

Epidemiology of racing injuries in Thoroughbred racehorses with special reference to bone fractures: Japanese experience from the 1980s to 2000s

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This report describes the descriptive epidemiology of racing fractures that occurred from the 1980s to 2000s on racetracks of the Japan Racing Association (JRA). The incidence of racehorse fractures during flat racing was approximately 1–2%. Fractures occurring during a race are more likely to occur in a forelimb. Fractures mostly occur at the third and fourth corners of oval tracks and on the home stretch. They also occur more frequently at the time of changing the leading limb. Comparison of the incidence of racing fracture between before and after reconstruction of the geometrical configuration of a racetrack revealed that there was an outstanding reduction in the number of serious fractures in the year before and after reconstruction. It was postulated that the improvement in racing time, possibly influenced by reconstructing the geometrical configuration of the racetrack, was connected to the reduction in the number of fractures. Of non-biological race- and course-related factors, type of course (dirt or turf), track surface condition, differences between racecourses, and racing distance significantly influence racing time. By using an instrumented shoe, vertical ground reaction forces (VGRFs) on the forelimb during galloping and the relationships between a rough dirt and woodchip track surface and a smooth dirt and woodchip surface were measured. Relating the incidence of racing fractures with track conditions in general showed that track surface has significant effects on the incidence of fracture, with the incidence of fractures increasing as track conditions on dirt worsen and a tendency for the incidence of fractures to decrease as track conditions on turf worsen. It seems probable that track condition in general may affect the incidence of fracture. The incidence of fracture in horses during both racing and training decreased as the years progressed.

Key words: bone fracture, epidemiology, racing injury, Thoroughbred racehorse

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Background

Bone fractures in racehorses are the most commonly occurring problem in the racing industry worldwide [46, 62, 109, 111]. Historical background and epidemiologic studies of fracture in racehorses have been well reviewed by Clegg [18], Parkin [94, 95], Riggs [108], Stover [118], and Verheyen [132].

Many studies of fractures in racehorses have been conducted around the world. However, there are significant differences in non-biological (race- and course-related)

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factors between Western countries and Japan in terms of horseracing, climate, racetrack shape, track surface components, race distance, number of runners, and horseshoes utilized. It is difficult to directly introduce and apply the data and findings from investigational studies in Western countries to the horse racing industry in Japan because of differences in risk factors at the country or regional level. For the purpose of addressing this problem, the Japan Racing Association (JRA) formed the Japanese Committee on the Prevention of Accidents to both jockeys and racehorses in April 1983 which is composed of veterinarians, facility managers, trainers, and jockeys. Up until the early 2000s, this committee conducted investigations to grasp the real conditions regarding the occurrence of fractures during races or training and to implement appropriate countermeasures in Japan. These investigations mainly focused on patterns and risk factors specific for bone fractures during flat racing. Compared with the published scientific articles on bone fracture and epidemiology of bone fracture in Thoroughbred racehorses on flat racetracks in Western countries, there have been few epidemiological studies of the effects of non-biological factors on locomotive injuries during racing and training on Japanese flat racetracks [53–56, 58, 83, 119, 125].

Horse Racing in Japan

The organization of horse racing in Japan and the structure of the JRA have been described in a previous report [78]. In summary, the JRA holds races at 10 race courses across Japan on oval-shaped courses primarily on weekends, with a total of 288 racing days per year. Thoroughbred horses race in a clockwise direction on eight tracks and counterclockwise on two tracks. The percentages of flat races run on turf courses and dirt courses during the period of review were 51.5% and 48.5%, respectively. Flat racing is conducted on both turf and dirt courses throughout the year. Training of Thoroughbred horses not at racecourses takes place on turf, dirt, and wood chip courses at two training centers: the Miho Training Center in eastern Japan and the Ritto Training Center in western Japan. About 4,400 racehorses are managed, stabled, and trained at the two training centers. On racing days, the horses are transported in vans to race courses nationwide, where race meetings are held. The JRA holds two types of horse races: Thoroughbred flat races and Thoroughbred jumping races (steeplechases). Over 95% of all races held during the racing calendar are Thoroughbred flat races. In Europe and the U.S.A., training takes place on turf and sand courses, American dirt courses, and artificial or synthetic tracks (sometimes referred to as all-weather or man-made tracks).

Track Surface Condition as Defined by the JRA

The components of a JRA turf course (10–12 cm Japanese lawn grass over 30–50 cm sandy soil) is similar to those of turf courses used by the New York Racing Association (NYRA) (12–14 cm tall fescue or Kentucky bluegrass over 25 cm sandy soil) [37, 38]. The components of a Japanese dirt course (7–8 cm cushion sand layer over hard substrate; thus, in Japan, it might be preferable to refer to it as a sand course rather than a dirt course) differs from those of dirt courses used in Western countries, such as those used by the NYRA (10–12 cm cushion sandy loam layer over a 25–27 cm base layer mixed with clay/silt/sand; thus, referred to as a dirt course) [37, 38]. The cushion sand used by the JRA is composed of river sand, which is of a fine particle size with a narrow particle size distribution [66].

Track surface conditions are classified by four grades according to the levels of moisture in the track for both Japanese dirt courses and turf courses, as follows [66].

Japanese Dirt Courses

Fast: dry

Good: some residual moisture

Muddy: very moist due to high water content

Sloppy: slippery due to excessive water content

Turf Courses

Firm: dry or slight moisture

Good: good amount of moisture

Yielding: very wet course that produces slower racing times

Soft: water-logged course that produces very slow racing times

Track Surface Maintenance Equipment

The JRA has developed different kinds of track surface maintenance equipment in order to maintain the uniformity of hardness and evenness of track surfaces. The rationale for doing so is based on the results of studies indicating that the incidence of racing fractures depends on the track surface condition [6, 7, 15, 16, 133, 136] as well as data suggesting the significance of track surface maintenance in prevention of racing and training injury (unsoundness) in horse [48, 99, 108, 118]. These findings emphasize the importance of maintaining appropriate track hardness so as to maintain its cushioning effect.

The JRA developed a track hardness measuring vehicle that is equipped to determine a track's hardness and sand thickness, and has instrumentation for analysis of the data

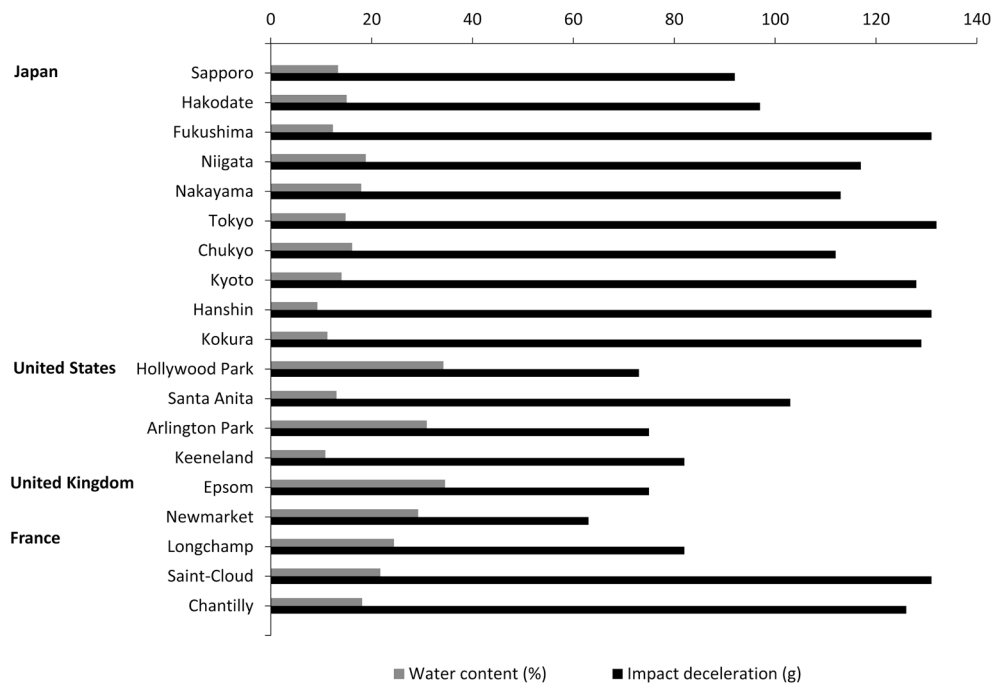


Fig. 1. Impact deceleration values at various JRA turf tracks and Western courses. Track hardness is expressed as impact deceleration value (g) measured using the JRA racetrack hardness measurement vehicle. Reference data for the U.S.A., U.K., and France are also shown. The data were collected in 1995–1996 outside of the racing season.

it collects [80]. Attached to the rear of the vehicle is an arm that is one meter long. At the end of this arm is a piezo-electric accelerometer, to which a 6 kg weight is attached. The principle of tracks measurements is fundamentally the same as that of a type of lightweight drop test apparatus [16]. The arm is thrust out, mechanically assisted by a spring, and the weight attached to the accelerometer makes contact with the track surface [80]. The impact deceleration is recorded by the data recorder [80]. This track hardness measuring vehicle indicates the hardness distribution of the track, i.e., deceleration at impact of the track in units of g (9.8 m/s^2) [80]. Measurements are made at 5-m intervals around the entire track [80]. The vehicle is used to determine how deceleration at impact changes when track conditions change from firm to soft on turf and from fast to sloppy on dirt [80]. Based on these data, an automatic water sprinkler is used to supply water to turf courses that require moisture to maintain grass growth. To eliminate excessive water on the track surface, a water absorption cross-channel roller is used [80]. A vehicle equipped with a rake is used to rake up accumulated sand away from the side rails.

Comparison of Racetrack Properties in Japan with Those of European and American Racetracks

It has often been suggested by people involved in horse racing in foreign countries that turf courses in Japan are hard. The JRA conducted a survey of track conditions by using the track hardness measuring van mentioned above at nine racecourses in Europe and North America during the period of 1992 to 1997 and outside of the racing season [66, 80]. The racecourses studied were Hollywood Park, Santa Anita, Arlington, and Keeneland in the United States of America (U.S.A.), Epsom and Newmarket in the United Kingdom of Great Britain and Northern Ireland (U.K.), and Longchamp, Saint Cloud, and Chantilly in the French Republic (France) (Fig. 1) [66]. Compared with the standard hardness of the JRA racecourses, 80 to 130 G, measured on non-race days, those of Saint Cloud and Chantilly in France were higher, while those of Keeneland, Arlington, and Hollywood Park in the U.S.A., Epsom and Newmarket in the U.K., and Longchamp in France were lower (Fig. 1).

Data Collected on Racing Fractures

For this review, data on fractures occurring during flat racing, track conditions, and racing time were retrieved

from both the annual JRA report on racehorse hygiene [121] and the Racehorse Information Management System, which manages information about medical care and race records of JRA-registered horses kept on a computerized database (M880/180 mainframe computer, host; WS3050RX, terminal; Hitachi, Ltd., Tokyo, Japan) [83]. A case was defined as any horse with an acute bone fracture that occurred during a race and then failed to race for three months or longer from the date of the fracture or was permanently retired, was euthanized, or died. Regardless of the severity of the fracture, i.e., ranging from compound catastrophic fractures to mild chip fractures, only cases that were confirmed as bone fractures by radiography and/or ultrasound were included in this data set. Cases that were diagnosed only on clinical presentation were not included.

Outline of Research on Racing Fractures in Thoroughbred Horses

In 2000, Professor Andrew F. Clarke in Melbourne University was charged with developing a project entitled "Epidemiology and risk factor analysis of racetrack fatalities" in Victoria, Australia [17]. A report of the project was published on a website [17]. The purpose of the project was to minimize the risks of occurrences such as falling in both jockeys and racehorses during racing, as well as to identify predisposing causes of future injury [17]. One of the clear messages from this project was that racing and training on firmer turf track surfaces might result in a greater risk of musculoskeletal injury in horses as well as increased risk for the jockeys riding them [17]. This project was followed by a Havemeyer Foundation Workshop entitled the "Epidemiology of Training and Racing Injuries," which was held over two days in 2005 in Melbourne, Australia [94]. In this first international symposium, experts from racing jurisdictions in the U.K., Japan (JRA), Macau, Australia, the U.S.A., Hong Kong, and New Zealand presented papers [94]. This meeting identified exercise measurements, case definitions, control selection, and racetrack rating as key issues for future research [94].

Current research on equine epidemiology is moving away from descriptive studies to analytical epidemiological studies to identify the causes of and risk factors for racing injuries [11]. Thus, there have been an increasing number of studies using analytical techniques to identify risk factors for racing injuries; these are mainly musculoskeletal injuries, but include cardiac sudden death, paroxysmal atrial fibrillation, and epistaxis, as well as miscellaneous and fatal injuries of unknown causes, with many focused on catastrophic or fatal injuries (resulting in the horse's direct death or euthanasia) due to racing fractures [6, 7, 10, 14, 24–28, 36, 41, 47, 63, 68, 69, 88–93, 133]. However, the

data concerning the incidence of and risk factors for racing musculoskeletal injuries are still somewhat controversial at the present time, thus leading to no definitive conclusions.

In general, musculoskeletal injuries from training and racing on flat racetracks are multifactorial events that involve the complex interaction of a number of risk factors including both biological (horse-related) factors and non-biological (extrinsic or environmental) factors. Biological risk factors include such things as subclinical/undiagnosed pre-existing bone and suspensory apparatus pathology (pathologic fracture) [92], biomechanical failure of cortical bone due to loading at strain rates during galloping [29], anatomical range of movement of the carpal joint in the case of carpal fracture [1], inherent leg conformation (long pastern as a risk factor for forelimb fracture) [3], hoof conformation (hoof-heel angle) [117], pre-race physical inspection [21, 22, 31], age and gender [4, 7, 10, 14, 20, 23, 25, 26, 28, 36, 69, 97, 118, 133], dam age and parity [131], trace elements [64], and endocrine pathology [64, 140]. The concept of pathologic fractures [64, 92, 105, 106, 133] incorporates such factors as osteochondral lesions beneath the articular cartilage (osteochondrosis) [92], traumatic osteochondrosis [9, 100], focal osteopetrosis [64], focal osteochondral necrosis/sclerosis [52, 54, 71, 74, 92], and macroscopic subchondral cracks in the condylar groove resulting from accumulation and coalescence of nanoscale microcracks [116] in the case of distal condylar fractures of the metacarpus/metatarsus (intra-articular fracture) and stress fracture due to continued repetitive overuse of fatigued bone tissue, e.g., fracture of the diaphysis of the scapula, humerus, metacarpus, thoracic and lumbosacral vertebrae, pelvis, and tibia [33–35, 117], pre-existing focal excessive bone remodeling and porosity in the proximal sesamoid bone leading to complete fracture [5], and pre-existing mild suspensory apparatus and tendon of the superficial digital flexor muscle injury as a predisposing factor for severe proximal sesamoid bone and metacarpal condylar fracture [21, 39–41, 55]. Non-biological risk factors include such things as training regimen [4, 12, 14, 19, 20, 24, 25, 27, 41, 45, 72, 89, 95, 97, 128, 129], shoe type [50], racetrack effect (geometrical configuration, e.g., radius of turns, angle of banking) [76], track rating [10], track surface type (dirt, turf, all-weather), racetrack surface condition [7, 10, 15, 37, 38, 62, 73, 90, 118, 130, 134, 137], training and racing longer since the horse's last layup (resting period) [4, 10, 14, 27, 36], greater cumulative distance and exercise intensity for the horse's racing and training career [4, 10, 23, 25, 27, 40, 89, 95, 129, 130], racing speed/time [76, 83], field size (number of runners in a race) [6, 91], racehorse's barrier position in the starting gate/post [6], stretch turn position (final turn) [135], number of turns [96], class of race (e.g., claiming race vs. maiden race) [6, 22], race type (e.g., flat

Table 1. Sites of locomotor injuries in JRA racehorses during training and racing (% , 1987–1996)

	Total number	Fracture				Soft tissue injury
		Limb	(Forelimb)	(Hind limb)	Other (skull, spine, etc.)	(dislocation, tendon injury)
Training	10,710	97.3	(71.9)	(25.4)	0.8	1.9
Racing	8,484	90.6	(78.1)	(12.5)	0.3	9.1

racing vs. National Hunt racing) [7, 28, 88, 134], racing progress [93, 125], jockey (professional vs. nonprofessional, i.e., amateur or conditional jockeys) [91], racing in a later race [69], number of starts per year at a racetrack [69], total number of starts at a racetrack [69], season (summer vs. winter) [69], and single-event overload (e.g., crush against the fence).

Research on Bone Fractures at the JRA Equine Research Institute

Differing from the investigation by the Committee on the Prevention of Accidents to Racehorses, the JRA Equine Research Institute has conducted considerable research on the biological risk factors for bone fracture. Of these, condylar fracture of the third metacarpus/metatarsus is the most common catastrophic fracture. The major areas of research have focused on condylar fracture of the third metacarpus/metatarsus [52–55, 74, 77, 122–124, 138, 139], carpal fracture [1], fracture-like condition in fibulae [51], tibial fracture [33], avulsion fracture in the radial tuberosity [79], bucked shins [58, 59, 75], epiphysitis [30, 126], the molecular biology of bone [57], and bone metabolism [44]. Regarding this research, it is especially noteworthy that the 1980 publication of Kaneko *et al.* was the first to emphasize that a pre-existing lesion (focal osteochondral sclerosis/necrosis beneath the articular cartilage) is a precursor of parasagittal fractures of the distal condyles of the metacarpus (McIII) and metatarsus (MtIII) (so-called “condylar fractures of the metacarpus/metatarsus”) [52]. So far, these fracture have been regarded as spontaneous or accidental fractures, although Rooney in the U.S.A. proposed a simple biomechanical hypothesis concerning the pathogenesis of condylar fracture of the metacarpus/metatarsus without any experimental evidence in 1974 [110]. Subsequently, researchers in Western countries have shown remarkable evidence of pre-existing bone disease, i.e., pathologic fracture, particularly in condylar fractures of the third metacarpus/metatarsus due to pre-existing bone pathology [9, 13, 64, 71, 105–108, 116, 133], fracture of the humerus, tibia, and pelvis due to pre-existing stress fracture [14, 34, 35, 117, 130], and proximal sesamoid bone fracture due to pre-existing bone, suspensory apparatus, and locomotor-related

neuronal pathology [4, 5], as the major risk determinants for potentially catastrophic fractures.

Outline of Fractures during Training and Racing in the JRA

The total number of musculoskeletal injuries that occurred in training and races during the period of 1987 to 1996 is shown in Table 1 [121]. The majority of fractures occurred in legs, particularly in forelimbs, during both racing and training (Table 1) [121]. Force plate data showed significantly greater vertical loading rates and horizontal loads in the forelimb than the hind limb during trotting [32]. There are details to be clarified regarding mechanisms leading to differences in injuries between forelimbs and hind limbs. The total number of fractures was 10,203 in the cases of 556,705 starters in flat racing at 10 racetracks from 1987 to 2000 [83], an incidence of 1.83%. The majority of forelimb fractures were intra-articular, that is, occurring in the bones of the carpus, the metacarpophalangeal joint including the distal condyle of the third metacarpus/metatarsus, the proximal sesamoid bones along with the suspensory interosseous ligament, and the phalanx [54, 83]. In JRA racehorses, distal condylar fracture of the third metacarpus/metatarsus is the most common catastrophic fracture, followed by fracture and injuries of the suspensory apparatus comprising the proximal sesamoid bones along with the suspensory interosseous ligament [83]. Fractures in the legs during training and racing are more likely to occur in forelimbs than hind limbs (Table 1) [121].

Metacarpal distal condylar and proximal phalangeal and carpal fractures are the most prevalent catastrophic fractures in all types of races, particularly in flat turf courses in the U.K. [13, 18, 88, 89, 91, 92] and Hong Kong [9], whereas, proximal sesamoid bone fracture is the most common catastrophic fracture in the U.S.A. on flat dirt courses [4, 47]. In the U.S.A., close associations have been reported between the development of metacarpal distal condylar fracture or catastrophic suspensory ligament rupture with moderate ligamentous suspensory apparatus injury and recent high-intensity (high-speed) exercise and longer interval since layup in male horses and horses between 2 and 5 years of age [41]. Although catastrophic proximal sesamoid bone

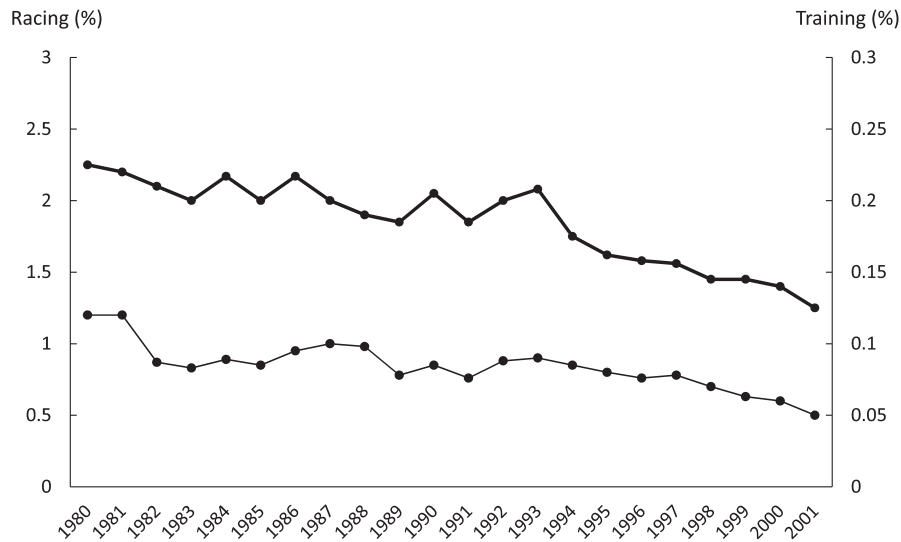


Fig. 2. Incidence of bone fracture during training and racing. —●—: Incidence during racing (affected horses with fractures/total starts), —●—: Incidence during training (affected horses with fractures/total horses in training).

fractures are less common in the U.K., proximal sesamoid bone fracture results in a significantly greater risk of catastrophic fracture on all-weather courses when compared with flat turf courses in the U.K., suggesting a strong association between type of racing track surface and proximal sesamoid bone fractures [63, 88]. Further epidemiological studies need to be conducted to clarify these relationships.

Annual Incidence of Fractures Sustained during Flat Racing

The incidence of fractures from the 1980s to 2000s during training on dirt, turf, and woodchip courses at 2 training centers and during racing on dirt and turf courses at 10 racecourses is shown in Fig. 2. The incidence of fractures sustained during flat racing on 10 JRA racecourses during the period of 1987 to 2000 was calculated based on the total number of starters (race entries; 556, 705 starters) [83]. The fractures ranged from mild injuries necessitating 3 months of rest for the horse before the next race to catastrophic fractures. The overall incidence of fractures over the 14-year period from 1987 to 2000 was 1.83% (95% confidence interval (95% CI)=1.80, 1.87) [83]. The overall incidence on turf and dirt courses over the 14-year period were 1.77% (95% CI=1.73, 1.82) and 1.90% (95% CI=1.84, 1.95), respectively [83]. Most fractures occurred within joints in the legs, particularly the forelimbs, during racing [54, 83]. There was a tendency toward reduced incidence of fractures for horses in racing as the years progressed (Fig. 2) [83]. The average incidence of catastrophic fractures leading to direct

euthanasia at racetracks during or after races for a 10-year period (1985–1994) was $0.32 \pm 0.07\%$ [121]. Most catastrophic fractures were limb fractures [54, 83]. There have been several reports on the incidence of catastrophic racing injuries from other countries. The incidence of catastrophic injuries during racing on flat courses was 0.29% (mainly musculoskeletal injury) in the U.K. [134]. In the U.S.A., the incidence of fatal musculoskeletal injuries was 0.14% in Kentucky [96] and 0.17% in California [26], whereas it was 0.06% in Australia [7]; the incidence of fatal injuries was 0.044% in Australia [10].

The results of two retrospective studies of racing injuries (mainly musculoskeletal injuries) at NYRA tracks from 1984 to 2002 were recently reviewed by Hill *et al.* [38] and Mohammed *et al.* [68]. The racetracks of the NYRA and JRA are similar in the aspects of shape, incline, and type (oval, flat, dirt, and turf racecourses). Hill *et al.* reported that the incidence of racing injuries for the period 1984–2002 at NYRA racetracks ranged from 0.35% to 0.73% for non-catastrophic injuries and from 0.08% to 0.185% for catastrophic injuries [38]. There is a difference in incidence of fractures during flat racing between the JRA and NYRA. It can be hypothesized that a reason for the difference in incidence of fractures mentioned above may be due to differences in the ways in which data are kept and reported between the JRA and the NYRA, particularly with respect to the medical information used by the JRA as compared with that used by foreign racing authorities. JRA horses are trained and enter into races and facilities managed on a daily basis and run under the control of the JRA; thus, all patho-

logical data of the horses are recorded and stored by the JRA. The statistics on racing and training injuries compiled by the JRA include non-fatal minor fractures such as chip fractures in carpal joints that are often not discovered until a few days after a horse has raced. Therefore, higher accident rates would be reported by the JRA.

Hill stated that the increased scrutiny of horses identified with prior injuries in pre-race physical inspections by regulatory (official, commission, or association) veterinarians who are experienced in diagnosing equine health conditions may lead to a reduction of catastrophic and recurrent injuries [38]. The importance of pre-race physical inspections for the prevention of racing injuries has been reported by other studies in the U.S.A. [21, 22]. JRA veterinarians identify horses with potential problems and pull them before races.

There is a paucity of statistical information on injuries during training because the incidence or risk of fractures in training is difficult to quantify [8, 62, 101, 111, 127, 128]. Over the 17-year period from 1981 to 1997, 16,884 out of a total of 18,884,329 horses counted by a coding system used when horses enter and exit racetracks during training at the 10 JRA racecourses and 2 training centers suffered a fracture, an incident rate of 0.089% [121]. However, the total number of horses counted by the coding system does not necessarily indicate the number of horses performing high-intensity (high-speed) exercise. Therefore, it is unclear whether or not the incident rate mentioned above represents the definitive value for horses during training.

Relationship between Incidence of Fractures during Flat Racing and Track Condition on Turf and Dirt Courses

The incidence risk between 1987 and 2000 was reported in a previous paper [83]. The risk of fractures increased significantly as track conditions on dirt courses became muddy ($P < 0.001$, Cochran-Armitage test) [83]. The risk of fractures tended to decrease as track conditions on turf courses became softer with higher water content ($P = 0.0711$, Cochran-Armitage test) [83]. As mentioned above, the incidence of racing fractures on dirt tracks in the JRA is higher than that on turf tracks in the JRA. Relating the risk of racing-related musculoskeletal breakdown with turf track conditions, published data from other countries have shown conflicting results. In Victoria State, Australia [7], and the U.K. [134], softer turf tracks with higher water content were associated with a lower risk than harder, drier turf tracks. Conversely, horses raced on firm turf tracks had significantly lower risks in the NYRA [69]. The reason for the conflicting results on turf tracks is not evident. In the NYRA, a greater incidence of fractures occurred on dirt courses than on turf courses. Turf courses have 1/3 the risk

compared with dirt tracks with a fast or good condition [38]. However, on NYRA dirt courses, muddy conditions create a significantly lower risk of fractures compared with the risk for fast dirt racetracks [38]. Contrary to this trend in the NYRA, on JRA dirt tracks, there is a significant trend for a higher incidence of fractures when dirt tracks become heavy due to higher water content [83]. These differences between the JRA and NYRA might be caused by the differences in the composition of the cushion and base layers of dirt racetracks, which are related to vertical hardness and horizontal shear strength, primarily depending on the materials used in constructing the dirt racetracks by the JRA and NYRA, as mentioned above [38, 39, 66]. In other words, there is a possibility that hoof-ground interactions differ on the dirt courses of the JRA and NYRA. We speculate that dirt courses in the NYRA may become more cohesive as the moisture content increases on the track surface (possibly easier to grip) than on dirt courses with lower moisture content because the dirt track surface used in the NYRA is primarily composed of clay/silt/sand [38, 39]. In contrast, the JRA dirt track surface is composed of fine particle-sized sand [66]. This difference in track surface composition between NYRA and JRA may affect the behavior of soil in the track surface, thus leading to differences in foot motion or slide on the track surface [2, 102–104]. Hoof acceleration and ground reaction force were considered as possible indices of vertical hardness and horizontal shear, which may be involved as possible risk factors for racing injuries [15, 114]. One study has reported that hoof acceleration and ground reaction force in Thoroughbred horses during running are influenced by types of track surfaces, i.e., dirt, synthetic, or turf track surface [114].

The firmness of the turf track and racing speed are thought to be important factors related to musculoskeletal injuries on turf, and it has been reported that harder turf tracks, which likely have greater vertical hardness and horizontal shear, have less of a cushioning effect and therefore exert a high impact, putting a large strain on the limbs as the hooves land on the ground [7, 90, 137].

Dirt courses were found to have a high incidence of racing fractures when tracks were in heavy [83]. This may reflect the characteristics of Japanese dirt track components, as mentioned above. A previous study reported that track surface conditions were unrelated to the occurrence of racing injuries for Thoroughbred horses [37]. To clarify the relationship between track condition and injuries, further studies need to be conducted on the interaction of the hoof with the track surface, the magnitude and character of load transfer between the ground (consistency, compliance, shearing strength, geometry, banking) and hoof, and limb mechanics (ground reaction forces, decelerations, accelerations, strains, stride vibrations) using both *in vitro* and *in vivo* studies.

Table 2. Relationship between track condition and racing time at Nakayama Racetrack (1990–1994)

Racing distance (m)		Track surface conditions			
		Firm	Good	Yielding	Soft
Turf	1,200	70.8 ± 1.4 ^{A,B} (152/1,821)	71.6 ± 1.4 ^A (31/371)	72.1 ± 1.0 ^B (14/149)	73.6 ± 1.6 ^{A,B} (19/203)
	1,600	96.9 ± 1.1 ^{A,B} (201/2,534)	97.7 ± 1.4 ^{A,B} (36/427)	98.9 ± 0.9 ^A (26/331)	99.9 ± 1.1 ^B (24/304)
	1,800	110.9 ± 1.4 ^A (120/1,501)	112.0 ± 1.8 ^{A,B,D} (30/389)	111.5 ± 1.6 ^{A,C,D} (4/53)	115.1 ± 1.8 ^{A,B,C,D} (10/117)
	2,200	136.3 ± 1.5 (29/336)	137.2 ± 1.3 (7/80)	138.3 ± 1.1 (10/134)	140.6 ± 1.2 (6/72)
	2,500	155.5 ± 1.6 ^{A,B} (44/493)	156.7 ± 1.2 ^{C,D} (7/67)	160.2 ± 1.4 ^{A,C} (4/39)	160.7 ± 1.0 ^{B,D} (3/30)
		Fast	Good	Muddy	Sloppy
Dirt	1,200	75.1 ± 0.9 ^{A,B,C} (379/4,650)	74.1 ± 1.2 ^A (100/1,229)	73.8 ± 1.6 ^B (62/739)	74.1 ± 1.2 ^C (60/638)
	1,800	117.3 ± 1.4 ^{A,B,C} (413/5,012)	116.1 ± 2.0 ^{A,D} (106/1,297)	115.4 ± 1.4 ^{B,D} (65/810)	115.8 ± 1.5 ^C (67/743)

Racing time(s) is expressed as the mean ± SD. Mean values with the same superscripts differ significantly (capital letters, $P < 0.01$; lowercase letters, $P < 0.05$; based on Student's *t*-test following one-way ANOVA). Numbers in parentheses indicate the number of winners/number of runners (Reproduced from M. Oikawa, R. Kusunose, 2005, *Vet. J.*, with permission from Elsevier Ltd.).

Table 3. Relationship between track condition and racing time at Kyoto Racetrack (1990–1994)

Racing distance (m)		Track surface conditions			
		Firm	Good	Yielding	Soft
Turf	1,200	71.6 ± 1.2 (95/1,231)	72.1 ± 0.9 (20/261)	72.0 ± 1.1 (15/157)	72.2 ± 1.0 (3/49)
	1,400	84.5 ± 1.2 ^{A,B} (119/1,542)	85.4 ± 1.2 ^A (15/201)	84.8 ± 1.0 (10/138)	86.0 ± 1.3 ^B (6/88)
	1,600	97.4 ± 1.4 ^A (119/2,328)	97.2 ± 1.0 ^B (15/377)	97.3 ± 1.1 ^C (10/86)	99.5 ± 1.5 ^{A,B,C} (6/82)
	1,800	110.5 ± 1.4 (91/1,059)	109.7 ± 1.3 (16/206)	110.4 ± 0.9 (7/86)	110.7 ± 0.1 (3/38)
	2,000	123.9 ± 2.0 ^A (144/1,419)	124.7 ± 1.5 ^B (17/201)	124.4 ± 1.7 ^C (16/191)	127.1 ± 1.3 ^{A,B,C} (7/90)
		Fast	Good	Muddy	Sloppy
Dirt	1,200	74.7 ± 1.1 ^{A,B} (210/2,421)	73.8 ± 1.4 ^A (37/403)	73.8 ± 1.0 ^B (43/582)	74.4 ± 1.3 (44/504)
	1,400	87.5 ± 1.3 ^{A,B} (228/2,711)	86.6 ± 1.7 ^{A,c} (36/406)	86.6 ± 4.7 ^B (46/588)	87.3 ± 1.3 ^c (37/450)
	1,800	115.2 ± 1.6 ^{A,B,c} (324/3,490)	114.2 ± 1.6 ^{A,d} (58/681)	113.6 ± 1.3 ^{B,d,E} (71/790)	114.7 ± 1.5 ^{c,E} (56/688)

Racing time(s) is expressed as the mean ± SD. Mean values with the same superscripts differ significantly (capital letters, $P < 0.01$; lowercase letters, $P < 0.05$; based on Student's *t*-test following one-way ANOVA). Numbers in parentheses indicate the number of winners/number of runners (Reproduced from M. Oikawa, R. Kusunose, 2005, *Vet. J.*, with permission from Elsevier Ltd.).

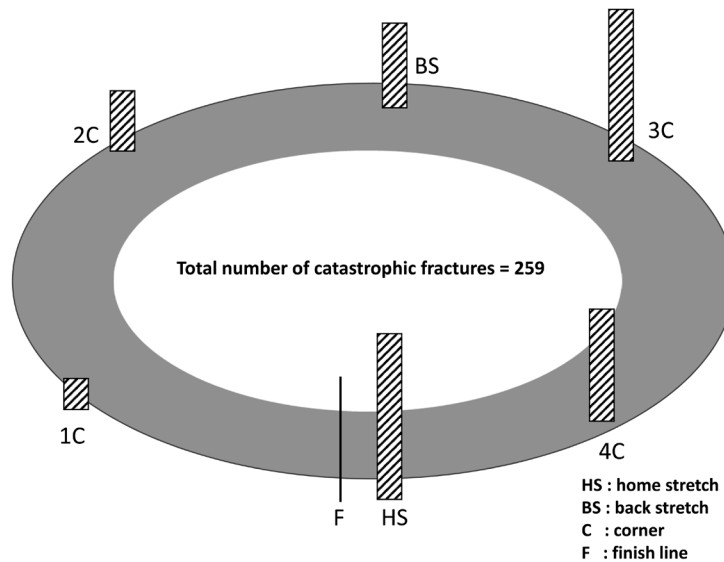


Fig. 3. Schematic drawing of locations of catastrophic fractures on turf and dirt tracks during racing on the 10 JRA racecourses. Bars with diagonal hatching indicate the number of horses experiencing catastrophic fracture.

Relationship between Racetrack Surface Condition and Racing Times in Flat Races

Because the incidence of racing fractures varies with track condition (the finding of all but one study), the relationship between track condition and racing times was evaluated for 183,465 Thoroughbred racehorses (99,803 starters on turf courses and 83,662 starters on dirt courses) that ran in 16,765 flat races held at 10 racecourses (Sapporo, Hakodate, Fukushima, Niigata, Tokyo, Chukyo, Hanshin, Kokura, Nakayama, and Kyoto) belonging to the JRA between 2000 and 2004 (Tables 2 and 3) [66]. Track surface condition affected the race time significantly in turf and dirt courses [66], although the effect of track surface condition on racing times was greater in dirt courses than in turf courses [66]. Furthermore, racecourse affected the race time significantly [66]. This may imply the effects of or difference between racecourses, such as the shape of the track, radius of curvature at the corners, slope, components of the vertical section of the track, and weather [66]. In other words, this finding suggests that racecourse-related factors (extrinsic or environmental factors) may influence racing time. Factors affecting racing times in flat races on JRA racetracks were reported by Oki [84–87]. These include factors such as the nature of training, programmer, purse, gender, age, weight carried, prior race performance, type of course (dirt or turf), track surface condition, genetics, racing distance, number of starters, and the connection

between the jockey and the horse [85]. Of these factors, the relationships between racecourses, racing distances, and racing times on JRA racetracks were analyzed statistically [66]. When the effects of differences between racecourses and in racing distance were removed, track surface condition conclusively influenced racing time in flat races at JRA racetracks [66]. It remains to be elucidated whether or not incidence of racing fracture is affected by racing time.

Interaction of the Hoof with Different Track Conditions

Energy from the shock of hoof contact with the ground and the forces resulting from the change in momentum of the legs and body transmitted between the track and hoof underlie the risk for injury to bones and soft tissues. Therefore, it is important to understand track surface properties such as vertical impact (hardness), horizontal shear, and rebound timing. For the purpose of clarifying the interaction of the horse and hoof with the track surface properties, a new device sandwiched between the hoof and shoe to measure vertical ground reaction forces (VGRFs) during cantering and galloping was developed by Kai *et al.* in the JRA [49]. By using this instrumented shoe, the VGRFs acting on the forelimb during galloping, and the relationship between the effect of a rough dirt and woodchip track surface (uneven track surface) were used to study the variation in peak VGRF in the forelimbs during galloping [48]. The variance in peak VGRF of the trailing forelimb

decreased significantly more on a harrowed dirt and woodchip track surface than on rough dirt and woodchip track surfaces [48, 120]. These results indicate that rough deformable track surfaces (unevenness and non-uniformity of the track surface) increase the variance of vertical forces at the hoof and positioning of the load on the hoof [48] and that track surface maintenance such as harrowing on dirt and woodchip tracks will also impact the health of locomotor organs in racehorses because uneven track surfaces exacerbates asymmetry of loading on the hoof.

Locations on Racetracks Where Racing Injuries Occur Based on Patrol Video

Analysis of racehorse fractures utilizing video recordings have been reported in the U.K. [93]. In Japan, the distribution of locations at which 259 cases of catastrophic fracture occurred on racetracks at 10 JRA racecourses over a period of three years (1983 to 1986) was analyzed from video recordings taken by cameras positioned to observe all parts of the tracks (referred to as “patrol video”) during races [81, 125] (Fig. 3). These cases were selected as those in which fractures occurred that were clearly identified on the patrol video. Although there are slight differences in the locations, fractures mostly occurred at the third and fourth corners, as well as on the home stretch (Fig. 3), partly due to the increase in the horse’s running speed and disturbances in running pace as a result of fatigue in the musculoskeletal system [125]. A similar pattern of racing fractures on racetracks in the NYRA has been reported by Hill [38].

Another study also analyzed the location at which catastrophic fractures occurred during races and the correlation between the leading leg and injured leg when fractures occurred [125]. On a straightaway and when coming out of a turn and onto a straightaway, the leading leg and injured leg were highly correlated, irrespective of whether the track was run in a clockwise or anticlockwise direction [125]. In contrast, there was low correlation between the leading leg and injured leg while traversing a turn and going from a straightaway into a turn. It is noteworthy that many accidents occurred just after a lead change [125]; similar findings were reported in the U.K. [93].

Trial for Reducing Racing Injuries by Restructuring the Geometry of a Racetrack

The JRA successfully reduced the number of fractures during races at the Hanshin racetrack by changing its geometry [76]. In the pre-remodel configuration, the third and fourth corners were very tight turns because there were straightaway between both corners, so horses had to

frequently change their leading limb, reduce their speed, and then accelerate [76]. Also, because the overall course was level, it was easy to gain speed. The third and fourth corners were made more gradual, and the straightaways between them were made into gentle curves with an increased radius of curvature. The centrifugal force on the limb, which may predispose the limb to injury, decreases as the radius of curvature is increased [65]. As a result of these modifications, there was a great reduction in the number of serious fractures, more so than of slight fractures, compared with the year before the reconstruction [76]. These results are thought to have occurred because the horses no longer had to change their leading limb while traversing a turn or entering a straightaway, thus reducing the number of fractures due to changing the leading limb. The average racing time on the turf and dirt courses for all distances was 2.37 seconds slower after reconstruction. The authors of the study assumed that the improvement in the hardness of the track and the resulting slower racing times, influenced by the reconstruction of the geometry of the racetrack, were responsible for the reduced number of fractures [76].

Incidence of So-called “Bucked Shins”

“Dorsal metacarpal disease” or “bucked shins” is a common bone disease that occurs at the dorsal cortex of the third metacarpal bone in young racehorses during early training [72]. This disease is an athletic performance-limiting problem as well as a common cause of lost training days [46, 111]. Although the classical description of the pathogenesis is associated with fractures, such as fatigue fractures, stress fractures, and microfractures in the dorsal aspect of the mid-diaphysis occurring during the growth period of the long bone, an initial bone lesion has not been demonstrated histologically. In the U.K., Verheyen *et al.* reported that increasing the exercise distance in short periods (up to 1 month) increases the risk of bucked shins, probably as a consequence of microdamage and the associated remodeling response [128]. Recent studies of its pathogenesis indicate that bucked shins occurs in young horses being trained during the bone growth period when microdamage of cortical bone in the dorsal aspect accumulates faster than bone remodeling (turnover rate of bone resorption and formation) as the bone’s adaptive or compensative response to repeated high loading during fast exercise [72, 73, 128]. In terms of bone mineral content, several methods to assess bone metabolism and maturity of the metacarpus to prevent bucked shins have been reported by Japanese researchers [60, 61, 122–124].

The incidence of bucked shins in 2-year-old racehorses in training varies by country and ranges from an incidence rate of <10% [46, 111] or 24% [128] in the U.K. to 25% in

the U.S.A. [12] and 65% in Australia [20]. Epidemiological surveys by the JRA have found a 66% incidence of bucked shins in 2-year-old Thoroughbred racehorses during their first 8 months of training [58]. This variability between countries may be related to differences in study populations, study design, training regimen, and/or racecourses.

It is well known that the incidence of bucked shins is affected by track-surface properties (types of track surfaces, i.e., dirt, synthetic, or turf track surface) [70, 73] as well as distance run and intensity of exercise [45, 73, 128]. In an experiment to test the hypothesis that frequency of intense (high-speed) exercise under the same Japanese racetrack surface conditions on the same track would affect the likelihood of bucked shins developing in young horses, no difference was found in the incidence of the bucked shins between a group that exercised once per week at maximal speed and a group that exercised twice per week at maximal speed [58]. This result suggests that the frequency of intensive exercise employed in the experiment did not affect the incidence of the disease [58].

Jockey Falls in the JRA

The majority of jockey falls in horse racing occur when a horse is catastrophically injured [43]. In international horse racing, jockey falls are reported to occur at a rate of 3 to 4 falls per 1,000 race rides, with 27% to 44% resulting in injury or death of the jockey [43]. The statistics for all JRA races in the three years from 1998 to 2000 show that the rate for during-race falls was 1.62 per 1,000 rides in Thoroughbred flat races [43, 82]. The Thoroughbred jockey fall incidence rate in flat races in the JRA was similar to those in California (1.62 falls per 1,000 rides) [43] and Australia (1.43 per 1,000 rides) [43]. The Thoroughbred jockey injuries incidence rate was 1.02 per 1,000 rides in California [43], 1.12 in Australia [42, 43], and 1.19–1.76 in Europe [67, 112]. The Thoroughbred jockey injury incidence rate per fall was 51% in California [43], 27% in Australia [42], and 34–44% in Europe [67, 112]. However, statistics for injuries to jockeys have not yet been reported in Japan; this needs to be done so that the effectiveness of measures instituted to reduce injuries to jockeys can be assessed.

Conclusions and Future Research Directions

The annual incidence of fractures is approximately 2% during racing and 0.1% in training. The difference in incidence between training and racing may be partially influenced by the magnitudes of the vertical ground reaction forces and/or shock energy during hoof impact on the ground at a racing gallop [15, 109]. There were significant

effects of track condition on the incidence of fractures, with the incidence of fractures increasing as track conditions on dirt worsened, and there was a tendency for the incidence of fractures to decrease as track conditions on turf worsened. These results suggest that track surface conditions may be a risk factor for racing fractures, although no definite evidence is available to indicate the relationship between track condition and the onset of fracture. Catastrophic fractures occurring during races have been analyzed using videos taken during a race. Fractures mostly occur at the third and fourth corners and on the home stretch. They also occur with increased frequency with lead changes. Analysis of relationships between the geometry of the racetrack (radius of curvature), the loads and decelerations of the hoof on impact with the ground, especially at the time of a lead change, or the centrifugal force when moving around corners needs to be performed in detail. The incidence of racing fractures is higher in JRA horses than the incidences reported by racing authorities outside of Japan. It is uncertain whether the differences in incidence between the racing communities outside of Japan and the JRA are due to geographic differences or methodological differences. While definitive evidence does not exist, the geometrical configuration of a racetrack must be considered a possible factor related to racing injuries. When viewed from the perspective of preventing racing injuries, it is hoped that additional studies can 1) evaluate variables of load magnitude and the character of load transfer between the ground, hoof, and limb with different track surface conditions, at different running speeds, and with different hoof conformations in order to determine the optimal track design and track surface, such as by utilizing the hoof-shaped impactor designed by Peterson *et al.* [98], the wireless data acquisition system for measurement of hoof accelerations in exercising horses designed by Ryan *et al.* [113], the track-testing device that simulates equine hoof impact designed by Setterbo *et al.* [115], foot-mounted accelerometers utilized by Witte *et al.* [136], and the instrument sandwiched between the hoof and shoe to measure vertical ground reaction forces and three-dimensional accelerations developed by Kai *et al.* [49], and 2) predict the risk of fracture on the basis of objective parameters, such as exercise and racing history (effects of cumulative exercise distance and speed) or early diagnosis of fatigue-related bone damage (fatigue or stress fracture), as fractures of this type occur when bone damage exceeds bone repair and pre-existing lesions can be precursors of catastrophic fractures (pathologic fracture).

Addendum

For further information on research into the effects of footing on a horse's biomechanical responses, on research of

the interaction between horse injury and racetrack surface, and on research of the composition, construction, and maintenance of arenas and racing tracks, readers are referred to the recent reviews “Racing Surfaces White paper 2011” (http://grayson-jockeyclub.org/resources/White_Paper_final.pdf), “Equine Surfaces White Paper 2016” (<http://www.fei.org/system/files/Equine%20Surfaces%20White%20Paper.pdf>), “Modeling equine race surface vertical mechanical behaviors in a musculoskeletal modeling environment” (2015. *Journal of Biomechanics*. 48: 566–572) and “Proceedings of the 12th International Equitation Science Conference. 2016. International Society for Equitation Science with the collaboration of the French Institute for Horses and Riding, France; ISBN: 9782915250510”.

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* Asterisk indicates the study was conducted by Japan Racing Association (JRA), JRA Equine Research Institute and Japanese researchers.