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Using accelerometers to identify a high risk of catastrophic musculoskeletal injury in three racing Thoroughbreds

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OBJECTIVE
To describe the process whereby the screening of racing Thoroughbreds with accelerometer-based inertial measurement unit (IMU) sensors followed by clinical evaluation and advanced imaging identified potentially catastrophic musculoskeletal injuries in 3 horses.

ANIMALS
3 Thoroughbred racehorses.

CLINICAL PRESENTATION
All cases demonstrated an abnormal stride pattern either during racing (cases 1 and 2) or while breezing (case 3) and were identified as being at very high risk of catastrophic musculoskeletal injury by an algorithm derived from IMU sensor files from > 20,000 horses' race starts. Veterinary examination and 18F-sodium fluoride (^{18}F-NaF) positron emission tomography were performed within 10 days of the respective race or breeze in each of the cases.

RESULTS
The intensity and location of the ^{18}F-NaF uptake in the condyles of the third metacarpal bone in cases 1 and 2 identified them as at potential increased risk of condylar fracture. The pattern and intensity of the ^{18}F-NaF uptake in case 3 indicated that the third carpal bone was likely responsible for the horse's lameness, with an impending slab fracture subsequently identified on radiographs. Following periods of convalescence, cases 1 and 2 returned to racing and were identified by the sensor system as no longer being at high risk of catastrophic musculoskeletal injury. Case 3 returned to training but has yet to return to racing.

CLINICAL RELEVANCE
When worn by Thoroughbreds while racing or breezing, these IMU sensors can identify horses at high risk of catastrophic musculoskeletal injury, allowing for veterinary intervention and the potential avoidance of such injuries.

Keywords: catastrophic injury, sensors, Thoroughbreds, PET scan, musculoskeletal

Musculoskeletal injuries are responsible for a high rate of racehorse attrition.[1] Even with the best outcomes, musculoskeletal injuries in racing Thoroughbreds result in loss of income, lower field numbers, and fewer career starts, while in the worst circumstances they result in loss of use or loss of life for the horse and life-altering or -ending injuries to the jockey.[2] The word "catastrophic" is often used in describing these events, as they are so sudden and the outcome is so dire at multiple levels when they do occur. It has been widely reported that the majority of these horses have preexisting pathology before the catastrophic event.[3–5] The common misconception that catastrophic injuries occur as a result of "stepping in a hole" or "taking a bad step" is not supported by pathological findings and has been consistently disproven. The California Postmortem Study identified common and consistent lesion characteristics and locations specific to individual bones.[6] The consistency of the lesions' configurations and locations supports the theory that the forces that cause these injuries are similar among the population and not the result of an isolated event.[6] Furthermore, the

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identification of preexisting pathologies in the forms of periosteal new bone formation at fracture sites, osteonecrosis, and stress fractures supports the conclusion that catastrophic injuries are the result of an ongoing acute or chronic disease process.[4,6,7]

The dilemma that exists is that these preexisting pathologies and disease processes often do not seem to be clinically apparent. This results in horses being deemed sound and fit to race by trainers and veterinarians alike. These horses continue to train and race until they suffer a career- or life-ending injury. At the time of the creation of the Jockey Club's Equine Injury Database in 2009, the incidence of race-day–related fatalities was 2.0 for every 1,000 starts. This figure had decreased to 1.25 for every 1,000 starts in 2022.[8] While this number includes nonmusculoskeletal sudden death fatalities, it does not account for fatalities in training, and mandated reporting of fatalities is not implemented across all American racing jurisdictions. The reduction in fatalities since the birth of the Equine Injury Database is largely owed to an increase in prerace veterinary oversight, tighter racing regulations surrounding medication usage, and modifications in training regimes and track surfaces.[9]

While improvements have been made, there is no denying that horse racing's social license to operate has come under renewed pressure because of these catastrophic injuries.[10] This, along with the well-supported evidence that the processes leading to catastrophic injuries are often developing for months prior to the terminal event, beseeches the Thoroughbred racing industry to seek and implement a method to identify these at-risk horses before they suffer a catastrophic injury.

Nowadays, human athletes are fitted with biometric sensors that record their biodata while they perform across a multitude of disciplines. However, the same is not true for equine athletes and there has been a lag within Thoroughbred racing in the application of available technologies involving wearable biometric sensors. Recently, a preliminary report[11] has been published that documents the use of biometric sensors during races to identify horses at risk of serious musculoskeletal injury. These are accelerometer-based inertial measurement unit (IMU) sensors that continuously record the locomotory movements of horses at racing speed at a high frequency (> 2,000 data points/s; StrideSAFE). From the records collected from > 20,000 races, an algorithm has been developed to analyze the movements of the limbs and torso of racing Thoroughbreds. These sensors, which are carried in a pocket located in the saddle cloth behind the saddle, identify horses at greatest risk of suffering a musculoskeletal injury if they continue to train and race.[11] The use of these sensors has expanded in recent years, and from April 29 through July 3, 2023, they were worn by every horse racing at Churchill Downs and Ellis Park racetracks in Kentucky and by a select group of horses in training at those tracks. A number of horses were identified as being at high risk for future catastrophic injury, and several were presented for additional evaluation. This is a report of 3 such cases placed in the highest risk category following races or breezes at Churchill Downs.

Methods

The sensors used were developed by StrideMASTER. They utilized integrated Global Positioning System (GPS) technology with an accelerometer-based IMU system to record the velocities, changes in rates of motion of individual limbs, and position in space of horse movements in 3 dimensions while the horses raced or breezed.[11] The IMU consisted of 3 commercially available micromachined microelectromechanical system accelerometers with a maximum of 16 G in each dimension at a sampling rate of 800 Hz, for a combined total of 2,400 G force measurements/s. Filters were designed to suppress noise and allow the critical features of dorsoventral, longitudinal, and mediolateral movement dynamics to pass to the algorithms characterizing the motion and strides for risk assessment.

Each individual horse's data were plotted against time to produce a file that represented its stride pattern. A risk factor regression algorithm was derived with commercially available modeling software (MATLAB; The Mathworks Inc). The predicted risk factor was determined by comparing an individual horse's stride pattern to an established ideal pattern drawn from the stride files of 37 graded stakes–winning horses. These served as a baseline against which the strides of all other horses were compared **(Figure 1)**. The stride patterns of the graded stakes winners were selected as representing the ideal because, on the basis of retrospective scrutiny of thousands of horses of all abilities, the strides of graded stakes winners demonstrated the least variation from stride to stride, thereby giving the model the greatest degree of uniformity.

Stride patterns were characterized by extracting a set of signal features related to acceleration, jerk, velocity, track position, and timing dynamics from the 3 dimensions of the horses' movements. These features were extracted from calibrated and normalized stride patterns and applied to a quadratic regression algorithm model. The model was derived by use of a machine learning algorithm from a training set of horses each with a known number of SDs from the ideal and for which a risk factor had subsequently been generated by considering the percentage of horses in this SD category that suffered a catastrophic injury. The algorithm was trained to predict risk category on the basis of the extent to which the stride pattern deviated from the ideal stride in the direction of characteristics previously observed in horses that had suffered catastrophic musculoskeletal injuries. The likelihood of a horse suffering such an injury was calculated for each risk factor via a retrospective analysis of the percentage of horses in each category that had suffered a fatal or career-ending musculoskeletal injury. These percentages were compared to those associated with the results for the lowest risk category that was risk factor = 1.

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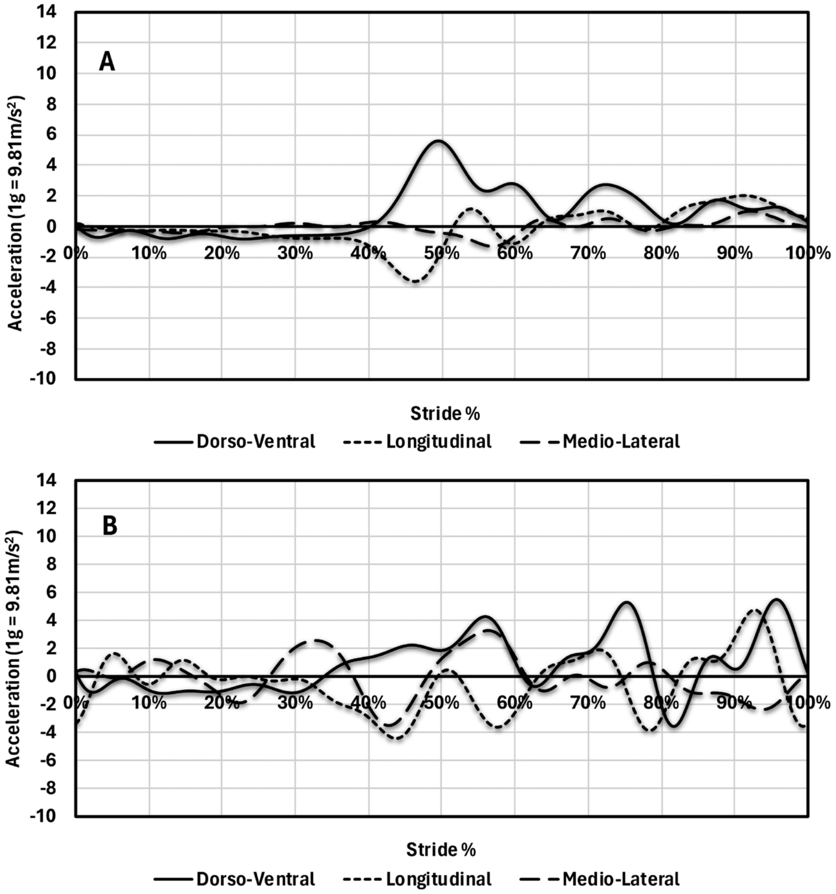

Figure 1—Graphical representation of an ideal single stride of a racing Thoroughbred (A; risk factor = 1) and that of a horse at very high risk of suffering a future catastrophic musculoskeletal injury (B; risk factor = 5, case 2) based on the algorithmic interpretation of data collected by use of an inertial measurement unit sensor system worn while the horse was racing. Each of the strides shown is actually a computer-generated composite of 20 consecutive strides, as there is usually some minor variation from stride to stride in all horses. The sensor system measured locomotory accelerations and decelerations in 3 planes, each of which is represented by a different line on the figure. The stride begins when the first hind limb strikes the ground and ends when the same limb again contacts the ground. For dorsoventral movements, deflections above the x-axis reflect upward motions. With respect to longitudinal movements, downward deflections reflect limbs pushing off the surface, while upward deflections indicate braking forces on the limbs. Upward deflections in the mediolateral plane reflect movements to the left, and downward deflections indicate movements to the right.

Risk status was categorized as 1 through 5. Using the ideal stride as the mean, risk factor = 1 was assigned to horses that produced a stride pattern that was ≤ 2 SDs from the mean. Horses with a risk factor = 2 produced a stride pattern that was in the range of > 2 to 3 SDs from the mean and, on the basis of catastrophic injury data from a population of 6,618 race starts in the database, were 18 times more likely to suffer a fatal or career-ending injury than horses in the lowest risk category. Those given a risk factor = 3 produced a stride that was between > 3 and 4 SDs from the ideal mean and were 86 times more likely to suffer a fatal or career-ending injury than horses in the risk factor = 1 category. Risk factor = 4 horses produced a stride pattern that ranged from > 4 to 5 SDs from the mean and were 313 times more likely to suffer a fatal or career-ending injury than horses in the lowest risk category, and risk factor = 5 horses produced a stride pattern that was > 5 SDs from the mean (Figure 1) and were 950 times more likely to suffer a fatal or career-ending injury than horses with a risk factor = 1. The incidence of risk category 1 assessments in this database of 6,618 starts was 70%, category 2 was 16.5%, category 3 was 7%, category 4 was 3%, and category 5 was 3.5%.

In the 66-day assessment period, stride pattern files were collected from 1,567 race starts. One hundred thirty-five horses were assessed as having a risk factor = 5. Six of them suffered catastrophic breakdowns while wearing the sensors for the first time. Efforts were made to contact the trainers of all the other horses to discuss their risk category and to follow-up with them regarding the horse's postrace soundness. Forty-two trainers who were responsible for 93 (69%) of the risk factor = 5 horses were successfully reached by phone and/or text. Prior to contacting these trainers, the horses' races and breezes were reviewed and their stride patterns were studied by a team of 3 veterinarians trained in interpreting the sensor data (DMS, MH, DHL). The resultant conclusions and associated recommendations were communicated to the horses' trainers. However, most details of any subsequent veterinary interventions, management changes, or injury events were lost to follow-up, although 38 horses had either delayed (> 80 days) or nonreturn to racing for unknown reasons 11 months later. The trainers of 7 of the horses kept in close contact with 2 of the authors (DMS, DHL) with respect to the status of their horses. The findings from the subsequent clinical evaluations of 3 of these horses are described in this case series.

Results

Case 1

A 3-year-old colt making its eighth lifetime start was categorized as a risk factor = 3 following the first race in which data on its stride were collected by the IMU sensors. The horse raced again 37 days later, with

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2 timed breezes in this intervening period. The second set of racing data obtained for this horse assigned a risk factor = 5, indicating deterioration of the stride pattern from that recorded in the previous race. The stride pattern produced in the second race showed increased mediolateral acceleration and movement to the left and less to the right during the front limb phase of the stride. This indicated that the horse was spending less time with its right front quadrant on the ground than with the left front quadrant. This was consistent with the stride pattern of the first race, albeit of greater magnitude in the latter race. The race footage was reviewed, and the trainer was contacted to discuss the sensor findings. The trainer and their veterinarian were concerned with the horse's comfort on postrace examination. After a radiograph identified an area of slight radiolucency in the right fetlock, the horse underwent a standing positron emission tomography (PET) scan 10 days following the second race. All 4 fetlocks and both carpi and tarsi were imaged with 18F-sodium fluoride (^{18}F-NaF). These images were interpreted by a board-certified radiologist. The most pertinent findings were that there was marked focal increased ^{18}F-NaF uptake at the axial aspect of the lateral palmar condyle of the right front fetlock, with palmar proximal extension as well as moderate regional dorsodistal increased ^{18}F-NaF uptake in the dorsal supracondylar area of the third metacarpal bone (MC3; **Figure 2**). This uptake was indicative of remodeling at the axial aspect of the lateral palmar condyle, potentially involving the lateral parasagittal groove along with hyperextension stress remodeling of the fetlock. On the basis of the location, shape, and intensity of the uptake, this lesion was considered to be at risk of progressing to a lateral metacarpal condylar fracture. Three to 6 months' rest was recommended along with potential structural imaging to determine whether surgery was indicated. Following these recommendations, the horse was taken out of training. Structural imaging was not obtained. The horse resumed breezing 139 days later and has since returned to racing. At the time of writing, the horse had raced once and had been assigned a risk factor = 2.

Case 2

A 3-year-old colt making its ninth lifetime start was assigned a risk factor = 5 during the first race in which it carried the sensor system. The colt had worn the sensor system while breezing 3 days prior to this race and at that time produced an irregular stride pattern similar to that produced while racing. The stride pattern indicated that the left front quadrant was the area of greatest concern (Figure 1). The race footage was reviewed, and the horse's trainer was contacted to discuss the findings. Although the trainer's veterinarian examined the horse and determined it to be subjectively sound, they and the trainer elected to perform a standing PET scan, including all 4 fetlocks and both carpi and tarsi. The procedure was performed 5 days following the race. The images were interpreted by a board-certified radiologist, with the pertinent findings involving both front fetlocks. The left front fetlock showed a focal, marked increase in ^{18}F-NaF uptake within the palmaromedial subchondral bone of distal MC3, at the axial aspect of the condyle. The uptake's greatest dimension was in a proximal-distal direction. There was minimal increased ^{18}F-NaF uptake within the palmarolateral subchondral bone of distal MC3 and mild, focal increased ^{18}F-NaF uptake at the dorsal aspect of the supracondylar region of distal MC3. Within the right front fetlock, there was local, moderate to marked increased ^{18}F-NaF uptake within the palmar subchondral bone of the medial and lateral condyles of distal MC3. There was a focal, mild increase in ^{18}F-NaF uptake at the dorsal apical aspect of the lateral proximal sesamoid bone and multifocal moderate increased ^{18}F-NaF uptake along the dorsal supracondylar region of distal MC3, along with focal, mild increased ^{18}F-NaF uptake within the dorsal cortex of distal MC3, approximately 2.5 cm proximal to the supracondylar site of uptake. The most significant

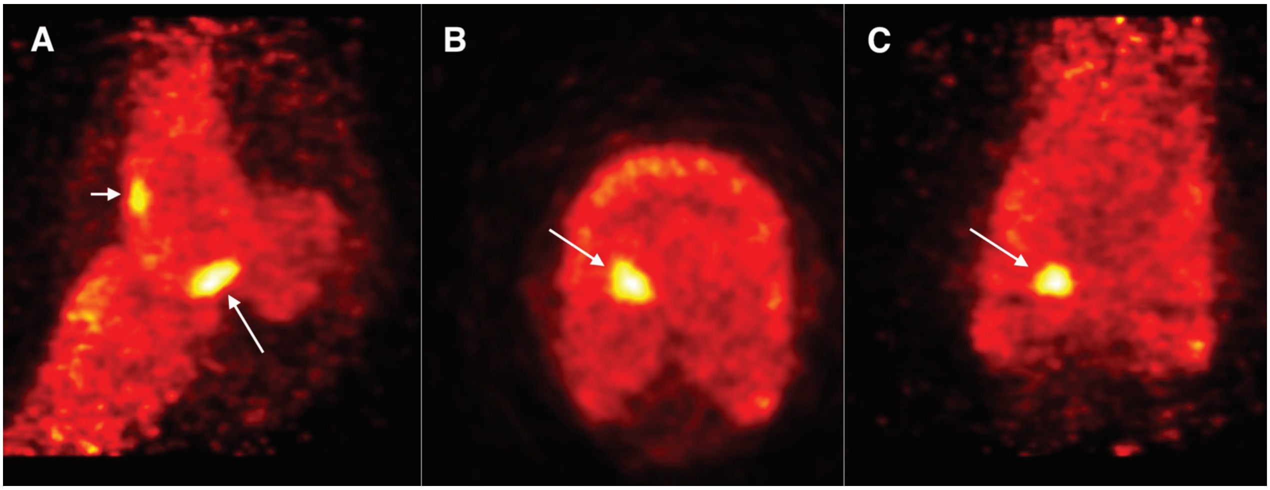

Figure 2—Multiplanar reformatted images, lateral view (A), transverse view (B), and dorsal view (C), of 18F-sodium fluoride (^{18}F-NaF) positron emission tomography (PET) data of the right front fetlock of case 1. Lateral is to the left of the images. Marked increased ^{18}F-NaF uptake was identified in the axial aspect of the lateral palmar condyle (long arrows) and moderate ^{18}F-NaF uptake in the dorsodistal supracondylar area of the third metacarpal bone (short arrow).

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of these findings was the increased uptake in the left front medial palmar condyle of MC3 **(Figure 3)**. The high ^{18}F-NaF uptake combined with the axial location, proximal-distal extension, and asymmetry with the right front fetlock suggested maladaptive stress remodeling with an increased risk for medial metacarpal condylar fracture. No training for 60 to 90 days with a repeat of the PET scan at 60 days was recommended to reassess rehabilitation before resuming training. The horse was removed from training and rehabilitated with paddock turnout and a slow return to exercise. A follow-up PET scan was not obtained. The horse resumed breezing 132 days after the race from which it was assigned a risk factor = 5. It subsequently raced twice and was assigned a risk factor = 1 both times.

Case 3

A 4-year-old intact male wore the sensor system when breezing on 3 consecutive occasions. It produced an abnormal loading pattern, with increased mediolateral acceleration to the left during the front limb phase of this stride, indicating that it was overloading its left front quadrant. The stride pattern deteriorated over successive breezes, becoming consistent with that of a risk factor = 5. The trainer and their veterinarian were informed of the findings. The trainer disclosed that the horse had returned to training 2 months earlier following a 6-month lay-up, which was implemented as conservative management of a nondisplaced sagittal slab fracture of the radial facet of the right third carpal bone. The trainer's veterinarian examined the horse and found it to have a score of 2/5 on the right front limb according to the American Association of Equine Practitioners Lameness Scale. Eight days after its latest breeze, the horse underwent a standing PET scan to further investigate the lameness. All 4 fetlocks and both carpi were imaged. The most significant findings were those of the right carpus and left front fetlock **(Figure 4)**. The left front

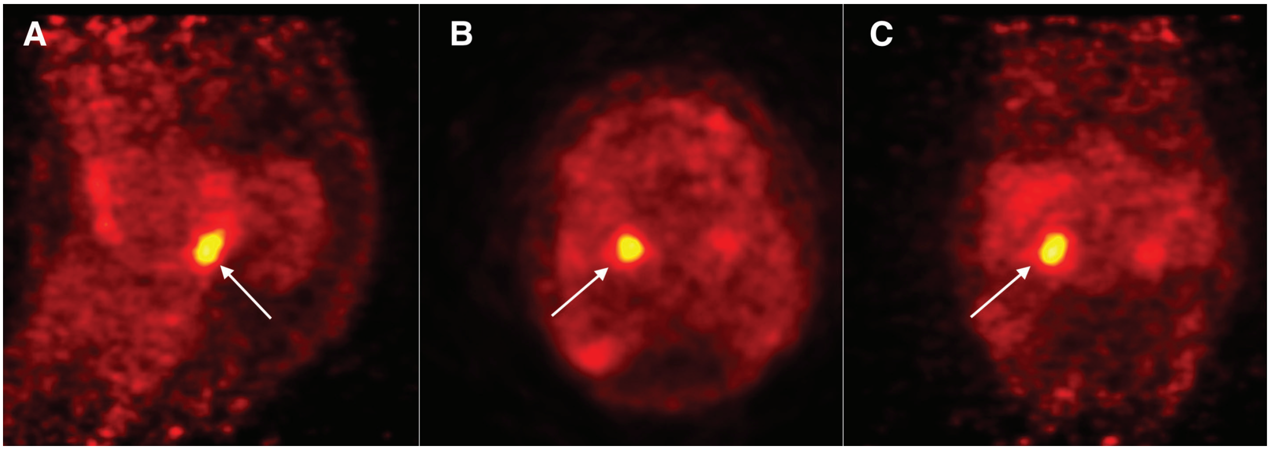

Figure 3—Multiplanar reformatted images, lateral view (A), transverse view (B), and dorsal view (C), of ^{18}F-NaF PET data of the left front fetlock of case 2. Lateral is to the right of the images. Marked ^{18}F-NaF was identified within the palmaromedial subchondral bone of the distal third metacarpal bone at the axial aspect of the medial condyle (long arrows).

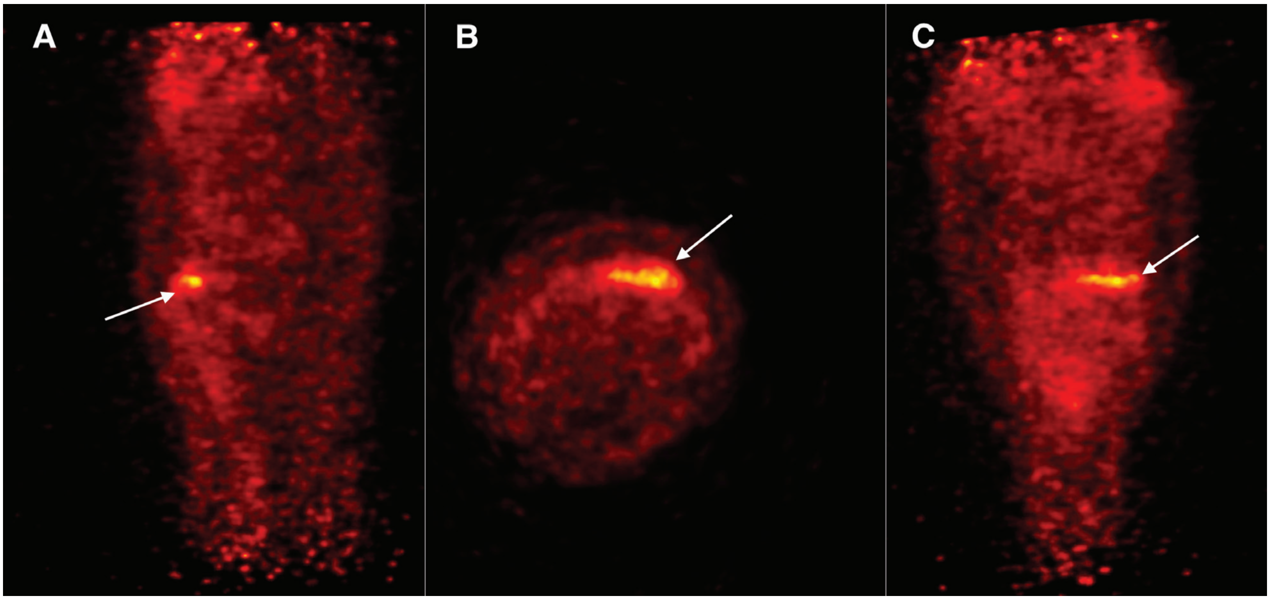

Figure 4—Multiplanar reformatted images, lateral view (A), transverse view (B), and dorsal view (C), of ^{18}F-NaF PET data of the right carpus of case 3. Lateral is to the left of the images. Moderate regional increased ^{18}F-NaF uptake was seen through the compact subchondral bone of the medial-proximal third carpal bone (long arrows).

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fetlock showed moderate focal increased ^{18}F-NaF uptake at the axial aspect of the lateral palmar metacarpal condyle and minimal focal increased uptake at the center of the medial palmar metacarpal condyle. There was also minimal focal increased uptake at the dorsoaxial aspect of the left medial sesamoid bone along with moderate regional increased uptake at dorsomedial MC3 in the supracondylar area. Mild focal increased uptake at dorsal central MC3 in the supracondylar area was noted in the right front fetlock. The right carpus had moderate regional increased uptake through the compact subchondral bone of the medial-proximal third carpal bone. The remodeling of the right third carpal bone was determined to be the most significant finding and the probable explanation for the lameness. An asymmetric uptake pattern in the front fetlocks was considered to be related to the right front lameness of carpal origin, with minimal changes in the right front fetlock and more remodeling of the left front fetlock likely due to increased loading of the latter in the face of the right carpal lesion. Further supporting this was the uptake pattern in the left front fetlock, which deviated from the more typical pattern of medial uptake of ^{18}F-NaF being greater than lateral uptake.[12,13] Following the PET scan results, radiographs were obtained of both carpi and front fetlocks. The right third carpal bone showed marked sclerosis with a lucent region indicative of an impending slab fracture along with subchondral bone remodeling of both front distal MC3s. The horse was given time off from training with regular paddock turnout and a slow return to exercise. It resumed breezing 156 days later but has yet to return to racing.

Discussion

The spectacle of a galloping horse suddenly falling to the ground after suffering a catastrophic musculoskeletal injury is calamitous to witness. Such injuries have been a tragic part of many high-speed equine competitive events since time in memoriam, and identifying horses at greatest risk of incurring such injuries has been a clinical conundrum that has resisted resolution for just as long, despite the fact that about 93% of these horses have preexisting subclinical pathologies at the site of the ultimate injury.[14] These lesions are seemingly subclinical because the horses harboring them appear to be sound at the walk and the trot. Were they not, they would not be in the race in which they suffer a catastrophic musculoskeletal injury. However, it is apparent that the sensations and forces experienced by the limbs of a horse galloping at stride frequencies of up to 150/min are very different from those associated with walking and trotting.[15] When racing, each limb is in contact with the ground for < 100 milliseconds and is accelerating and decelerating so fast that it evades visual detection.

It is important to differentiate between the function of GPS-based devices and accelerometers. Global Positioning System–based devices determine a horse's instantaneous location and, when it is moving from one point to another, calculate the distance between the 2 points and the time it took the horse to go from the first to the second point, and express these measurements as the horse's speed. The accuracy of these measurements can vary greatly. For example, the GPS in the sensor used in the described cases is accurate to within 10 cm, while the accuracy of that in a smartphone is about 5 m. By contrast, the accelerometer-based IMU sensors worn by the horses featured in the described series of cases are determining the *rates of change* in momentum per unit change in time (ie, acceleration or deceleration) in the dorsoventral, longitudinal, and mediolateral planes as indirect measurements of the forces (F) being experienced, in accordance with Newton's second law of motion ($F = ma$, where m = the mass being accelerated and a = acceleration or deceleration). By virtue of the high frequency of their measurements, these IMUs are the first that have been demonstrated to effectively record the forces and vibrations to which a horse's body is being subjected during a gallop at maximum speed.

The frequencies at which these sensors can record movements in the dorsoventral, longitudinal, and mediolateral planes and the resultant algorithm that is applied to these recordings have been central to the ability of this sensor system to detect motions that are far from what is ideal for racehorses at these speeds and are at increased risk of sustaining a catastrophic injury. The degree to which this risk factor is elevated has been categorized at levels that range from 2 to 5, with the risk increasing as the number increases when compared to the minimal risk factor = 1. Thus, this accelerometer-based IMU sensor system is not a diagnostic instrument. Rather, it serves as a risk assessment tool with which to screen horses during races and breezing and to assign them to 1 of 5 risk factor categories. This includes identifying those most at risk of suffering a catastrophic injury should they continue to train and race. As demonstrated by the 3 cases described herein, it still requires a thorough veterinary clinical evaluation to diagnose the problem or problems afflicting the horse. Use of advanced imaging and other technologies may be essential parts of the actual diagnostic process given that many of these cases appear sound to the naked eye.

While every effort was made to notify the trainers of horses assigned a risk factor = 5 regarding the heightened catastrophic injury risk of their horses and to communicate recommendations regarding the need for a follow-up veterinary diagnostic evaluation, we are unsure of how successful these efforts were. Some phone calls were not returned, and many of the horses that raced at Churchill Downs and Ellis Park during the sensor data–collection period did not train at these tracks. For unknown reasons (and there are many possibilities), 38 of these horses had not returned to racing 11 months later.

Identifying "false positives" and "false negatives" is a metric that is often calculated when evaluating the sensitivity and specificity of a diagnostic test. However, calculating such a number is irrelevant in relation to the use of this IMU sensor system for several reasons. First, the assessment of the IMU

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stride pattern by the algorithm does not constitute a diagnostic test. It is a risk assessment tool. The algorithm assesses the level of risk of catastrophic breakdown on the basis of the recorded stride pattern and assigns each horse to 1 of 5 risk factor categories. Every horse is at some degree of risk every time it races or breezes. The level of risk is very low for the approximately 70% of horses with a risk factor = 1, but it is not zero. The risk factor for the remaining approximately 30% of horses varied from 18 (risk factor = 2) to 950 (risk factor = 5) times higher than that for risk factor = 1 horses. It is important to keep in mind that, at the current stage in the development of the sensor system and its associated algorithm, the risk assessment factor is based on the population of horses, race starts, and injuries in the database and may not exactly reflect the level of risk to an individual horse. As the use of the IMU sensor system increases, it is hoped that the number of files for individual horses will also grow and eventually enable the level risk of catastrophic injury to be more individualized to a given horse. The algorithm in use is regularly updated as data from more horse starts and injuries are added. As such, the algorithm is a dynamic instrument and, as the database increases, it can be expected that there will be some change in the likelihood of catastrophic injury associated with each risk category. It is anticipated that with further data the algorithms will be more capable of pinpointing those horses at greatest risk.

The primary aim of using this sensor system is to eventually prompt an appropriate clinical evaluation that leads to an intervention that prevents the occurrence of a catastrophic injury in 100% of the most at-risk horses (risk factor = 5). While there were no regulations mandating advanced diagnostic imaging for horses with a risk factor = 5, several of these horses' trainers with whom contact was made eventually sought advanced diagnostic evaluations including PET scans. In all but the 3 cases described herein, those horses had continued to breeze and sometimes race without wearing sensors after their trainers were informed of concerns regarding their risk for catastrophic injury. In all cases of horses with a risk factor = 5 that were presented for PET scans, the images revealed areas of increased uptake of ^{18}F-NaF that were compatible with increased risk of such injuries. We elected to report on the 3 cases that were evaluated within 10 days of being assigned a risk factor = 5 because they had not been breezed subsequent to that race, whereas in the other cases, the possibility that there had been additional damage to 1 or more limbs could not be ruled out.

In this case series, the data collected using these sensors, coupled with assessment of the horse's risk factor by the algorithm, provided an unprecedented objective depiction of the forces of locomotion produced by individual horses at racing speed. In these 3 clinical cases, the IMU sensor system measured these forces in 3 directions—dorsoventral, mediolateral, and longitudinal—collecting 800 data points/s in each direction for a total of 2,400 points/s. The format in which data were displayed allowed us to observe variations in motion forces in each limb and phase of the stride. Marked deviations from the norm in the mediolateral plane gave us the potential to identify the quadrant that was at the greatest risk of injury, thereby providing vital information to the horses' veterinarians and trainers and guiding them in their clinical evaluation of the horse.

Prerace examination of Thoroughbreds includes watching the horse in motion while trotting in hand in a straight line on a firm, level surface. The same is typical for the majority of equine soundness evaluations, be they carried out by a trainer or their veterinarian. The trot is a 2-beat symmetric gait consisting of a diagonal sequence of the 2 contralateral pairs of fore- and hind limbs. During the trot, the head and pelvis move up and down at equivalent amplitudes twice per stride. The ground contact time of each limb at the trot is similar.[16] Depending on the phase of the stride in which discomfort is felt by a horse, it may easily adjust its movement to increase propulsion from a sound limb and decrease shock absorption in a painful limb. The result is an asymmetric vertical head and pelvic movement.[15] This asymmetry, depending on its magnitude, can be observed visually or measured objectively with the use of inertial sensors.[17] The trot differs significantly from the gallop, which is an asymmetric 4-beat gait. In the gallop, the forelimbs land asynchronously and are followed by an airborne phase.[13] The horses also change lead legs. During the airborne phase, the hind limbs draw forward, tuck under the horse, and then land individually in close succession, in the same sequence as the corresponding forelimbs. As each limb has its own function and ground contact time, when pain is felt in a limb at the gallop, the gait adjustments made by the horse to alleviate discomfort are not as readily apparent as with the asymmetries seen at the trot.

Not every horse that exhibits discomfort and deviations from the ideal stride at a racing gallop will exhibit lameness at a trot. Due to its viscoelastic properties, the response of bone to load depends on the rate of application of the load.[18] The bending and torsional loads exerted on the distal limb are greater during high-speed work, and discomfort felt when the bone is under these conditions at a gallop might not be elicited during the trot.[18] This can pose a problem for the veterinarian examining the horse. The potential for the IMU sensor system to suggest the quadrant or quadrants at risk offers the veterinarian an area to focus on when examining a horse that has been identified as being at high risk for catastrophic injury when galloping but is subjectively sound at a trot. In doing so, it may facilitate the identification of an area for diagnostic imaging and reaching a diagnosis. It should be noted that improving the ability of the sensors' algorithm to better identify the quadrant or quadrants at greatest risk of catastrophic injury requires additional clinical data from more risk factor = 5 horses to enable fine-tuning and improvement of the algorithm. Furthermore, increasing the number of planes in which data are recorded could enhance the sensitivity of the sensor system with respect to assessing a horse's at-risk status.

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The horses in this case series each underwent advanced imaging in the form of an ^{18}F-NaF PET scan within 10 days of being assigned a risk factor = 5. No further fast exercise was undertaken in this period, thereby maximizing the likelihood that the abnormalities identified on the PET scan were associated with the source of the risk factor = 5 score. Positron emission tomography provides "functional" or "molecular" imaging, in that it identifies areas of increased bone remodeling or soft tissue metabolism, often doing so before any structural changes are evident.[12,13,19–21] Imaging these horses with the standing PET unit provided some advantages, such as not requiring them to undergo general anesthesia.[22] Furthermore, it facilitated imaging of multiple sites in a short period of time, with a complete scan of a fetlock taking approximately 3 minutes. The introduction of an on-site standing PET unit at Churchill Downs in the spring of 2023 made it accessible and convenient for horses being trained at the racetrack to utilize this amenity. However, while growing, the availability of standing PET when compared to that of CT or MRI is still comparably low. At the time of writing, 10 standing PET units exist in the US, with 3 in the Commonwealth of Kentucky. Structural imaging utilizing MRI or CT was not performed on these risk factor = 5 horses. Consequently, the extent to which these modalities can identify pathologies on horses deemed to be at highest risk by the sensor system remains to be ascertained.

The sites and distribution of increased ^{18}F-NaF uptake in the fetlocks and carpus of the 3 cases indicated that they were at increased risk of condylar fracture or fracture of the third carpal bone, respectively, had they continued to train and race. Both types of injuries have the potential to be career- or life-ending. The 3 horses had been cleared to race and train by both the trainers' veterinarians and the regulatory veterinarians in prerace examinations, as overt lameness was not evident when examined at a trot. The sensors' identification of these horses as being at the highest risk of a serious musculoskeletal injury resulted in these horses undergoing increased clinical scrutiny, consequently receiving appropriate periods of convalescence and avoiding severe injury. All 3 of the horses have returned to training and in 2 cases returned to racing where, on the basis of recordings made by the same IMU sensor system, their risk of injury had been greatly reduced.

Currently, several commercially available inertial sensor systems exist that have been specifically designed to utilize objective data to identify stride asymmetry and lameness at the trot. However, application of these systems on horses at the gallop has not been transferable.[17,23–25] While these have proven to be useful diagnostic aids when evaluating asymmetry at a trot, their application as mass screening tools is impractical in racing Thoroughbreds. This stems from the labor intensity involved in their data collection and lack of corroboration between asymmetry at the trot and deviations from the ideal stride at the gallop.

While not every horse that is assigned a risk factor = 5 will suffer a fatal catastrophic injury, the gait irregularities detected by the sensor system indicate a heightened susceptibility to musculoskeletal injuries. These injuries can also necessitate extended periods of convalescence and, in certain cases, surgical intervention or retirement from racing if not identified early in their existence.[1] These occurrences result in additional costs, loss of earnings, smaller racing fields, fewer lifetime starts, shorter racing careers, and limited opportunities for horses to pursue a second career following retirement from racing.[26–30]

The data provided by the sensors worn by horses racing and breezing at Churchill Downs and Ellis Park Racetrack identified the 3 horses described in this series of cases as being at high risk of a catastrophic musculoskeletal injury. Clinical evaluation included advanced imaging that identified lesions indicating pathological changes that, had they continued to train and race, might have resulted in catastrophic injury. These are the first published cases to have benefited directly from the use of this accelerometer-based IMU sensor system. Recent advances in the use of this sensor technology in airplanes have led to the ability to record pitch, yaw, and roll, which are angular measures around the vertical and horizontal planes. Future inclusion of these measurements in the sensor system utilized in these 3 cases may lead to a more comprehensive description of the stride characteristics of racing Thoroughbreds. The ongoing and widespread deployment of these accelerometer-based IMU sensors across race tracks can be expected to ultimately result in further refinement of the interpretive algorithm and enhancement of the accuracy of at-risk quadrant identification. As it stands, these sensors currently offer the greatest potential for use as a risk-assessment tool with which to identify racing and breezing horses at highest risk of suffering catastrophic musculoskeletal injuries. As demonstrated by the series of cases described herein, the continued and broader use of this sensor system, in combination with appropriate follow-up veterinary intervention, can further reduce the incidence of catastrophic life- and career-ending musculoskeletal injuries in the US and worldwide.

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Disclosures

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