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Alterations to the synovial invaginations of the navicular bone are associated with pathology of both the navicular apparatus and distal interphalangeal joint when evaluated using high field MRI

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No EQUATOR network checklist was used.

Abstract

Limited information exists regarding associations between distal interphalangeal joint (DIPJ) abnormalities and synovial invagination changes in the distal sesamoid (navicular) bone. This retrospective, analytical study aimed to measure specific characteristics of the synovial invaginations of the navicular bone to determine whether any single characteristic was associated with abnormalities in the DIPJ or navicular apparatus (NA) using high field MRI and a sample of 200 horses' feet. The DIPJ and NA were graded independently by three scorers. The grades were averaged, creating a global pathology score for the DIPJ, NA, and synovial invaginations. Higher global scores represented more severe pathology. The number of invaginations, depth of penetration, invagination shape, and cross-sectional area (CSA) of the largest invagination were recorded. Interobserver agreement was measured using Cohen's Kappa. Associations of global scores of the DIPJ and NA with individual invagination characteristics were assessed using linear mixed modeling. A significant relationship was found between the number of invaginations and global DIPJ score, with higher invagination numbers associated with higher DIPJ scores. For invagination depth and CSA, a significant relationship was noted with global scores of both the DIPJ and NA. Reliable relationships between the shape of synovial invaginations and global scores of DIPJ and NA were not found, likely due to poor interobserver scoring (0.305). These findings suggest that primary DIPJ disease and NA pathology should be considered when noticing alterations to navicular synovial invaginations on MRI. This contrasts traditional views that synovial invagination abnormalities are indicative solely of NA pathology.

KEYWORDS
distal sesamoid bone, foot, horse, imaging

Abbreviations: CSA, cross-sectional area; DDFT, deep digital flexor tendon; DIPJ, distal interphalangeal joint; MRI, magnetic resonance imaging; NA, navicular apparatus.

1 | INTRODUCTION

Despite abundant literature on diagnostic imaging findings of the equine foot, there is a lack of information regarding associations between imaging changes of the synovial invaginations of the distal border of the distal sesamoid bone (navicular bone) and concurrent imaging changes within the distal interphalangeal joint (DIPJ) and navicular apparatus (NA). It is the lack of such information that leads to the debate about the etiology and clinical relevance of alterations of the synovial invaginations of the navicular bone.[1–3]

Previous studies reported variation in the number and appearance of synovial invaginations in nonlame horses.[1,4,5] Certain changes to the synovial invaginations as seen radiographically, such as the presence of >7 invaginations, an increase in size, an abnormal shape and invaginations located in the medial and lateral obliquely oriented sides of the bone, are considered abnormal.[6,7] These abnormalities are still commonly considered pathognomonic for navicular disease.[8–10] The relevance of understanding alterations in synovial invaginations of the navicular bone on diagnostic imaging is important, as treatment decisions and predictions for future soundness and athletic performance are often made based upon them. To date, no studies have evaluated the relationship between imaging findings of the synovial invaginations of the navicular bone and concurrent imaging findings elsewhere in the foot (such as the DIPJ). A recent study demonstrated communication of the synovial invaginations of the navicular bone with the DIPJ,[5] so it is possible that DIPJ abnormalities are associated with abnormal changes to the synovial invaginations of the navicular bone.

The objectives of the current study were to evaluate how variations within the synovial invaginations of the distal border of the navicular bone (invagination number, depth of penetration, cross-sectional area and shape) were associated with imaging changes in the DIPJ and the NA. These characteristics were chosen based on the traditional understanding that they are indicative of navicular bone disease. For the purpose of this study, we have termed the collective of the navicular bone, navicular bursa, collateral and distal impar sesamoidean ligament and the deep digital flexor tendon the "navicular apparatus (NA)." As the synovial invaginations of the navicular bone communicate with the DIPJ, our hypothesis was that more severe imaging changes of the synovial invaginations (increased number, increased depth of penetration, increased cross-sectional area and abnormal shape) would be associated with more severe imaging changes within the DIPJ rather than that of the NA.

2 | MATERIALS AND METHODS

2.1 | Selection and description of subjects

The study was a retrospective, analytical study design and involved the use of data from client-owned animals undergoing care at the College of Veterinary Medicine at North Carolina State University with informed consent. Given the nature of the study, Institutional Animal Care and Use Committee approval was not obtained. The University Hospital director and animal owners approved the use of the data.

MRI scans were reviewed for horses that had undergone an MRI scan of both front feet at North Carolina State University, College of Veterinary Medicine Equine Hospital between January 2012 and December 2017. MRI scans were included in the study if a standard protocol (defined by completion of all standard sequences; Supporting Information 1) was acquired for each foot. The decisions on which sequences were included as the standard protocol and final inclusion of subjects in the study were made by an American College of Veterinary Radiology (ACVR) and ACVR-Equine Diagnostic Imaging-certified veterinary radiologist (N.C.N.). The specific reason the horse underwent an MRI scan or other pertinent clinical data, such as lameness or results of diagnostic analgesia, were not included. Both feet from each horse were evaluated.

2.2 | Data recording and analysis

Images were evaluated using viewing software (Client Outlook eUnity Mach 7, South Burlington, VT) on workstations equipped with LCD monitors (Dell Optiplex Windows 10 OS, Atlanta, GA). All MRI studies meeting the inclusion criteria were evaluated by an ACVR and ACVR-Equine Diagnostic Imaging-certified veterinary radiologist (N.C.N.), an ACVSMR-Equine certified clinician (C.R.H.) and an equine surgery resident (T.J.M.). The flow chart shown in Figure 1 outlines the image review process for each scan.

Three anatomical regions were evaluated on each scan: the navicular apparatus (NA), the distal interphalangeal joint (DIPJ), and the synovial invaginations of the navicular bone. Each anatomical region was then subcategorized into individual components that were assigned a score based on the severity of MRI changes present.

For NA, the following components were evaluated: the navicular bursa, the collateral sesamoidean ligament, the distal sesamoidean impar ligament, the navicular bone, and the distal aspect of the deep digital flexor tendon (DDFT). The navicular bursa was further subcategorized into two subcategories: degree of fluid distension and degree of synovial proliferation. The navicular bone was further subcategorized into three subcategories: the medulla, the proximal margin of the bone, and the flexor cortex.

The distal aspect of the DDFT was subcategorized into three regions, as previously reported[11,12]: the DDFT at the level of the collateral sesamoidean ligament and proximal recess of the navicular bursa, the DDFT between the proximal and distal extents of the navicular bone, and the DDFT distal to the distal border of the navicular bone. Two differing versions of the NA were used for statistical analysis. One included the DDFT (all 10 subcategories), and one excluded the DDFT (7 subcategories). The NA was evaluated in this way due to the understanding that certain changes to the DDFT may not be associated with NA pathology.

The DIPJ was evaluated for abnormalities of the following structures: articular cartilage, subchondral bone, synovial membrane,

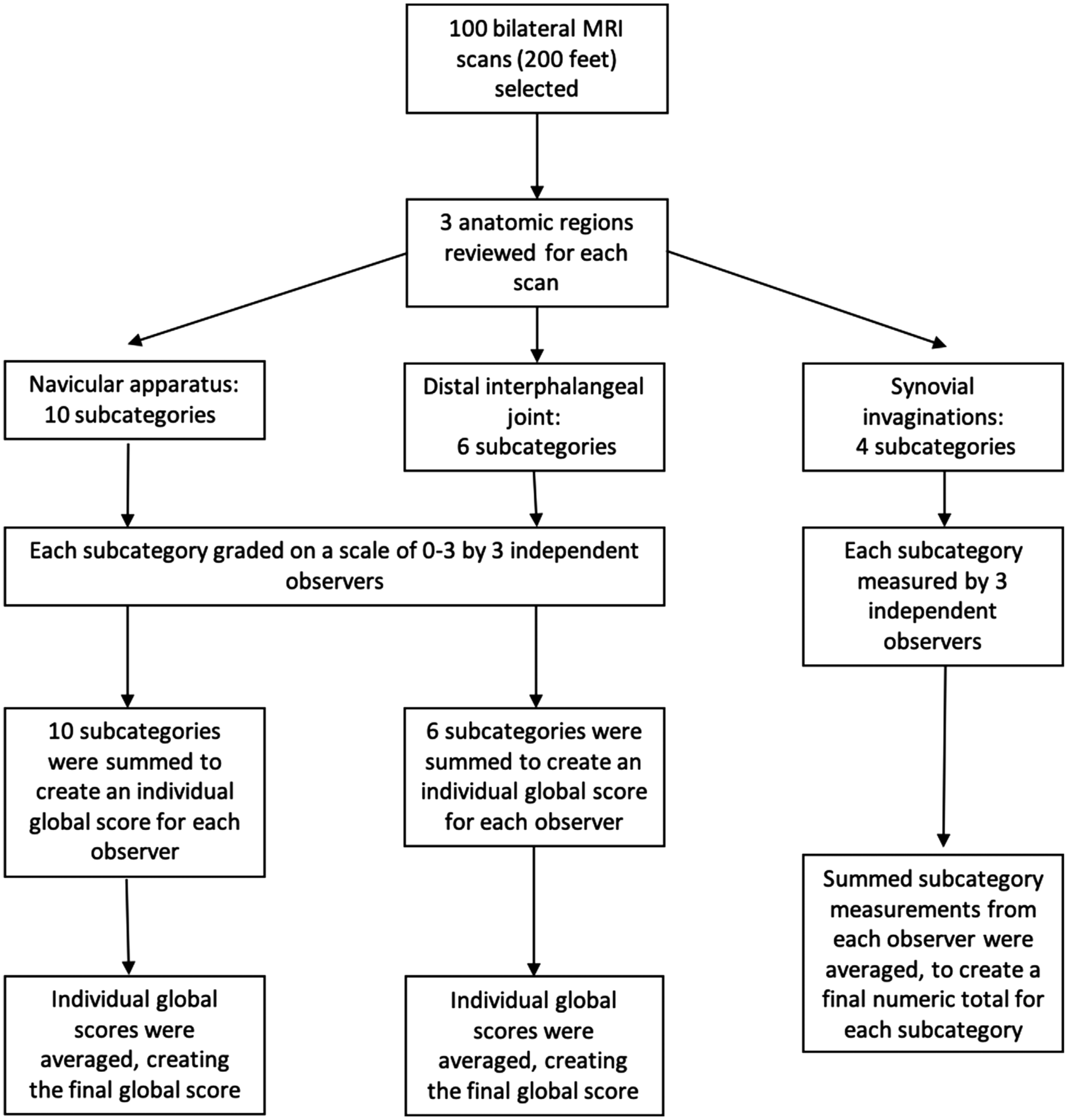

FIGURE 1 Flow chart outlining the image review process

synovial fluid, and periarticular margins (osteophyte formation). When evaluating the synovial membrane, the degree of synovial proliferation was recorded, and when evaluating synovial fluid, the degree of fluid distension was recorded. When evaluating osteophyte formation, two subcategories were recorded: the number of osteophytes and the height of each individual osteophyte.[13]

Two differing versions of the DIPJ were used for statistical analysis. One included the degree of fluid distension (all 6 subcategories), and one was excluded (5 subcategories). The DIPJ was evaluated in this way, as it was determined that prior joint medication, which was not included in the analysis, could have an effect on the degree of distension.

Each individual structure of the NA and the DIPJ listed above was then scored on a grade of 0–3 (0, no change; 1, mild; 2, moderate; 3, severe change) using a modified version of previously described grading schemes (Supporting Information S2).[12,14,15] This would then be used to determine a global score to represent overall pathology within the DIPJ and the NA.

Four characteristics of the synovial invaginations of each navicular bone were evaluated: the total number of synovial invaginations, the

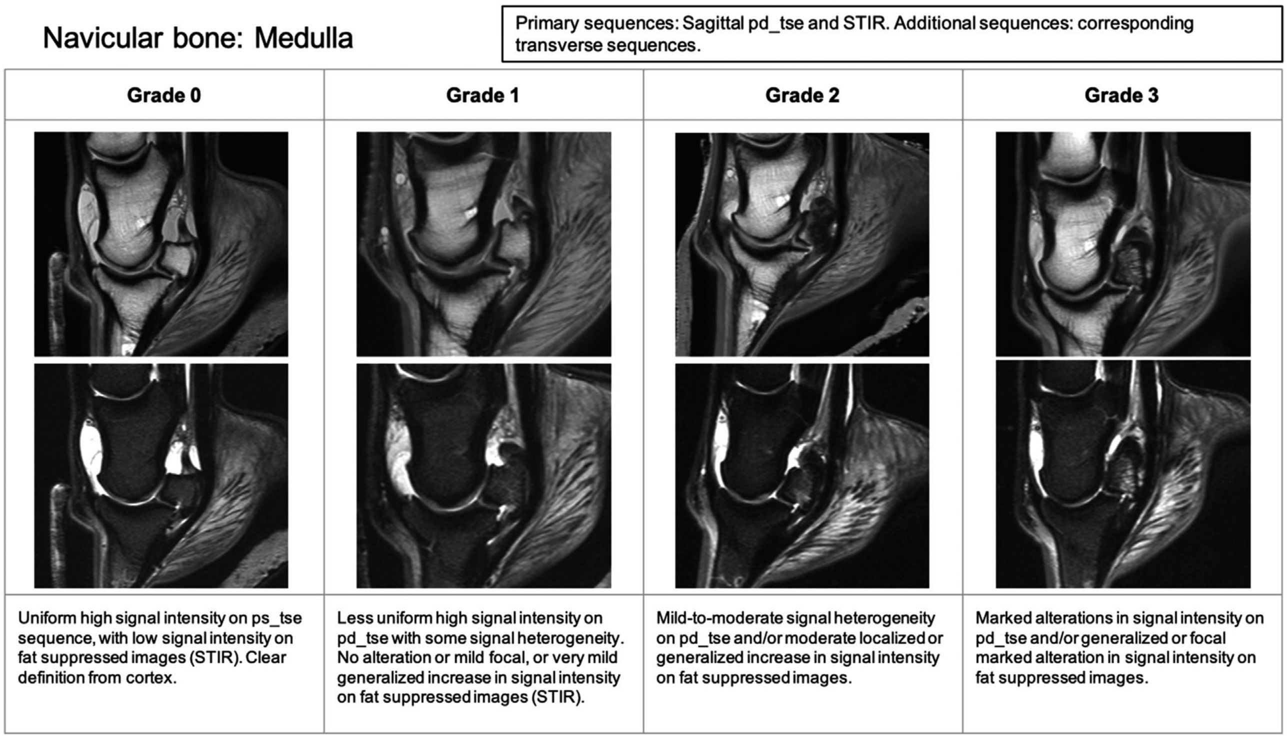

FIGURE 2 Example of the scoring guide used. Grades 0–3 of the navicular bone medulla are depicted. See Supplemental File 3 for the full scoring guide with high resolution images

depth of penetration of each individual synovial invagination recorded, the cross-sectional area (CSA) and the shape. For the purposes of this study, the phrase cross-sectional area was used rather than transverse sectional area to clarify that multiple imaging planes (i.e., sagittal, transverse, and dorsal) were used. The depth of penetration was defined as the length of proximal extension of a single invagination from the synovial fossa into the spongiosa of the navicular bone. When measuring the CSA, only the largest invagination at its largest point was measured using the ellipse region of interest tool on the viewing software. When measuring shape, each individual synovial invagination was recorded as previously described as linear (L, normal), branched (Br, abnormal), or lollipop (LP, abnormal).[1,3,6,16]

Initially, 10 scans were individually graded by each scorer. Following this initial evaluation, a consensus on grading of the DIPJ and the NA subcategories and a consensus on evaluating/measuring all components of the synovial invaginations of the navicular bone was formed. A scoring guide was then created by all authors to assist the scoring process of subject scans (Supporting Information S3). An example of the guide is depicted in Figure 2. All scans were then evaluated, with the authors using the grading scheme and scoring guide as references during each scan. The scans were scored in a random order, and both feet from one patient's scan were not scored consecutively.

After each individual had graded each individual structure of the DIPJ and NA, the sum of the scores for both the DIPJ and NA were recorded. This was termed the individual global score for the DIPJ and NA. The maximum individual global score for the DIPJ was 18, and the maximum individual global score for the NA was 30. A higher final global score was indicative of imaging findings consistent with more severe pathology. The two individual global scores from all scorers were then summed and averaged to create the final global score for the DIPJ and NA, which were used in the statistical analysis of associations with each individual category of synovial invaginations. A higher final global score was indicative of imaging findings consistent with more severe pathology.

For the total number of synovial invaginations of the navicular bone, a whole number was recorded by each scorer for each scan. For the depth of penetration of each synovial invagination, measurements (in mm) to two decimal places were recorded. For the cross-sectional area of the largest invagination, measurements (in mm^2) to two decimal places were recorded. For shape, each individual synovial invagination was recorded as linear (L), branched (Br), or lollipop (LP). The specifics of how each category was scored are outlined in the scoring guide.

Once each individual scorer completed the scoring of the total number, depth of each invagination and CSA of the largest synovial invagination for each navicular bone, the results were summed and then averaged to create a final total for each of these categories for each scan. For the shape of each invagination, an average could not be created, and therefore, all scorers' results for the shape for each synovial invagination were used in the statistical analysis.

When the depth of penetration of the synovial invaginations of the navicular bone was used in the final analysis, the data were evaluated in three different ways to account for outliers. These were the average depth of penetration of all the synovial invaginations of the navicular bone, referred to as average depth; the total depth of penetration of all the synovial invaginations of the navicular bone, referred to as total depth; and the single synovial invagination of the navicular bone with the greatest depth of penetration, referred to as maximum depth.

For each of the individual global DIPJ scores, the global NA scores, and for evaluation of the categories of synovial invaginations of the navicular bone, interobserver agreement testing was performed.

2.3 | Statistical analysis

Statistical analyses were selected and performed by a statistician (J.B.R.), using open source statistical analysis software (R Core Team R version 4.1.2, Vienna, Austria). Associations of the global scores of the DIPJ and NA with all categories of the synovial invaginations of the navicular bone were examined through the use of linear mixed modeling with DIPJ or NA scores as the outcome and each characteristic included as a predictor one at a time. A random intercept was included for each horse as both legs were analyzed. A combined model was not considered due to concerns of multicollinearity. Examinations were carried out on the components that make up the overall NA and DIPJ scores similarly.

For the purpose of generating a single value per observation for the shape of invaginations, each horse was assigned a value based on the shape of the plurality of observed invaginations with ties being assigned in order of priority to L, Br, and then LP. Associations between shape and overall NA/DIPJ scores were investigated using linear mixed modeling with a random effect for patients as two legs were analyzed per patient. ANOVA was then used to determine the presence or absence of an effect before looking at coefficient estimates to determine pairwise differences.

Interobserver variability was measured by testing the intraclass correlation coefficient using a two-way model (raters and subjects both treated as random). This procedure was carried out for all characteristics of invaginations with the exception of shape. Interobserver agreement was measured for shape using a test of the unweighted Cohen's Kappa. Fleiss's kappa was used to measure interrater agreement on the subscores of the NA and DIPJ scoring systems. Significance was set at $P > 0.05$.

3 | RESULTS

A total of 100 MRI scans with complete studies of both feet were included in the study, totaling 200 individual feet observed and scored. Patient clinical data and reasons for scanning were not recorded. All images were acquired using a 1.5 Tesla MRI unit (Siemens Magnetom Symphony, Malvern PA, USA, 8 channel knee coil). All scans were performed under general anesthesia in the lateral recumbency of whichever forelimb was determined to be the primary interest. Each foot was scanned separately, and the knee coil switched to the contralateral foot after completion of all sequences for the initial limb. Transverse, sagittal and dorsal image planes were chosen for each foot using the included anatomy of that limb to ensure that all scan planes were relative to the foot anatomy, not the MRI gantry.

TABLE 1 Descriptive statistics for synovial invaginations

	Outcome	
Parameter	Average	Range
Total number	5.16	1–9
Average depth (mm)	4.00	0.5–7.0
Total depth (mm)	20.77	0.5–50.19
Maximum depth (mm)	5.4	0.5–15.57
Cross sectional area (mm^2)	8.3	0.35–42.03

TABLE 2 Descriptive statistics for DIPJ and NA global scores

Global scores			
	Average	Range	Maximum possible score
DIPJ	6.795	0–17.33	18
NA	6.61	0–29	30

TABLE 3 Significant relationships between synovial invagination parameters and global DIPJ scores

Association	*P*-value	Quantitative measurement
DIPJ and number of invaginations	0.00295	0.4 increase in global DIPJ score with 1 increase in invagination
DIPJ and average depth	0.00363	0.5 increase with every 1 mm depth increase
DIPJ and total depth	5.84×10^{-8}	0.17 increase with every 1 mm depth increase
DIPJ and maximum depth	2.32×10^{-6}	0.11 increase with every 1 mm depth increase
DIPJ and cross sectional area	1.33×10^{-3}	0.17 increase with every 1 mm^2 area increase

The agreement of the individual NA scores was excellent, with an intraclass correlation coefficient score of 0.832. The agreement of the individual DIPJ scores was also excellent, with an intraclass correlation coefficient score of 0.899. The agreement when evaluating the invaginations was variable, with a good value when evaluating total number (0.721), good when evaluating all categories of height (0.589), excellent when evaluating cross-sectional area (0.869) and poor when evaluating shape (0.305). The descriptive statistics for synovial invagination measurements and global score statistics are shown in Tables 1 and 2, respectively.

The association between the global scores of the DIPJ and the global scores of the NA with the measurable characteristics of the synovial invaginations of the navicular bone was performed (Tables 3 and 4). When performing the analysis of the associations of categories of the synovial invaginations of the navicular bone with the DIPJ, analysis was performed both with and without the degree of fluid distension

TABLE 4 Significant relationships between synovial invagination parameters and global NA scores

Association	P value	Quantitative measurement
NA and average depth	1.19×10^{-5}	1.15 increase in global NA score with every 1 mm depth increase
NA and total depth	1.27×10^{-5}	0.15 increase with every 1 mm depth increase
NA and maximum depth	6.42×10^{-5}	0.67 increase with every 1 mm depth increase
NA and cross sectional area	1.09×10^{-4}	0.22 increase with every 1 mm^2 area increase

included. No effect on the outcome was seen by doing this; therefore, the results outlined for the DIPJ include all 6 components (including the degree of fluid distension scores). When performing the analysis of the associations of categories of synovial invaginations of the navicular bone with the navicular apparatus, horses with DDFT injuries were removed from the analysis and evaluated again, given the uncertainty that all pathologies are from similar etiologies. No effect on the outcome was seen by doing this; therefore, the results outlined for the navicular apparatus include all 10 components (including the DDFT scores).

A significant linear relationship was found between the total number of synovial invaginations and the global score of the distal interphalangeal joint (*P*-value 0.00295), with every additional invagination being associated with an increase in the global DIPJ score of 0.4 points on average (Table 3). No significant linear relationship was found, however, between the total number of invaginations and the global score of the navicular apparatus (*P*-value 0.174).

When evaluating the average depth, total depth and maximum depth of the synovial invaginations, a significant linear relationship was found between all 3 categories and both the global DIPJ (Table 3) and NA (Table 4) scores. When evaluating the cross-sectional area of the largest invagination, there was a significant linear relationship between this parameter and both the global DIPJ (Table 3) and NA (Table 4) scores.

The results were inconclusive when evaluating shape. When the dominant shape was determined to be lollipop, the overall DIPJ and NA scores were 1.4 and 3.6 points higher, respectively, than those of horses in which the dominant shape was linear. When the dominant shape was linear, there was no statistically significant difference in either DIPJ or NA score when compared with horses in which the dominant shape was branched. When the dominant shape was branched, there was no statistically significant difference in DIPJ or NA score when compared with horses in which the dominant shape was lollipop.

4 DISCUSSION

Based on our results, our hypothesis that more severe imaging changes of the synovial invaginations would be associated with more severe imaging changes within the DIPJ rather than that of the NA can be partially accepted. In support of our hypothesis, our study revealed that there was no significant relationship between the number of synovial invaginations and the global score for NA. This finding challenges conventional knowledge and the results of other investigations that suggest that an increased number of synovial invaginations indicates navicular disease and/or navicular syndrome.[6] Instead, we found that an increased number of synovial invaginations was associated with a higher global DIPJ score. There are no prior studies that show imaging findings consistent with DIPJ disease rather than navicular apparatus pathology to be associated with an increased number of synovial invaginations of the navicular bone.

The exact etiology as to why and how abnormal synovial invaginations develop and the physiological role they play are still not understood. Without understanding the reason for their development, understanding the association of increasing numbers of the synovial invaginations of the navicular bone with an increased DIPJ global score rather than an NA global score cannot be made, although certain theories are plausible. Given that the invaginations into the navicular bone are an extension of the DIP joint,[5] it is possible that new invaginations occur from changes primarily within the DIP joint versus the NA. Such a cause could be intrasynovial pressure changes due to joint pathology that increases the volume of synovial effusion, causing small defects into the bone that then present as invaginations. However, given that removal of DIPJ fluid distension from the analysis did not change our results, other theories may be considered. It could be argued that alterations in inflammatory mediators within the synovial fluid of the DIP joint could lead to degradation of the cortical bone in the synovial fossa of the navicular bone, leading to the formation of new invaginations. It has been established that the balance of synovial mediators such as certain matrix metalloproteinases and prostaglandins/leukotrienes changes in osteoarthritic joints.[17–21] Additionally, increased stress when the DIPJ is placed under extensive axial rotation and collateromotion,[22] especially in horses with greater medial/lateral imbalance,[23,24] may then lead to the formation of new synovial invaginations.

In partial support of our hypothesis, our results also revealed that horses with an increase in depth of penetration (average, total and maximum) of the synovial invaginations and horses with an increase in cross-sectional area of the largest synovial invagination of the navicular bone were statistically more likely to have a higher global DIPJ score. These findings have also not been shown before. Again, it is possible that pressure changes, synovial inflammatory mediator changes within a diseased DIPJ or external forces placed on the DIPJ could play a role in this association. The findings of increased number and size of navicular synovial invaginations in horses with DIPJ disease challenge conventional thinking that synovial invagination changes are solely indicative of pathology within the navicular apparatus.

The significance of the associations between the DIPJ and synovial invaginations of the navicular bone did not change when the degree of fluid distension of the DIPJ was excluded from the analysis. This subcategory was removed from the analysis to account for some joints appearing with less fluid distension if recently medicated. It was also removed from the analysis, as there is an accepted idea that a subset of athletic horses carry increased effusion within the DIPJ, without any clinical abnormalities. Although neither reason was shown to have a significant effect on the outcome of our analysis, likely due to our approach to grading all parts of the joint, further studies exploring these ideas would be worthwhile.

This study showed that horses with both an increased depth of penetration of synovial invaginations and an increase in cross-sectional area of the largest synovial invaginations are statistically more likely to have a higher global NA score. Histological changes present from compression on the navicular bone of horses suffering from navicular syndrome can help explain why an increased depth and cross-sectional area were statistically associated with a higher global NA score in this study.[25–27] Multiple studies[7,28,29] have shown that in horses with chronic navicular disease, repetitive compression causes navicular bone changes such as trabecular thinning, widening of trabecular spaces, osteonecrosis, and adipose tissue edema. It is possible that changes to the synovial invagination sizes occur from similar forces and subsequent histological changes.

Given that we found that horses were more likely to have both a higher NA and DIPJ score with a greater depth of penetration and cross-sectional area, it could be argued that different etiologies (outlined above) are responsible for similar imaging findings. Care must therefore be taken when trying to explain changes to synovial invaginations of the navicular bone by one single entity. Similarly, it would not be possible to tell from analyzing synovial invaginations alone whether horses with enlarged/elongated synovial invaginations have associated distal interphalangeal joint or navicular apparatus pathology.

We found that the lollipop shape of synovial invaginations had a higher NA and DIPJ global score than the linear shape of invaginations. No significant difference was noted in global scores of NA or DIPJ between lollipop and branched and branched and linear shaped synovial invaginations. These results must be interpreted in light of the interobserver agreement, which was poor when assessing shape (Cohen's kappa coefficient of 0.305).

Despite extensive work to build a consensus within our group for defining the shape of the synovial invaginations, there were challenges in implementing these definitions. The dorsal plane was found most beneficial when defining the shape of the invaginations; however, placing a given invagination into either the L, LP, or BR category was challenging. This was likely due in large part to slice thickness artifacts; however, sequences included in the study may not have been optimal for displaying invagination shapes. As mentioned previously, scans performed prior to August 2016 were obtained using a dorsal FLASH sequence. This accounted for 67 of 100 scans and therefore 134 of 200 feet. On the FLASH scan (which is T1 weighted), fluid has a relatively lower signal resulting in poor signal contrast between the synovial invaginations, surrounding sclerosis and the trabecular medulla. Scans obtained after August 2016 contained a dorsal PD_TSE scan, accounting for 33 of 100 scans and therefore 66 of 200 feet. This sequence generally had better signal contrast between the fluid of the invagination (hyperintense) and the surrounding sclerosis (hypointense). However, with both sequences, assessment of the shape was challenging.

Interestingly, associations between the NA and the synovial invaginations did not change in statistical significance, whether the DDFT was incorporated into the assessment of the association or not. Analysis was performed without the DDFT, as it was hypothesized that certain lesions within the distal DDFT have a different pathogenesis than many of the other NA changes noted. However, without a change in significance, it leads to thinking there are multiple etiologies responsible for imaging changes to the NA, and it is appropriate to include the DDFT as part of the analysis.

It is likely that the scoring guide positively affected interobserver reliability scores. All of the interobserver agreements were deemed good or excellent, with the exception of the assessment of the shape. One limitation of this study is that individual components of the MRIs were not blinded. For example, if a DIPJ was noted to have changes resulting in a higher articular cartilage score, it is possible that the score would be biased when evaluating effusion or soft tissue proliferation scores. Our hope is that the use of this scoring guide helped reduce this limitation.

We found that the FLASH (Siemens) sequence (SPGE, General Electric; CE-FFE-T1, Philips) was the best for visualization of osteophytosis and more subtle changes in the flexor surface of the navicular bone. This is important to recognize, as this is not standard for every imaging protocol of the foot. Therefore, it could be seen that the degree of osteophytosis is underrecognized in those protocols only using a traditional T1 image. Additionally, the specific dorsal collateral ligament sequence was beneficial to visualize impar ligament changes as well as DDFT changes distal to the navicular bone. Again, while forming the scoring guide, it was recognized that finding these changes reliably on other sequences could prove to be difficult. These findings could be considered when building an imaging protocol to most completely image the equine foot.

Measurement of the cross-sectional area as a parameter to analyze synovial invaginations of the navicular bone has not been performed before. The authors included this analysis as it something that is readily scrutinized on a palmaroproximal-palmarodistal radiographic view of the navicular bone. However, the dorsopalmar dimension (length) is another readily scrutinized measurement that could be utilized. Further studies could be performed using this measurement when evaluating synovial invaginations.

The study design specifically limited the inclusion criteria to MRI images only, without any clinical data. The scorers therefore had no knowledge of clinical data such as age or breed, athletic data, historical data such as presence/grade of lameness, prior diagnostics, treatment or response to treatment. Although both feet were included in this study to reduce lameness bias, interpretation of the clinical impact must be performed with caution. Additionally, by grouping all individual anatomic components of the navicular apparatus into a global NA score, as with the DIPJ, we understand that this may be an oversimplification of associations between changes to the synovial invaginations and specific structures within the two anatomic groups.

In conclusion, our study showed an association between more severe imaging findings of the distal interphalangeal joint of the horse with more severe imaging findings of the synovial invaginations of the navicular bone (increase in number, depth of penetration and cross-sectional area). Our study also showed an association between more severe imaging findings of the navicular apparatus of the horse with more severe imaging findings of the synovial invaginations of the navicular bone (limited to depth of penetration and cross-sectional area). Although limited to imaging findings alone, these results suggest that changes to the synovial invaginations should prompt the clinician to more broadly consider underlying causes and clinical implications. This contrasts historical thinking whereby the cause of changes to the navicular synovial invaginations is solely due to navicular pathology.

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CONFLICT OF INTEREST

The authors have declared no conflict of interest.

LIST OF AUTHOR CONTRIBUTIONS

Category 1

a) Conception and design: McParland, Schnabel, Nelson, Horne, Robertson

b) Analysis of data: McParland, Schnabel, Nelson, Horne

c) Interpretation of data: McParland, Schnabel, Nelson, Horne, Robertson

Category 2

a) Drafting the article: McParland

b) Revising it critically for important intellectual content: McParland, Schnabel, Nelson, Horne, Robertson

Category 3

a) Final approval of the version to be published: McParland, Schnabel, Nelson, Horne, Robertson

Category 4

a) Agreement to be accountable for all aspects of the work ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved: McParland, Schnabel, Nelson, Horne, Robertson

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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