transverse plane at the level of the distal aspect of the third metacarpal bone for a 3-year-old French Trotter before (A) and after 2 (B) and 4 (C) months of race training on a sand track with a soft surface (soft-track group), which depict the progressive development of mild bone densification on the dorsomedial aspect of the distal condyle of the third metacarpal bone. Notice there was a heterogeneous and mild hypointense area characteristic of spongious bone at the dorsomedial aspect of the condyle before initiation of training (A) that became progressively larger and more evident after 2 (B) and 4 (C; grade 2 lesion [arrows]) months of training. ***See*** Figures 2 and 3 for remainder of key.

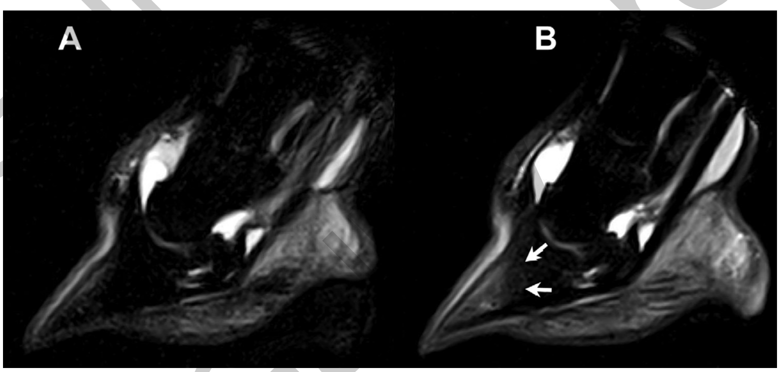

Figure 5—Short tau inversion recovery FSE MRI images of the second and third (distal) phalanges of the left forelimb obtained in the sagittal plane for a 3-year-old French Trotter before (A) and after 4 months (B) of race training on a sand track with a hard surface (hard-track group) that depict the development of a moderate (grade 3 lesion) bone marrow edema–type lesion (arrows; B) on the distodorsal aspect of the distal phalanx. ***See*** Figures 2 and 3 for remainder of key.

Diagnostic imaging of all 4 limbs of each horse was performed before and after 2 and 4 months of training, and lesion severity was graded on a scale of 0 (no lesions) to 4 (severe, clinically relevant lesion) for each limb. A total of 86 lesions were identified, of which 40 (46.5%) were classified as subclinical (grade 1) and 46 (53.5%) were potentially clinically relevant (grade ≥ 2). Thirty-seven lesions were identified in the horses of the soft-track group, of which 24 (65%) were subclinical with only 2 (5%) and 1 (3%) lesions classified as moderate (grade 3) or severe (grade 4), respectively. Forty-nine lesions were identified in the horses of the hard-track group, of which only 16 (33%) were subclinical with 9 (18%) and 6 (12%) lesions classified as moderate and severe, respectively. To our knowledge, the present study was the first controlled prospective study to identify an association between track firmness and musculoskeletal injuries in horses involved in harness racing.

To our knowledge, the present study was also the first to collect data from complementary diagnostic imaging modalities (radiography, ultrasonography, MRI, and scintigraphy) for all study horses. A main limitation of the present study was that some joints, such as the carpal and tarsal joints, were not completely assessed by the use of those modalities, and there was a potential for some lesions to remain unidentified. The lesion grading systems used for the various imaging modalities were modified from previously described systems[28–30] because the objective of the present study was to identify small and often subclinical pathological changes before the onset of lameness. For the feet, the grading system was based on STIR images because subtle musculoskeletal changes were most evident on that MRI sequence.

The surface firmness of both the hard and soft tracks was regularly monitored throughout the 4-month training period. The mean surface firmness of the hard track was 2.5 times that of the soft track overall and 3 times that of the soft track when only the first of the 5 impacts was considered. The first impact of the soil impact tester is closely correlated with the impact shock to the limbs of a horse trotting at 40 km/h.[23] When the impact measurements obtained during the present study were compared with those obtained for 7 other training surfaces for trotters by our research group (unpublished data) and described in another study,[23] the mean peak deceleration for the first impact was similar to that for the soft-track of the present study. However, the hard track used in the present study is realistic. In fact, the trainer of the present study regularly used it for training horses during the winter, but judged it to be too dry and hard to be used in the summer without intense watering.

Although the training protocol used in the present study was quite intense and had a short duration, it was representative of training protocols frequently used for young French Trotters. This protocol induced grade 2 to grade -4 musculoskeletal lesions in the limbs of horses of both the hard-track and soft-track groups. Even though lesions were more frequently identified in the forelimbs (n = 51) than in the hind limbs (35), that difference was not significant. Moreover, the proportion (35/86 [41%]) of hind limb lesions was fairly high and similar to the prevalence of hind limb lameness reported for Standard-

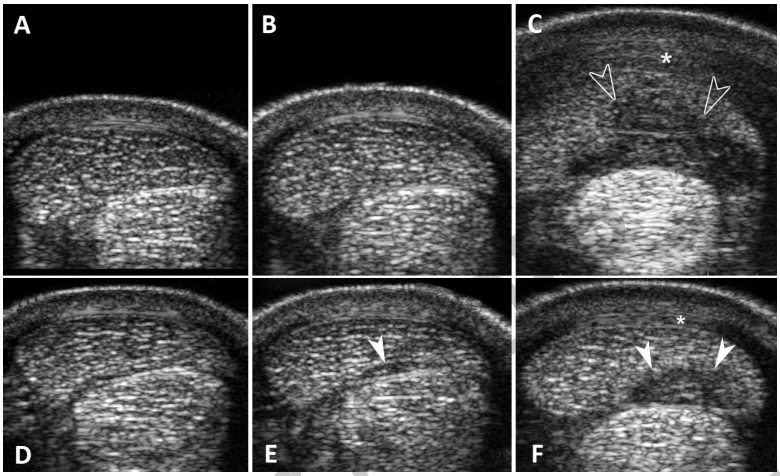

Figure 6—Ultrasonographic images of the left (A, B, and C) and right (D, E, and F) forelimbs obtained in the transverse plane at the level of the midshaft region of the third metacarpal bone for a 3-year-old French Trotter before (A and D) and after 2 (B and E) and 4 (C and F) months of race training on a sand track with a hard surface (hard-track group), which depict the progressive development of bilateral tendinopathy of the SDFT. No evidence of tendinopathy was present in either forelimb before initiation of training. In the left forelimb, severe tendinopathy (grade 4 lesion; arrowheads) was present after 4 months of training (C). In the right forelimb, mild tendinopathy (grade 2 lesion; arrowhead) was present after 2 months of training (E), which progressed to moderate tendinopathy (grade 3 lesion; arrowheads) after 4 months of training (F). The SDFT of both limbs had evidence of peritendinous swelling (*) after 4 months of training; it was moderate in the right forelimb (F) and severe in the left forelimb (C). In all panels, palmar is to the top. *See* Figure 2 for remainder of key.

breds involved in harness racing.[31,32] Incidentally, for the horses of the soft-track group, the majority (7/13 [54%]) of grade 2 to grade 4 lesions were identified in the hind limbs, which might have been associated with an increase in the propulsive effort required to pull the sulky on a soft surface.[q]

Lesions of the distal condyles of the third metatarsal bone were commonly identified in the horses of the hard-track group. In lame Standardbred racehorses,[31–33] the metatarsophalangeal joint is frequently identified as the source of the lameness. Details regarding the specific location of each musculoskeletal lesion were beyond the scope of the present study, but most of the lesions identified were considered characteristic of POD.[27,34] In Thoroughbred racehorses, cumulative race exposure and training intensity during the preceding season are positively associated with severity of POD disease, which indicates the disease is caused by repetitive loading forces.[35] Results of the present study suggested that a hard track surface may also be a risk factor for the development of POD. Although the structure, loading, and remodelling of the distal condyles of the third metacarpal and metatarsal bones have been extensively studied,[36–38] further analysis of biomechanical factors is necessary to elucidate the effect of track surface firmness on the pathogenesis of POD lesions. The longitudinal and vertical loading rates of limbs at high forces are greater on hard surfaces than on soft surfaces[22,q] and may be key factors in the development of musculoskeletal lesions in the limbs of horses involved in harness racing.

In the present study, tendinopathy of the SDFT was diagnosed more frequently than desmopathy of the suspensory ligament, which is contrary to results of studies[17,33] involving Standardbred racehorses. Suspensory desmopathy is caused by cumulative damage over weeks to months[32] and is positively associated with age.[39] The short duration of the training period combined with the young age of the horses of the present study may have contributed to the high frequency of tendinopathy of the SDFT relative to desmopathy of the suspensory ligament.

Three of the 6 horses of the hard-track group had marked to severe bilateral tendinopathy of the SDFT of the forelimbs, whereas none of the horses of the soft-track group had grade 3 or grade 4 tendinopathy of the SDFT of the forelimbs. That finding supported the results of other studies,[9,11] which indicate track surface firmness in conjunction with training or race speed is a major risk factor for tendinopathy of the SDFT. However, contrary to the results of other studies,[33,40,41] all of the SDFT lesions identified in the present study were systematically located on the dorsal or dorsolateral aspect of the tendon. Impact shock and consecutive vibrations increase with surface firmness[23,42] and may have been particularly high at the dorsal and dorsolateral aspect of the SDFT for the horses of the hard-track group and contributed to the lesion localization.

All 9 bone marrow edema–type lesions identified in the feet of the horses of the present study were categorized as grade 2 or 3 lesions and were identified in the forefeet, of which 8 were identified in the forefeet of horses of the hard-track group. Most of those lesions were of only discrete or mild clinical relevance and had no consequence on the training programs for the affected horses. Although those lesions did not induce any radiographic changes, they are important findings because repeated stress to boney structures of the foot may lead to fractures of the distal phalanx.[31,32]

In the present study, only 1 horse developed marked to severe lesions (n = 2) of the radial carpal bone with synovitis of the middle carpal joint, despite the fact that carpal lesions including fractures and sclerosis of the third carpal bone are some of the most common joint injuries reported in Standardbred racehorses.[17,31,43] The small population, short duration of the training period, and strict selection of horses on the basis of normal limb conformation for the present study may have contributed to this difference.

The most severe lesions identified in the horses of the present study most commonly developed in the left limbs, which were the limbs on the inside of the turns during race training. That finding, particularly in regards to the incidence of SDFT lesions, concurs with descriptions of musculoskeletal lesions in Thoroughbred and Arabian racehorses[44–46] and suggested that race training should be conducted in a clockwise as well as counterclockwise direction around the track.

Two of the 6 horses of the hard-track group that developed bilateral tendinopathy of the forelimb SDFT became clinically lame, and the training program for those 2 horses had to be modified (decrease in intensity), which likely resulted in underestimation of the number and severity of lesions detected in that treatment group. Despite that underestimation, the horses of the hard-track group developed a greater number and more severe limb lesions than did the horses of the soft-track group, which supported our hypothesis that the number and severity of musculoskeletal lesions in both the forelimbs and hind limbs of horses trained on the hard sand track would be greater than those of horses trained on the soft sand track.

Results of the present study indicated that horses involved in harness racing and trained on a track with a hard surface developed a greater number of lesions and lesions of greater severity than did similar horses trained on a track with a soft surface. This confirmed that track surface firmness is a risk factor for musculoskeletal injuries in horses trained for harness racing.

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The authors declare that there were no conflicts of interest.

Footnotes

a. Novarea, Gellainville, France.
b. Clegg impact soil tester (2.25-kg hammer weight), SD Instrumentation Ltd, Tellisford, Bath, England.
c. T100, TimerGPS, Oulu, Finland.
d. Detogesic, Zoetis, Malakoff, France.
e. Torbugesic, Zoetis, Malakoff, France.
f. Sadra Radiologie, Montabard, France.
g. EDR3-Mark II, Sound-Eklin, Carlsbad, Calif.
h. Teceos, CisBio International, Paris, France.
i. Dimazon, MSD Santé Animale, Beaucouzé, France.
j. CDM Lavoisier, Paris, France.
k. Millenium MPR, General Electric Healthcare, Waukesha, Wis.
l. MatLab, Math Works, Natick, Mass.
m. Aloka ProSound Alpha10, Hitachi Medical Systems Europe Holding AG, Zug, Switzerland.
n. EQ2, Hallmarq Veterinary Imaging Ltd, Guildford, Surrey, England.
o. IQ-viewer Pro, version 2.6.0, Image Information Systems Europe GmbH, Rostock, Germany.
p. SAS, version 9.2, SAS Institute, Cary, NC.
q. Crevier-Denoix N, et al. Projet SafeTrack: analyses des résultats (oral presentation). Equimeeting, Le Haras du Pin, France, September 2015.

References

1. Moyer W, Spencer PA, Kallish M. Relative incidence of dorsal metacarpal disease in young Thoroughbred racehorses training on two different surfaces. *Equine Vet J* 1991;23:166–168.
2. Verheyen KL, Newton JR, Price JS, et al. 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.
3. Arthur RM. Comparison of racing fatality rates on dirt, synthetic, and turf at 4 California racetracks, in *Proceedings*. 56th Annu Conv Am Assoc Equine Pract 2010;56:405–408.
4. Murray RC, Walters JM, Snart H, et al. Identification of risk factors for lameness in dressage horses. *Vet J* 2010;184:27–36.
5. Parkin TD. Track surfaces and lameness: epidemiological aspects of racehorse injury. In: Ross MW, Dyson SJ, eds. *Diagnosis and management of lameness in the horse*. 2nd ed. St Louis: Elsevier Saunders, 2011;972–977.
6. Dimock AN, Hoffman KD, Puchalski SM, et al. Humeral stress remodelling locations differ in Thoroughbred racehorses training and racing on dirt compared to synthetic racetrack surfaces. *Equine Vet J* 2013;45:176–181.
7. MacKinnon MC, Bonder D, Boston RC, et al. 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.
8. Bailey CJ, Reid SW, Hodgson DR, et al. Flat, hurdle and steeple racing: risk factors for musculoskeletal injury. *Equine Vet J* 1998;30:498–503.
9. Williams RB, Harkins LS, Hamond CJ, et al. Racehorse injuries, clinical problems and fatalities recorded on British racecourses from flat racing and National Hunt racing during 1996, 1997 and 1998. *Equine Vet J* 2001;33:478–486.
10. Parkin TD, Clegg PD, French NP, et al. Race- and course-level risk factors for fatal distal limb fracture in racing Thoroughbreds. *Equine Vet J* 2004;36:521–526.
11. Reardon RJ, Boden LA, Mellor DJ, et al. Risk factor for superficial digital flexor tendon tendinopathy in Thoroughbred racehorses in hurdle starts in the UK (2001–2009). *Equine Vet J* 2012;44:564–569.
12. Young DR, Nunamaker DM, Markel MD. Quantitative evaluation of the remodeling response of the proximal sesamoid bones in training-related stimuli in Thoroughbreds. *Am J Vet Res* 1991;52:1350–1356.
13. Nunamaker DM. Relationships of exercise regimen and racetrack surface to modeling/remodeling of the third metacarpal bone in two-year-old Thoroughbred racehorses. *Vet Comp Orthop Traumatol* 2002;15:195–199.
14. Ely ER, Avella CS, Price JS, et al. Descriptive epidemiology of fracture, tendon and suspensory ligament injuries in National Hunt racehorses in training. *Equine Vet J* 2009;41:372–378.
15. Ramzan PH, Palmer L. Musculoskeletal injuries in Thoroughbred racehorses: a study of three large training yards in Newmarket, UK (2005–2007). *Vet J* 2011;187:325–329.
16. Reed SR, Jackson BF, McIlwraith CW, et al. Descriptive epidemiology of joint injuries in Thoroughbred racehorses in training. *Equine Vet J* 2012;44:13–19.
17. Bertuglia A, Bullone M, Rossotto F, et al. Epidemiology of musculoskeletal injuries in a population of harness Standardbred racehorses in training. *BMC Vet Res* 2014;10:11.
18. Robin D, Chateau H, Pacquet L, et al. Use of a 3D dynamometric horseshoe to assess the effects of an all-weather waxed and a crushed sand track at high-speed trot. *Equine Vet J* 2009;41:253–256.
19. Setterbo JJ, Garcia TC, Campbell IP, et al. Hoof accelerations and ground reaction forces of Thoroughbred racehorses measured on dirt, synthetic, and turf track surfaces. *Am J Vet Res* 2009;70:1220–1229.
20. Crevier-Denoix N, Robin D, Pourcelot P, et al. Ground reaction force and kinematic analysis of limb loading on two different beach sand tracks in harness trotters. *Equine Vet J Suppl* 2010;42:544–551.
21. Crevier-Denoix N, Pourcelot P, Holden-Douilly L, et al.

Discrimination of two racing surfaces based on forelimb dynamic and hoof kinematic variables at the canter. *Vet J* 2013;198(suppl 1):e124–e129.
22. Munoz-Nates F, Pourcelot P, Ravary-Plumioen B, et al. Comparison of track surfaces with two different foundations: effects on the dynamic variables measured in one harness horse at a training trot. *Equine Vet J Suppl* 2016;48:38.
23. Munoz-Nates F, Chateau H, Van Hamme A, et al. Accelerometric and dynamometric measurements of the impact shock of the equine forelimb and hind limb at high speed trot on six different tracks—preliminary study in one horse. *Comput Methods Biomech Biomed Engin* 2015;18(suppl 1):2012–2013.
24. American Association of Equine Practitioners. AAEP Lameness scale. Available at: www.aaep.org/info/horse-health?publication=836. Accessed Jul 13, 2016.
25. Didierlaurent D, Contremoulins V, Denoix JM, et al. Scintigraphic pattern of uptake of 99mTechnetium by the cervical vertebrae of sound horses. *Vet Rec* 2009;164:809–813.
26. Powell S. The fetlock region. In: Murray RC, ed. *Equine MRI*. Ames, Iowa: Wiley-Blackwell, 2011;315–359.
27. Powell SE. Low-field standing magnetic resonance imaging findings of the metacarpo/metatarsophalangeal joint of racing Thoroughbreds with lameness localised to the region: a retrospective study of 131 horses. *Equine Vet J* 2012;44:169–177.
28. Rantanen NW, Jorgensen JS, Genovese RL. Ultrasonographic evaluation of the equine limb: technique. In: Ross MW, Dyson SJ, eds. *Diagnosis and management of lameness in the horse*. 2nd ed. St Louis: Elsevier Saunders, 2011;182–205.
29. Reef VB. Musculoskeletal ultrasonography. In: Reef VB, ed. *Equine diagnostic ultrasound*. St Louis: WB Saunders Co, 1998;39–186.
30. Smith MA, Dyson SJ, Murray RC. Reliability of high- and low-field magnetic resonance imaging systems for detection of cartilage and bone lesions in the equine cadaver fetlock. *Equine Vet J* 2012;44:684–691.
31. Torre F, Ross MW. Lameness in the Standardbred horse. *J Equine Vet Sci* 2002;22:429–436.
32. Mitchell JB, Mitchell JS, Nolan PM, et al. The North American Standardbred. In: Ross MW, Dyson SJ, eds. *Diagnosis and management of lameness in the horse*. 2nd ed. St Louis: Elsevier Saunders, 2011;1014–1036.
33. Torre F. The European Standardbred. In: Ross MW, Dyson SJ, eds. *Diagnosis and management of lameness in the horse*. 2nd ed. St Louis: Elsevier Saunders, 2011;1036–1047.
34. Barr ED, Pinchbeck GL, Clegg PD, et al. Post mortem evaluation of palmar osteochondral disease (traumatic osteochondrosis) of the metacarpo/metatarsophalangeal joint in Thoroughbred racehorses. *Equine Vet J* 2009;41:366–371.
35. Pinchbeck GL, Clegg PD, Boyde A, et al. Horse- training- and race-level risk factors for palmar/plantar osteochondral disease in the racing Thoroughbred. *Equine Vet J* 2013;45:582–586.
36. Riggs CM, Whitehouse GH, Boyde A. Structural variation of the distal condyles of the third metacarpal and third metatarsal bones of the horse. *Equine Vet J* 1999;31:130–139.
37. Rubio-Martínez LM, Cruz AM, Gordon K, et al. Structural characterization of subchondral bone in the distal aspect of third metacarpal bones in Thoroughbred racehorses via micro–computed tomography. *Am J Vet Res* 2008;69:1413–1422.
38. Bani Hassan E, Mirams M, Ghasem-Zadeh A, et al. Role of subchondral bone remodelling in collapse of the articular surface of Thoroughbred racehorses with palmar osteochondral disease. *Equine Vet J* 2016;48:228–233.
39. Kasashima Y, Takahashi T, Smith RK, et al. Prevalence of superficial digital flexor tendonitis and suspensory desmitis in Japanese Thoroughbred flat racehorses in 1999. *Equine Vet J* 2004;36:346–350.
40. Denoix JM, Mialot M, Levy L, et al. Etude anatomo-pathologique des lésions associées aux images échographiques anormales des tendons et ligaments chez le cheval. *Rec Méd Vét* 1990;166:45–55.
41. Dyson SJ. Ultrasonographic evaluation of the metacarpal and metatarsal regions in the horse. *Equine Vet Educ* 1992;4:139–144.
42. 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;42:488–495.
43. Steel CM, Hopper BJ, Richardson JL, et al. Clinical findings, diagnosis, prevalence and predisposing factors for lameness localised to the middle carpal joint in young Standardbred racehorses. *Equine Vet J* 2006;38:152–157.
44. Rooney JR, Genovese RL. A survey and analysis of bowed tendon in Thoroughbred racehorses. *J Equine Vet Sci* 1981;1:49–53.
45. Lam KH, Parkin TD, Riggs CM, et al. Descriptive analysis of retirement of Thoroughbred racehorses due to tendon injuries at the Hong Kong Jockey Club (1992–2004). *Equine Vet J* 2007;39:143–148.
46. Kalisiak O. Parameters influencing prevalence and outcome of tendonitis in Thoroughbred and Arabian racehorses. *Pol J Vet Sci* 2012;15:111–118.

Appendix 1

Outline of the 4-month (16-week) training protocol used in a study to evaluate the effect of track surface firmness on the development of musculoskeletal injuries in twelve 3-year-old French Trotters.

Week	Distance and speed for each training session
1 to 2	10,000 m at 25 km/h.
3 to 5	5,000 m at 25 km/h and 5,000 m at 30 km/h.
6 to 9	5,000 m at 25 km/h and 5,000 m at 35 km/h.
10 to 11	5,000 m at 25 km/h and 5,000 m at 37.5 km/h.
12 to 13	5,000 m at 25 km/h and 5,000 m at 40 km/h.
14 to 16	5,000 m at 25 km/h followed by two 2,000-m segments at 35–40 km/h. Within each of those 2 segments, 200 m were ran at a maximal speed (ie, between 40 and 45 km/h).

Six horses were evaluated during the summer of 2012 and the remaining 6 horses were evaluated during the summer of 2013. Horses were paired on the basis of sex and body mass. Within each pair, horses were randomly assigned to 1 of 2 treatment groups (ie, were trained on a sand track with either a hard or soft surface). Horses in both treatment groups were trained by the same professional trainer for 4 months and were trained exclusively on the assigned track. Horses were trained 3 times/wk throughout the training period, except for week 9 during which horses underwent midprotocol clinical and imaging examinations and were trained only twice. Horses were maintained in paddocks when they were not being trained. Each training session except for those during weeks 14 to 16 consisted of a 5,000-m warm-up period followed by a 5,000-m work period as outlined.

Appendix 2

Technical parameters used for the various MRI sequences obtained for each metacarpophalangeal and metatarsophalangeal (fetlock) joint and both forefeet of the horses in Appendix 1.

Anatomic region	MRI sequence	Plane	Repetition time (ms)	Echo time (ms)	Inversion time (ms)	Flip angle (°)	Slice thickness (mm)	Space between slices (mm)	Matrix (pixels)	Field of view (mm)
Fetlock joint	T1 GRE	Transverse and sagittal	50	8	—	55	5	6	256 X 256	160
	STIR FSE	Transverse and sagittal	2,000	22	95	90	5	6	256 X 256	170
	T2 FSE MI	Transverse	1,544	88	—	90	5	6	256 X 256	170
Forefoot	T1 3-D GRE HR	Frontal	24	8	—	40	2.5	—	512 X 512	170
	T1 3-D GRE	Transverse	23	7	—	40	4	—	256 X 256	170
	T2 FSE	Transverse	1,681	88	—	90	5	6	256 X 256	170
	T2*oW 3-D GRE HR	Frontal	33	13	—	26	2.5	—	512 X 512	170
	STIR FSE	Sagittal	3,220	27	95	90	5	6	256 X 256	170

All horses underwent MRI examination before initiation, during week 9, and at the completion of the 4-month training protocol. The forefeet were scanned only for the 6 horses evaluated in 2013. The inversion time for the STIR FSE sequence varied depending on the horse and conditions of examination (preset value of the inversion time in the system = 95 milliseconds), and the optimal inversion time was set by use of the STIR TEST sequence acquired just prior to the STIR FSE sequence.

— = Not applicable. T1 3-D GRE HR = High-resolution T1 3-D GRE. T2 FSE MI = T2 FSE with motion correction. T2*oW 3-D GRE HR = High-resolution T2 3-D GRE out of phase.

Appendix 3

Grading system used to evaluate severity of musculoskeletal lesions observed on ultrasonographic images of the horses of Appendix 1.

Grade	Definition
0	No lesions observed (clinically normal).
1	Discrete focal hypoechoic lesion.
2	Mild hypoechoic to anechoic lesion that involves < 10% of the cross-sectional area of a tendon and extends < 2 cm in a proximodistal manner.
3	Moderate hypoechoic to anechoic lesion that involves < 30% of the cross-sectional area of a tendon and extends 2 to 6 cm in a proximodistal manner.
4	Severe, mostly anechoic lesion that involves ≥ 30% of the cross-sectional area of a tendon and extends > 6 cm in a proximodistal manner.

Appendix 4

Grading system used to evaluate severity of musculoskeletal lesions observed on MRI sequences of the horses of Appendix 1.

	Definition		
	Distal condyles of the third metacarpal or metatarsal bones and PSBs		Distal phalanx
Grade	T1 sequences	STIR sequences	STIR sequences
0	No lesions observed.	No lesions observed.	No lesions observed.
1	Focal or mild decrease in SI adjacent to subchondral bone, more prominent focal lines of low SI consistent with focally increased trabeculare bone density.	No lesions observed.	Focal or mild increase in SI along the dorsal margin (parietal surface).
2	Limited zone of mild decrease in SI that affects < 25% of the metacarpal or metatarsal condyle, or mild decrease in SI of the trabecular bone of the PSBs.	Focal zone or mild increase in SI.	Increase in SI on the dorsal margin to the dorsal aspect of the semilunar sinus.
3	Decrease in SI that affects between 25% and 50% of the metacarpal or metatarsal condyle, or moderate decrease in SI of the trabecular bone of the PSBs.	Local zone of increased SI that affects < 25% of the metacarpal. or metaytarsal condyle, or moderate increase in SI of the PSBs.	Increase in SI that extends from the body of the distal phalanx up to the semilunar line.
4	Wide zones of markedly decreased SI that affects > 50% of the metacarpal or metatarsal condyle, or a severe decrease in SI of the trabecular bone of the PSBs.	Wide zones of increased SI that affects ≥ 25% of the metacarpal or metatarsal condyle or severe increase of the PSBs.	Marked increase in SI that extends in a palmar direction from the dorsal margin of the phalanx to the semilunar line.

PSB = Proximal sesamoid bone. SI = Signal intensity.