Summary of PhD theses

Comparative diagnostic imaging of the metacarpophalangeal joints in Thoroughbred racehorses: a longitudinal study

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1. Background and objectives of the doctoral dissertation

Musculoskeletal injury is the leading cause of lost training days, morbidity and catastrophic breakdown in Thoroughbred racehorses. The metacarpophalangeal joint is particularly vulnerable because of its anatomy and the extreme cyclic loads encountered during high-speed gallop. Repetitive loading stimulates modelling of bone mass and architecture, whereas remodelling removes and replaces fatigued or microdamaged bone. If microdamage accumulates faster than it can be repaired, fatigue-related osseous injury and fracture may develop.

Diagnostic imaging is central to the detection and monitoring of these changes. Radiography remains an important first-line and screening modality, but early stress-related osseous abnormalities may be subtle or invisible because of superimposition and limited contrast resolution. Standing fan-beam computed tomography (FBCT) and low-field magnetic resonance imaging (MRI) allow detailed cross-sectional evaluation of the distal limb without general anaesthesia. These modalities provide complementary information: CT depicts mineralised bone directly through X-ray attenuation, whereas MRI demonstrates changes in bone signal and can simultaneously evaluate associated soft tissues and osteochondral structures.

At the start of this doctoral project, most available imaging studies were cross-sectional or focused on horses already presenting with

lameness. Longitudinal data describing how the fetlock of an actively training, non-lame racehorse changes over several racing seasons were limited. This distinction is important because an imaging abnormality identified during screening does not automatically represent clinically relevant disease. Reliable reference information on the temporal behaviour of osseous findings is needed to distinguish training-related adaptation from lesions that may represent fatigue injury or an increased risk of fracture.

The present project therefore established a prospective, longitudinal and multimodality imaging dataset of young Thoroughbred racehorses from the onset of training. Repeated radiographic, FBCT and low-field MRI examinations were combined with clinical and objective lameness assessment. The project focused on three anatomical regions that are exposed to substantial load during fetlock extension: the sagittal ridge (SR) and condyles of the third metacarpal bone (McIII), and the proximal sesamoid bones (PSBs).

Radiographic abnormalities of the SR are common in Thoroughbred yearlings and have been associated with joint effusion, lameness and reduced sales prices. Computed tomographic examinations of young Thoroughbreds have demonstrated dorsal SR hypoattenuating lesions, subchondral bone (SCB) plate thickening and increased trabecular attenuation. However, the longitudinal behaviour of these findings during the first year of training had not been characterised in detail. The SR component of the project was therefore designed to

describe both objective changes in attenuation and the temporal development of focal CT abnormalities.

The PSBs are integral components of the suspensory apparatus and are exposed to large tensile and compressive forces during high-speed locomotion. Radiographic changes such as enlarged vascular channels and abnormalities of the abaxial margin may be associated with racing performance and with more severe PSB pathology. Ex vivo research has also shown that bone density is altered by training and may differ in fractured PSBs. Nevertheless, there was little longitudinal information on overall PSB radiodensity in living horses followed from the onset of race training.

Training-related densification of the palmar aspect of the metacarpal condyles is also well recognised. Advanced imaging studies have linked marked sclerosis, parasagittal groove abnormalities and microdamage with condylar fracture. Magnetic resonance imaging derived measurements of the extent of low-signal condylar densification have been proposed as potentially clinically useful, but thresholds developed with one modality cannot be assumed to be applicable to another. Direct longitudinal comparison of FBCT- and low-field MRI-derived measurements in the same population of actively training Thoroughbreds was therefore required.

Objectives

- To describe the CT appearance of the SR of McIII using subjective and objective assessment and to document the

progression of these findings during the first year of training and racing.

- To determine whether mean attenuation of the dorsal and palmar halves of the SR increases after the commencement of race training and to assess whether dorsal SCB hypoattenuating lesions change in size or appearance over time.
- To evaluate the radiographic appearance of the forelimb PSBs using a predefined grading system, follow radiographic changes for approximately two and a half years, and quantify longitudinal changes in overall PSB radiodensity on FBCT images.
- To investigate associations between PSB radiodensity and exercise exposure, body size, limb side and medial-lateral location, and to evaluate factors associated with abaxial margin changes.
- To measure the maximal extent of metacarpal condylar densification in the axial, middle and abaxial thirds on FBCT and low-field MR images, describe its longitudinal development, and compare measurements obtained using the two modalities.
- To determine whether condylar densification is associated with racing exposure and body size and whether MRI- and CT-derived measurements are sufficiently similar to be interpreted using common thresholds.

2. Materials and methods

2.1. Study population and lameness examination

A convenience sample of 40 Thoroughbred yearlings was enrolled at the onset of racehorse training. Horses had no history of metacarpophalangeal joint disease and no clinically apparent lameness at inclusion. Signalment, body weight, height at the withers and racing exposure were recorded. Four re-examinations were planned at approximately six-month intervals (times 1-4), resulting in a potential follow-up period of approximately two and a half years.

At each examination, both forelimbs were assessed clinically with particular attention to the fetlock region. Joint distension, local or diffuse swelling, heat, pain on palpation or manipulation and restriction of passive motion were recorded. Subjective lameness assessment was supplemented by objective gait analysis. From time 1 onwards, flexion tests and examination on the lunge or led in circles on soft and hard surfaces were performed when behaviour allowed. Horses with forelimb lameness underwent diagnostic perineural anaesthesia to localise the source of pain.

2.2. Diagnostic imaging

All diagnostic imaging was performed in standing sedated horses. Both metacarpophalangeal joints were examined radiographically using standard and additional projections. Repeated imaging was performed using consistent positioning protocols as far as possible.

Fan-beam CT examinations were acquired with a 16-detector multislice helical scanner with a 90 cm bore. Both fetlocks were scanned from the distal third of the metacarpus to the proximal phalanx. Acquisition parameters affecting Hounsfield unit (HU) measurements were kept identical throughout the study: 135 kV, 350 mA, 0.5 s rotation time, 300 mm field of view and 0.5 mm acquired slice thickness. Sagittal, frontal and transverse reconstructions were generated for image analysis.

Low-field MRI was performed using a standing 0.27 T system. The protocol included sagittal, frontal and transverse T1-weighted gradient recalled echo sequences, T2*-weighted gradient recalled echo sequences, STIR sequences and a transverse T2-weighted fast spin echo sequence. The sagittal T1-weighted sequence was used for linear measurement of condylar densification.

2.3. Image analysis and statistical methods

For the SR study, only times 0-2 were analysed because the first year of training was considered the most informative period for early adaptation. The SR was divided into dorsal and palmar halves and mean attenuation was quantified in HU. Dorsal SCB hypoattenuating lesions were assessed for location, shape and proximodistal and dorsopalmar extent. SCB plate thickening and trabecular hyperattenuation were recorded subjectively.

For the PSB study, overall bone radiodensity was measured on FBCT images with large regions of interest designed to include the

whole PSB while excluding adjacent soft tissues. Radiographs were graded using predefined criteria based mainly on vascular channel number and width, and the presence of abaxial new bone, abaxial margin concavity and irregularity of the abaxial surface was recorded.

For the metacarpal condyle study, the palmar aspect of each medial and lateral condyle was divided into axial, middle and abaxial thirds. On sagittal T1-weighted MR images, the greatest linear extent of low-signal densification perpendicular to the articular surface was measured in each third. Corresponding measurements were obtained on sagittal CT reconstructions as the greatest linear extent of hyperattenuating bone. A preliminary repeatability study compared CT reconstruction slice thicknesses of 0.5, 1, 2 and 3 mm; 2 mm reconstructions provided the best repeatability and were used for subsequent analysis.

A single assessor performed all measurements. MRI measurements were completed before CT measurements, and MRI values were not visible during CT assessment. Statistical analysis used mixed-effects models to account for repeated observations within horses. Depending on the outcome, linear or logistic mixed models were used. The number of total race starts was selected as the most biologically meaningful measure of cumulative racing exposure in the main models. Because body weight and height were associated and moderately correlated, the body weight:height ratio was used in

the multivariable PSB and condylar models. Correlations between MRI and CT measurements were assessed using Spearman's rank correlation, and paired differences between modalities were tested using non-parametric methods.

3. Results

Forty Thoroughbred yearlings (26 colts and 14 fillies) from 10 trainers were examined at time 0. Thirty-one horses returned at time 1, 23 at time 2, 13 at time 3 and 8 at time 4. Attrition reflected trainer or owner compliance, cessation of training, retirement and two deaths unrelated to musculoskeletal injury. By times 3 and 4 all participating horses were in active race training, had performed fast work and had raced at least once.

At times 1, 3 and 4, three horses at each examination showed forelimb lameness; no overt forelimb lameness was detected at time 2. Lameness was substantially improved or abolished with palmar digital, abaxial sesamoid or low four-point nerve blocks. Most longitudinal imaging changes described below therefore occurred in horses without clinically relevant fetlock pain.

3.1. Sagittal ridge of the third metacarpal bone

The mean attenuation of the SR increased rapidly after the onset of training. In the dorsal half, observed mean values increased from 914.5 +/- 92.2 HU at time 0 to 998.1 +/- 84.7 HU at time 1 and 999.8 +/- 81.0 HU at time 2. Corresponding palmar values were 741.9 +/- 74.4 HU, 806.0 +/- 80.9 HU and 813.1 +/- 86.9 HU. The increase from time 0 to time 1 was significant in both halves ($p<0.001$), whereas there was no further significant increase between times 1 and 2. The dorsal half was significantly denser than the palmar half ($p=0.023$).

Dorsal SR hypoattenuating lesions were common at baseline but tended to regress rather than progress. Lesions were detected in 33/80 limbs (41.3%) at time 0, 22/62 limbs (35.5%) at time 1 and 14/46 limbs (30.4%) at time 2. No new lesion was identified at a follow-up examination if it had not been present previously. In 11 limbs, a lesion was no longer detectable at a later examination, and no lesion increased in size during the study period. All lesions were dorsodistal, most commonly axial, and the most frequent morphologies were proximodistally elongated defects and lesions extending towards the trabecular bone.

Subchondral bone plate thickening of the dorsal SR was present in more than 90% of limbs at all three examinations. Patchy trabecular hyperattenuation became progressively more common, increasing from 17.5% of limbs at time 0 to 33.8% at time 1 and 52.2% at time 2. These findings, together with the HU increase, indicate substantial training-related osseous adaptation in the region during the first year.

3.2. Proximal sesamoid bones

Overall PSB radiodensity changed significantly over time. Mean HU was lowest at time 0 (1064.0 +/- 65.1) and highest at time 3 (1194.5 +/- 78.6). At time 4, mean HU decreased to 1109.4 +/- 77.2 but remained above baseline. One horse with particularly low values at time 4 had undergone eight weeks of rest followed by a gradual return to light training, illustrating the potential reversibility of workload-related densification.

In the multivariable model, PSB radiodensity increased with cumulative racing exposure: each additional race start was associated with an estimated increase of 6.1 HU ($p<0.001$). A greater body weight:height ratio was also associated with higher HU (119.0 HU per unit increase, $p<0.001$), and medial PSBs had greater overall radiodensity than lateral PSBs ($p=0.01$).

Radiographic abaxial margin features also changed during follow-up. Abaxial new bone was strongly associated with higher PSB grade; the odds of detecting new bone were more than 20 times higher in grade 3 than grade 0 PSBs ($p=0.004$), and new bone was more frequent laterally ($p=0.04$). In contrast, the odds of abaxial concavity and surface irregularity decreased with increasing age, and both features were more common in medial PSBs. Serial radiographs demonstrated that concavities and irregularities could become less conspicuous or resolve while horses remained in training.

The distribution of PSB grades did not change in a simple linear direction. From time 0 to time 4, the observed proportions of grade 0 and grade 3 PSBs increased, whereas grades 1 and 2 decreased. The longitudinal behaviour of individual radiographic abnormalities therefore showed that some apparently adverse features may improve over time, while a subset of PSBs develops more marked grading changes.

3.3. Metacarpal condylar densification

For the condylar study, 39 horses were available at time 0 because one horse could not undergo MRI. After exclusion of condyles with incomplete MR sampling, 438 complete condyles were analysed across all time points. Repeatability of CT linear measurements was best with 2 mm reconstructions (coefficient of variation 7.6%), compared with 10.8%, 12.2% and 10.4% for 0.5, 1 and 3 mm reconstructions, respectively.

The middle third of the condyle was the most frequent site of maximal densification with both imaging modalities and at all examination rounds. In condyles where the maximum was axial or abaxial at baseline, the location often shifted towards the middle third over time, particularly on CT. This supports the concept of spatially patterned load-related adaptation rather than uniform thickening of the palmar subchondral bone.

MRI and CT measurements were significantly related but not interchangeable. There was a moderate positive correlation between maximal MRI and CT measurements for the whole condyle (Spearman rho=0.69, $p<0.001$) and for the middle third (rho=0.69, $p<0.001$), with weaker correlations in the axial and abaxial thirds. Paired comparisons demonstrated significantly larger CT measurements than MRI measurements for the whole condyle and for most regional comparisons. Thus, a numerical threshold derived from one modality should not be transferred directly to the other.

In multivariable mixed-effects models, increasing maximal condylar densification on both MRI and CT was associated with an increasing total number of race starts ($p<0.001$). Greater body weight:height ratio was also associated with larger measurements on MRI ($p=0.001$) and CT ($p=0.003$). CT measurements were additionally greater in the middle than the abaxial third ($p=0.05$). These results demonstrate progressive adaptation with racing exposure and suggest that body size modifies the osseous response to repetitive loading.

4. Discussion and conclusions

The principal finding of this work is that substantial osseous change can occur in the fetlocks of actively training Thoroughbred racehorses in the absence of clinically relevant lameness. Across the SR, PSBs and metacarpal condyles, bone density or the extent of densification generally increased with training and racing exposure. The pattern was not static: reduced work was associated with lower PSB radiodensity, and several focal radiographic or CT abnormalities became less conspicuous with time.

The rapid increase in SR attenuation during the first six months, followed by a plateau, is compatible with early adaptive modelling after the onset of higher-speed exercise. Greater attenuation dorsally than palmarly is biologically plausible because the dorsal SR is directly involved in articulation with the sagittal groove of the proximal phalanx during loading. At the same time, the high prevalence of dorsal SCB plate thickening and the increasing frequency of patchy trabecular hyperattenuation indicate that interpretation should consider both the distribution and temporal behaviour of the change.

The longitudinal behaviour of dorsal SR hypoattenuating lesions is clinically relevant. These lesions were common at baseline, did not enlarge during follow-up, and in several limbs decreased in size or disappeared. None of the follow-up examinations identified a newly developed lesion that had not been visible previously. In this

population, therefore, the mere presence of a small dorsal SR hypoattenuating lesion in a young horse should not automatically be interpreted as progressive disease. Morphology, surrounding sclerosis, clinical findings and longitudinal change remain important.

The PSB results further demonstrate a close relationship between workload and bone density. The association with number of race starts, and the reduction in mean HU after a period of reduced training, support the interpretation that PSB radiodensity is dynamic. Higher density of medial PSBs may reflect asymmetrical loading. The association with body weight:height ratio suggests that mechanical demand related to body size also contributes to the adaptive response.

Radiographic PSB findings require similarly cautious interpretation. Abaxial new bone was associated with higher PSB grade and therefore may represent a more advanced adaptive or pathological response. In contrast, abaxial concavities and irregularities became less likely with age and could improve on serial radiographs despite continued training. The coexistence of improvement in some features and worsening grading in others underlines the value of longitudinal assessment rather than a single examination.

The condylar study showed a consistent spatial pattern, with maximal densification most often located in the middle third. Increasing racing exposure was associated with increasing densification on both CT and MRI. These findings are consistent

with repetitive load-related adaptation of the palmar condyles, but the study did not directly establish a fracture-risk threshold. Densification should therefore be interpreted as a descriptive imaging feature rather than as a diagnosis of fatigue injury in isolation.

The moderate correlation between MRI and CT indicates that both modalities identify the same general biological phenomenon, but the systematic difference in measured extent is crucial. Computed tomographic values were consistently greater. Differences in slice thickness, spatial resolution, volume averaging and the physical basis of image contrast are likely contributors. Computed tomography more directly depicts mineralised bone, whereas MRI reflects changes indirectly through signal intensity. Consequently, modality-specific reference values are required and MRI-based thresholds should not be transferred to FBCT.

The study has limitations. Attrition was high, which is common in longitudinal racehorse research and may introduce survivorship bias. The number of horses at later examinations was small. Training programmes were not standardised, no calibration phantom was used for HU measurements, and there was no histological validation of imaging findings. Intrasynovial anaesthesia was not performed in horses that developed lameness. The findings should therefore be interpreted as longitudinal reference data from a defined population rather than universal diagnostic cut-offs.

In conclusion, repeated FBCT, low-field MRI and radiographic examinations demonstrated progressive and partly reversible osseous adaptation in the metacarpophalangeal joints of young Thoroughbreds during active training and racing. Densification of the SR, PSBs and metacarpal condyles increased with exercise exposure, while selected focal abnormalities of the SR and PSB margins could improve over time without cessation of training. The systematic difference between MRI and CT measurements emphasises the need for modality-specific interpretation. Together, these findings provide a framework for more informed interpretation of advanced imaging findings during screening, clinical investigation and future injury-prevention research.

5. Novel scientific findings

5.1. A prospective longitudinal multimodality imaging dataset of the metacarpophalangeal joints of Thoroughbred racehorses without clinically relevant lameness was established, with horses being followed from the onset of race training through repeated CT, MRI, and radiographic examinations over approximately two and a half years.

5.2. Substantial training-related osseous adaptation was demonstrated at the evaluated sites (the metacarpal condyles, PSBs, and SR) in the metacarpophalangeal joints of Thoroughbred racehorses during race training, in the absence of overt lameness, demonstrating progressive changes in bone density and morphology associated with repetitive high-speed loading.

5.3. An increase in density was observed in the SR during the first six months of race training.

5.4. Greater density of the SR was observed in the dorsal half compared with the palmar half.

5.5. Variation in shape was identified among the hypoattenuating lesions in the dorsal aspect of the SR.

5.6. A decrease in SR hypoattenuating lesion size was observed, and resolution of some lesions was recorded during the first year of training.

5.7. An increase in PSB radiodensity was identified in association with the number of race starts.

5.8. A decrease in overall PSB radiodensity was associated with light or reduced training.

5.9. Radiographic improvement of PSB grades, abaxial margin concavities, and irregularities was observed, despite active training.

5.10. Computed tomographic reconstructions with 2 mm slices were found to be the most consistent for metacarpasl condylar densification measurements.

5.11. The greatest extent of densification was most frequently measured in the middle third of the condyles.

5.12. Metacarpal condyle densification measurements obtained on FBCT and low-field MR images were found to be correlated but differed significantly, with CT measurements being larger than MRI measurements.

5.13. An increase in condylar density was identified in association with the number of race starts and the body weight ratio.

6. Publications related to the doctoral research

a) Publications in peer-reviewed scientific journals

1. Boros K, Nagy A. Diseases of the fetlock joint in Thoroughbred racehorses. Part 1: The role of biomechanics and bone adaptation in the development of injuries. Literature review. Hungarian Veterinary Journal 2022;144:387-396.
2. Boros K, Nagy A. Diseases of the fetlock joint in Thoroughbred racehorses. Part 2: Articular and osseous abnormalities. Hungarian Veterinary Journal 2023;145:67-80.
3. Boros K; Dyson S, Kovács Á, Lang Z, Nagy A. Computed Tomographic Evaluation of the Sagittal Ridge of the Third Metacarpal Bone in Young Thoroughbred Racehorses: A Longitudinal Study. Animals. 2024;14(5):812. https://doi.org/10.3390/ani14050812
4. Boros K, Dyson S, Pollard D, Nagy A. A longitudinal study of radiodensity and radiographic appearance of the proximal sesamoid bones in Thoroughbred racehorses. Equine Vet J. 2026;58(4):946-958. https://doi.org/10.1111/evj.70075

b) Conference presentations

National

1. Boros K, Dyson S, Nagy A. Computed tomographic and radiographic findings in the metacarpophalangeal joints of non-

lame Thoroughbred yearlings. Hungarian Association of Equine Practitioners Congress 2022, Vecsés , clinical research report

2. Boros K, Dyson S, Nagy A. Computed tomographic and radiographic findings in the metacarpophalangeal joints of non-lame Thoroughbred yearlings. Hungarian Academy of Sciences, Veterinary Science Committee; Doctoral School of Veterinary Science, Academic Reports 2023, Budapest, clinical research report
3. Boros K, Dyson S, Nagy A. Computed tomographic evaluation of the sagittal ridge of the third metacarpal bone in Thoroughbred racehorses in their first year of training: a longitudinal study. Hungarian Association of Equine Practitioners Congress 2023, Kecskemét, clinical research report
4. Boros K, Dyson S, Nagy A. Comparative diagnostic imaging of the metacarpophalangeal joints in Thoroughbred racehorses: a longitudinal study. Hungarian Academy of Sciences, Veterinary Science Committee; Doctoral School of Veterinary Science, Academic Reports 2024, Budapest, clinical research report
5. Boros K, Dyson S, Nagy A. Computed tomographic evaluation of the sagittal ridge of the third metacarpal bone in Thoroughbred racehorses in their first year of training: a longitudinal study. Hungarian Symposium of Agricultural Doctoral Students 2024, Budapest, clinical research report
6. Boros K, Dyson S, Pollard D, Nagy A. Radiographic and computed tomographic evaluation of the proximal sesamoid

bones in Thoroughbred racehorses: a longitudinal study. Hungarian Association of Equine Practitioners Congress 2024, Gárdony, clinical research report

7. Boros K, Dyson S, Pollard D, Nagy A. Radiographic and computed tomographic evaluation of the proximal sesamoid bones in Thoroughbred racehorses: a longitudinal study. Hungarian Academy of Sciences, Veterinary Science Committee; Doctoral School of Veterinary Science, Academic Reports 2025, Budapest, clinical research report

8. Boros K, Dyson S, Pollard D, Nagy A. Comparative magnetic resonance imaging and computed tomographic evaluation of the metacarpal condyles in Thoroughbred racehorses. University Research Scholarship Programme Conference 2025, Budapest, clinical research report

9. Boros K, Dyson S, Pollard D, Nagy A. Comparative magnetic resonance imaging and computed tomographic evaluation of the metacarpal condyles in Thoroughbred racehorses. Hungarian Academy of Sciences, Veterinary Science Committee; Doctoral School of Veterinary Science, Academic Reports 2026, Budapest, clinical research report

10. Boros K. MRI and CT findings in the fetlock joints of Thoroughbred racehorses. Hungarian Academy of Sciences, 200 Years of the Hungarian Academy of Sciences 2026, Budapest

International

1. Boros K, Dyson S, Nagy A. Computed tomographic and radiographic findings in the metacarpophalangeal joint of Thoroughbred yearlings. British Equine Veterinary Association Congress 2022, Liverpool, clinical abstract, https://doi.org/10.1111/evj.12_13855
2. Boros K, Dyson S, Nagy A. Computed tomographic evaluation of the sagittal ridge of the third metacarpal bone in Thoroughbred racehorses in their first year of training: a longitudinal study. European College of Veterinary Sports Medicine and Rehabilitation Congress 2023, Paris, clinical abstract
3. Boros K, Dyson S, Pollard D, Nagy A. Radiographic and computed tomographic evaluation of the proximal sesamoid bones in Thoroughbred racehorses: a longitudinal study. European Veterinary Diagnostic Imaging Congress 2024, Athens, clinical abstract, https://doi.org/10.1111/vru.13470
4. Boros K, Pollard D, Nagy A. Longitudinal computed tomographic and magnetic resonance imaging evaluation of bone density changes in the metacarpal condyles of Thoroughbred racehorses. International Conference: Applying Science to the Care of the Thoroughbred Racehorse 2025, Hong Kong, poster presentation
5. Boros K, Dyson S, Pollard D, Nagy A. Comparative computed tomographic and magnetic resonance imaging evaluation of metacarpal condylar densification in Thoroughbred racehorses. British Equine Veterinary Association Congress 2026, Birmingham, clinical abstract