Influence of the position of the foot on MRI signal in the deep digital flexor tendon and collateral ligaments of the distal interphalangeal joint in the standing horse

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Summary

Reasons for performing study: **Hyperintense signal is sometimes observed in ligaments and tendons of the equine foot on standing magnetic resonance examination without associated changes in size and shape. In such cases, the presence of a true lesion or an artifact should be considered. A change in position of a ligament or tendon relative to the magnetic field can induce increased signal intensity due to the magic angle effect.**

Objectives: **To assess if positional rotation of the foot in the solar plane could be responsible for artifactual changes in signal intensity in the collateral ligaments of the distal interphalangeal joint and in the deep digital flexor tendon.**

Methods: **Six isolated equine feet were imaged with a standing equine magnetic resonance system in 9 different positions with different degrees of rotation in the solar plane.**

Results: **Rotation of the limb induced a linear hyperintense signal on all feet at the palmar aspect of one of the lobes of the deep digital flexor tendon and at the dorsal aspect of the other lobe. Changes in signal intensity in the collateral ligaments of the distal interphalangeal joint occurred with rotation of the limb only in those feet where mediolateral hoof imbalance was present.**

Conclusions: **The position and conformation of the foot influence the signal intensity in the deep digital flexor tendon and in the collateral ligaments of the distal interphalangeal joint.**

Potential relevance: **The significance of increased signal intensity in the deep digital flexor tendon and in the collateral ligaments of the distal interphalangeal joint should be interpreted with regard to the position and the conformation of the foot.**

Introduction

Increased signal intensity in a ligament or a tendon is an important finding on magnetic resonance (MR) imaging as it may indicate the presence of a lesion. Desmitis of the collateral ligaments of the distal interphalangeal joint and lesions of the deep digital flexor tendon, in horses, commonly present with increased signal intensity (Busoni *et al.* 2005; Zubrod *et al.* 2005; Murray *et al.* 2006a,b; Dyson *et al.* 2008). However, the position of tendons and ligaments, relative to the magnetic field, may also influence the signal intensity during MR imaging. (Erickson *et al.* 1991). An increase in signal intensity occurs in tendons and ligaments on images obtained with a short time of echo (T1-weighted or proton density images), when the long axis of the collagen fibres is at an angle of 55 ± 10° relative to the magnetic field. This phenomenon, called the magic angle effect, is due to variation in dipolar interaction depending on the relative alignment of the protons with the magnetic field (Erickson *et al.* 1991, 1993; Bydder *et al.* 2007).

Such changes in signal intensity have been recognised in MR imaging of the foot of horses under general anaesthesia, both with high field (Busoni and Snaps 2002) and low field (Spriet *et al.* 2007; Spriet and McKnight 2009) MR systems. Standing equine MR systems have a configuration similar to recumbent low field MR systems, with the magnetic field perpendicular to the sagittal plane of the limb. Therefore the increased signal intensity, due to magic angle effect, observed in the collateral ligaments of the distal interphalangeal joint and at the palmar and dorsal aspects of the deep digital flexor tendon with the recumbent low field MR systems might be expected with the standing MR systems. With recumbent horses, the magic angle effect occurs when the long axis of the limb is not perfectly perpendicular to the magnetic field. This easily occurs while positioning a recumbent horse in a MR system but is unlikely to occur with a standing horse, due to the inherent weightbearing position. With equine standing MR units, variation in the position of the limb, relative to the magnetic field, may, however, occur secondary to internal or external rotation of the foot. This can be due either to toe-in or toe-out conformation or due to oblique positioning of the horse relative to the scanner. Such a variation in the relative position of the magnetic field and the limb may induce some changes in signal intensity due to the magic angle effect.

It was hypothesised that rotation of the foot would induce some changes in signal intensity in the deep digital flexor tendon and the collateral ligaments of the distal interphalangeal joint.

The primary goal of the study was to evaluate the effect of positional rotation on signal intensity in the deep digital flexor tendon and collateral ligaments in different pulse sequences. The secondary objective was to determine if there was an association between the changes in signal intensity and conformation of the foot.

Materials and methods

The distal extremities of 6 thoracic limbs, isolated from 6 different horses, were used for this study. All horses had no known history of lameness and were subjected to euthanasia for reasons unrelated to the study. The limbs were isolated by section through the radius, shortly after euthanasia. The feet were assessed for their conformation. Rotational deformity was noted as absent, toe-in or toe-out. As the limbs were isolated from the body, toe-in and toe-out conformations were defined as a deviation of the sagittal plane of the foot from the sagittal plane of the metacarpal area. The mediolateral balance of the foot was also considered. The feet were classified subjectively as normal mediolateral balance, higher medial coronary band or higher lateral coronary band. A more objective assessment of the mediolateral balance was also obtained by measuring the angle between the articular surface of the distal phalanx and the solar surface of the foot, using the dorsal MR images.

The feet were imaged using a 0.27 Tesla open MR unit and dedicated radiofrequency coil[1]. The limbs were stabilised in a 'standing' position using a wooden device to support the caudal aspect of the radius. No attempt was made to apply load to the limbs. Each foot was imaged in 9 different positions; '0º position' was defined as the sagittal plane of the limb, in the metacarpal area, perpendicular to the magnetic field, which represents the ideal normal position. The other positions were obtained with rotating the foot in the solar plane (around an imaginary vertical axis going through the centre of the hoof capsule). External and internal rotations of 7.5, 15, 22.5 and 30º were obtained. A wooden board with marks for the different angles was designed to fit in the magnet. Marks where placed on the hoof wall at the toe and on each quarter to accurately position the feet. The same imaging protocol was repeated for each foot in each position. The first foot (Foot 1) was imaged using 9 different pulse sequences including sagittal T1-weighted high-resolution spin echo sequence, sagittal T2-weighted high-resolution fast spin echo sequence, dorsal T1-weighted 3D gradient echo sequence, dorsal T1-weighted high resolution spin echo sequence, transverse T1-weighted 3D gradient echo sequence, transverse T2-weighted fast spin echo sequence, transverse oblique T1-weighted spin echo sequence, transverse oblique T2-weighted fast spin echo sequence and transverse oblique proton density spin echo sequence.

The 5 other feet were imaged with sagittal T1-weighted high-resolution spin echo sequence, transverse T1-weighted 3D gradient echo sequence and dorsal T1-weighted high-resolution spin echo sequence, based on the results of the first foot. The technical parameters of the pulse sequences used are given in Table 1, and orientation of the different imaging planes illustrated in Figure 1.

TABLE 1: Pulse sequence parameters

Sequence	TR (ms)	TE (ms)	NEX	Flip angle (degree)	Slice thickness (mm)	Slice interval (mm)	Acquisition time (min:s)
SE T1 HR	400	18	4	90	3.5	0.7	5:49
FSE T2 HR	1969	87	3	90	3.5	0.7	4:13
3D GE T1	22	7	1	40	2.2	0	2:20
SE T1	475	21	2	90	5	1	2:50
FSE T2	2000	84	3	90	5	1	3:48
SE PD	1500	24	1	90	5	1	3:27

SE = spin echo; FSE = fast spin echo; GE = gradient echo; HR = high resolution; TR = time of repetition; TE = time of echo; NEX = number of acquisition.

The dorsal plane was defined as perpendicular to the solar surface. The transverse plane was perpendicular to the flexor surface of the navicular bone. The oblique transverse plane was parallel to the sole.

The images were assessed subjectively for changes in signal intensity in the deep digital flexor tendon and the collateral ligaments of the distal interphalangeal joint. Signal intensity was graded as normal or increased. Changes in the tendon were characterised according to their palmar or dorsal localisation, the involvement of the lateral or medial lobe and the proximal to distal extent. For assessment of the proximal to distal extent, 4 different areas were considered using anatomical landmarks: proximal to the collateral sesamoidean ligament, at the level of the collateral sesamoidean ligament, at the level of the navicular bone and at the level of the distal impar sesamoidean ligament.

The images for each foot were read in a random order. The reader was not aware of the position of the foot. The relationship between the changes in signal intensity and the position of the foot was assessed using the Chi-squared test and multinomial logistic regression.

Results

Conformation of the feet

Two feet were classified as having good conformation, with absence of rotational deformity and a normal mediolateral hoof balance, including Foot 1 used for imaging with multiple pulse sequences. Three feet had a toe-out conformation associated with a higher lateral coronary band. One foot had a higher lateral coronary band but no remarkable rotational deformity. The angle between the articular surface of the distal phalanx and the solar surface of the foot measured 0 and 1º for the 2 feet graded subjectively as normal mediolateral balance, and ranged 3–7º for the feet graded as having mediolateral imbalance.

Variation in signal intensity between different pulse sequences with different positions

Deep digital flexor tendon: Changes in signal intensity occurred, with both internal and external rotation, as a linear hyperintense
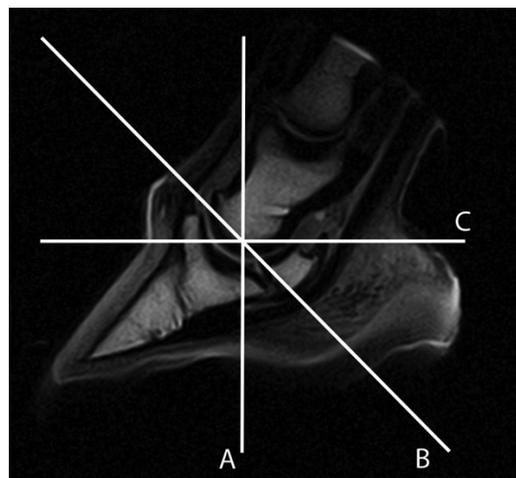

Fig 1: Orientation of the imaging planes. Sagittal T1-weighted image of an equine foot used to illustrate the orientation of the transverse and dorsal planes. Line A represents the orientation of the dorsal plane, line B the transverse plane and line C the transverse oblique plane.

signal at the palmar aspect of one of the lobes of the distal deep digital flexor tendon of Foot 1 (Fig 2). A linear hyperintense signal was also present at the dorsal aspect of the other lobe with higher degrees of rotation (Fig 3). The hyperintense signal was present only on T1-weighted and proton density images. No change in signal intensity was observed with rotation on the T2-weighted images (Fig 2).

Collateral ligaments of the distal interphalangeal joint: No change in signal intensity was observed with rotation in the collateral ligaments of the distal interphalangeal joint of Foot 1 with any of the pulse sequences. The ligaments always presented low signal intensity (Fig 2).

Variation in signal intensity on T1-weighted images with different positions and different feet

Deep digital flexor tendon: Increased signal intensity within the deep digital flexor tendon was present in 3/6 feet at the 0º position, in 2/6 feet at the 7.5º position and in 6/6 feet for all other positions. A significant relationship was found between increased signal intensity in the tendon and positional rotation of the foot in both directions (Pearson Chi-squared P<0.001; Fisher's exact P<0.001).

On the 3 feet presenting increased signal intensity in the 0º position, the increased signal was present at the palmar aspect of the lateral lobe. These 3 feet presented a toe-out conformation, whereas the other 3 feet had no rotational deformity. The 7.5º internal rotation on these 3 feet resulted in the presence of normal signal intensity in the tendon.

External rotation resulted in the presence of increased signal intensity at the palmar aspect of the lateral lobe of the DDFT on all feet and at the dorsal aspect of the medial lobe of the DDFT on all feet with rotation of 15º or higher and on 1/6 feet with a rotation of 7.5º. No change in signal intensity was observed at the palmar aspect of the medial lobe or at the dorsal aspect of the lateral lobe with external rotation.

Internal rotation resulted in the presence of increased signal intensity at the palmar aspect of the medial lobe of the DDFT on all feet with rotation of 15° or higher, and on 2/6 feet with a rotation of 7.5°. Increased signal intensity at the dorsal aspect of the lateral lobe was observed with internal rotation on all feet with a rotation of 15° or higher but was not present with a rotation of 7.5°. No change in signal intensity was observed at the palmar aspect of the lateral lobe or at the dorsal aspect of the medial lobe with internal rotation of the foot.

Significant relationships were found between the location of the hyperintense signal and the direction of rotation of the foot (Pearson Chi-squared P<0.001; Fisher's exact P<0.001).
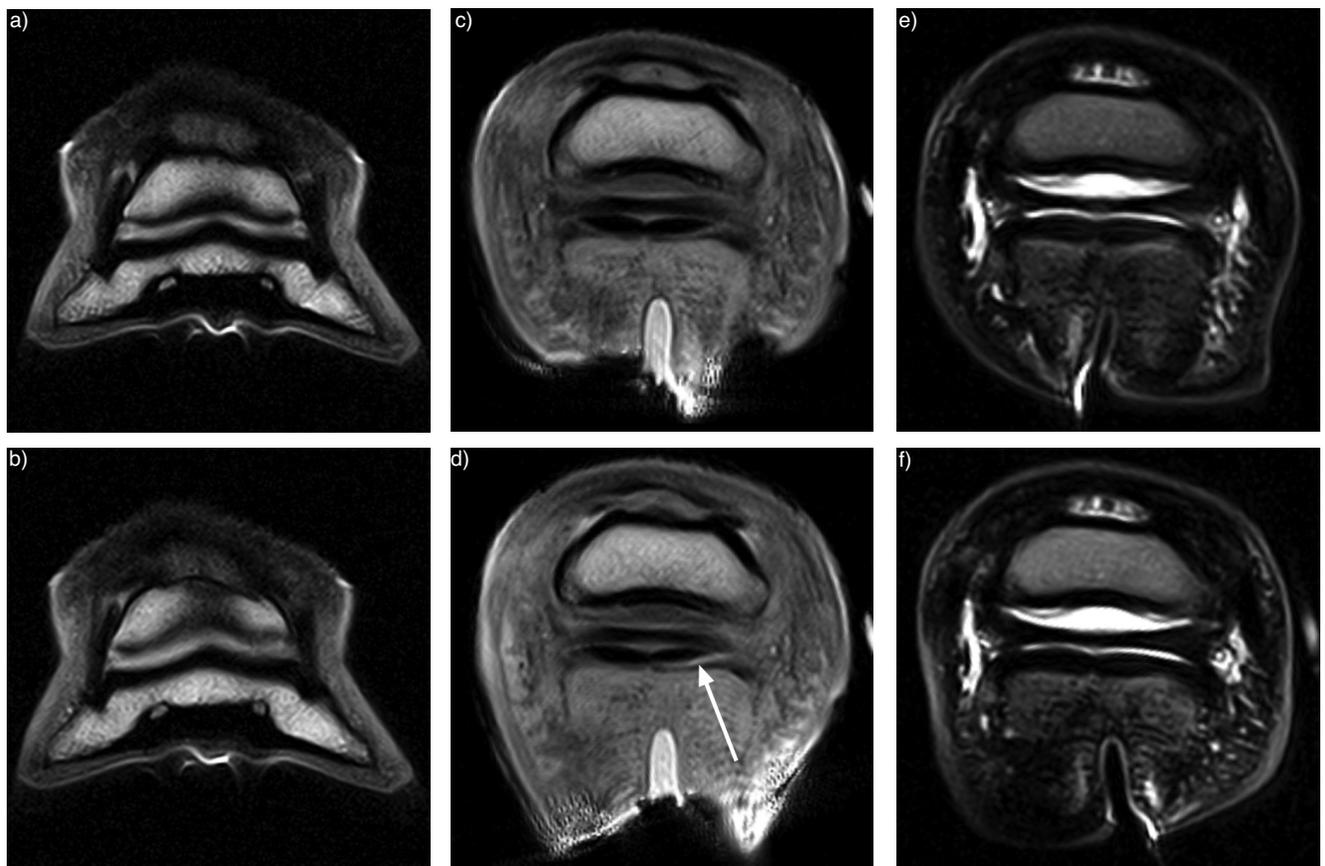

Fig 2: Effect of rotation on the signal intensity in different pulse sequences. Dorsal spin echo T1-weighted images at the level of the collateral ligaments of the distal interphalangeal joint (a and b), transverse gradient echo 3D T1-weighted (c and d) and spin echo T2-weighted images (e and f) at the level of the collateral sesamoidean ligament of a foot with normal conformation (Foot 1). Images a, c and e were obtained at the 0° position whereas images b, d and f were obtained with 15° of external rotation. Both collateral ligaments of the distal interphalangeal joint present a hypointense signal at the 0° position (a). There is no change in signal intensity in the collateral ligaments with 15° of external rotation (b). A linear hyperintense signal (arrow) is present at the palmar aspect of the lateral lobe of the deep digital flexor tendon with 15° of external rotation on the T1-weighted image (d) but not on the T2-weighted image (f).

When present, the palmar hyperintense signal was always seen at the level of the navicular bone and collateral sesamoidean ligament. It extended farther proximally and distally with a higher degree of rotation: with rotation of 15° and higher, the palmar hyperintense signal always extended from the level of the distal sesamoidean impar ligament to proximal to the collateral sesamoidean ligament (Fig 3). The dorsal hyperintense signal was present most commonly only at the level of the distal sesamoidean impar ligament and at the level of the navicular bone (Fig 3). The dorsal hyperintense signal extended proximal to the collateral sesamoidean ligament in 12 out of the 39 series where it was present. These 12 instances all presented rotation of 15° and higher.

Collateral ligaments of the distal interphalangeal joint: Increased signal intensity was present in the lateral collateral ligament of
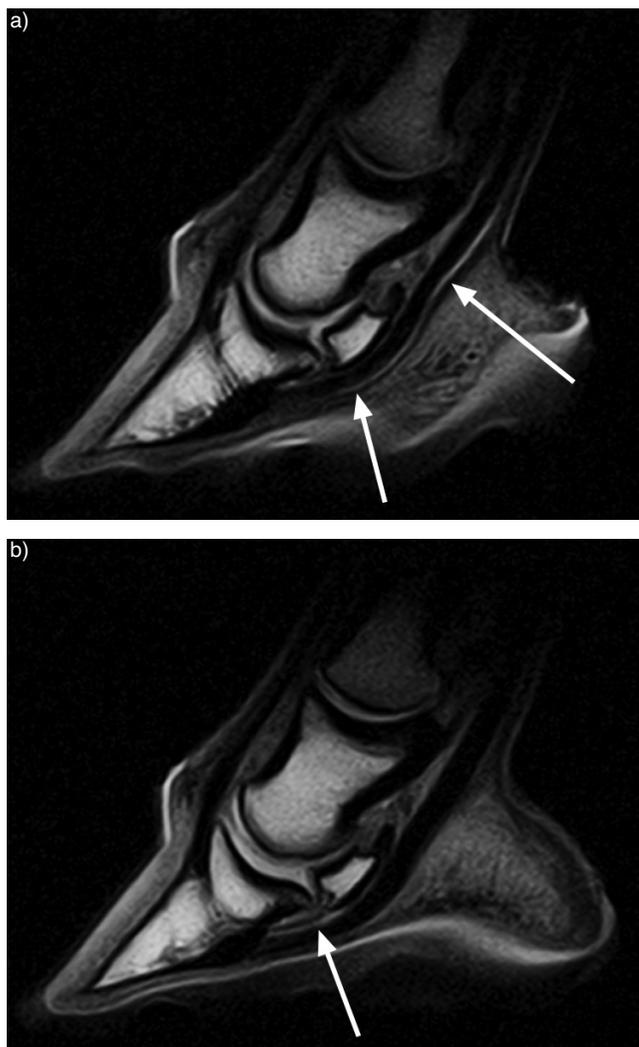

Fig 3: Linear increased signal intensity in the deep digital flexor tendon due to rotation on T1-weighted images. Spin echo T1-weighted sagittal images of Foot 1 with 22.5° of external rotation. Image a was obtained through the lateral lobe. A linear hyperintense signal is present at the palmar aspect of the lateral lobe extending from the level of the distal sesamoidean impar ligament to the level of the middle phalanx (arrows). Image b is obtained through the medial lobe of the deep digital flexor tendon. A linear hyperintense signal is present at the dorsal aspect of the medial lobe at the level of the distal sesamoidean impar ligament and navicular bone (arrow).
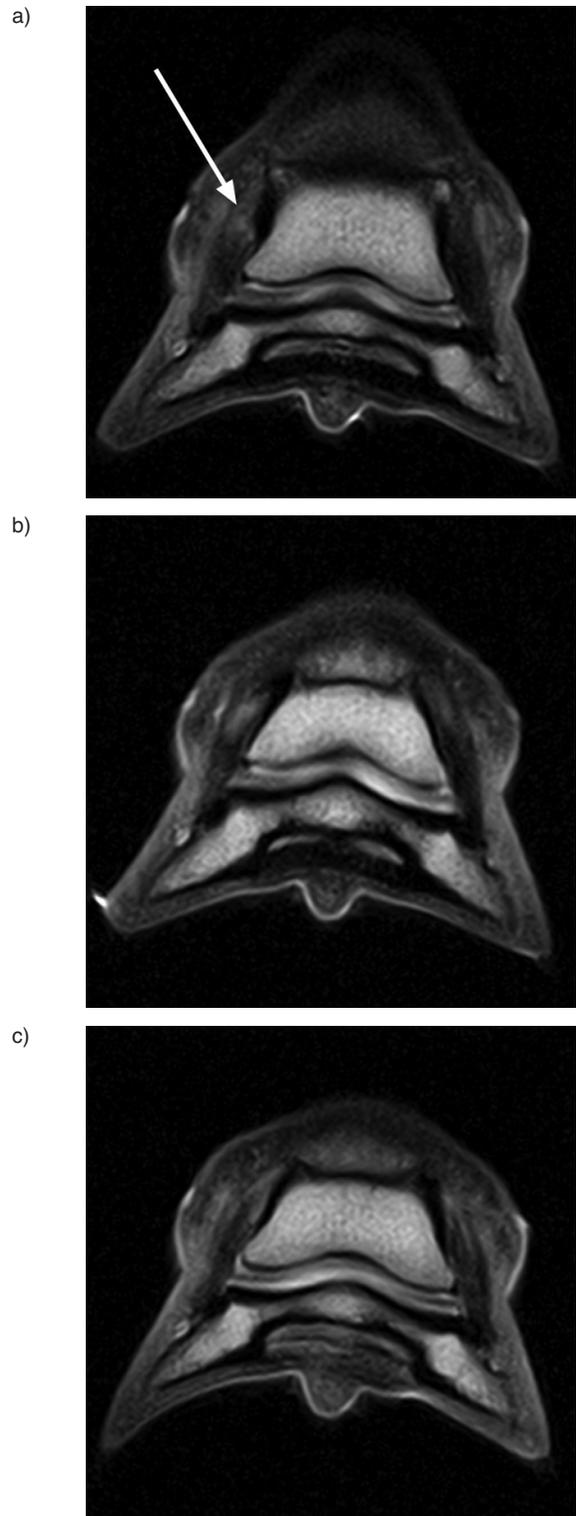

Fig 4: Effect of rotation on the signal intensity in the collateral ligaments of a foot with mediolateral hoof imbalance on T1-weighted images. Dorsal spin echo T1 weighted images of Foot 2 at the level of the collateral ligaments of the distal interphalangeal joint with 0° of rotation (a), 15° of external rotation (b) and 30° of internal rotation (c). Lateral is to the left. This foot presents mediolateral foot imbalance with a higher lateral coronary band. A mild increase in signal intensity is present at the origin of the lateral collateral ligament on image a (arrow). A more pronounced increase in signal intensity is present with external rotation (b). On image c, with internal rotation, both the lateral and medial collateral ligaments present a normal hypointense signal.

4/6 feet. The increased in signal intensity was more prominent at the proximal aspect of the ligament (Fig 4). Only one of these 4 feet presented increased signal intensity on all positions. The hyperintense signal was always present with external rotation of 15° and higher. Two of these feet did not present increased signal intensity with internal rotation. With the 2 other feet, the changes seen with internal rotation were less intense than with external rotation and in one of the feet were not present at 15° and higher (Fig 4). Normal signal intensity was present in the medial collateral ligament on all feet in all positions.

All 4 feet with increased signal intensity in the lateral collateral ligament presented mediolateral hoof imbalance with the lateral aspect of the coronary band higher than the medial aspect, and an angle between the articular surface of the distal phalanx and the solar surface of the foot of 3° and higher. To account for this, multinomial logistic regression was performed. Mediolateral foot imbalance, direction and angle of rotation were all significantly associated with the signal intensity in the lateral collateral ligament (P<0.05).

Discussion

Positional rotation of the foot in the solar plane is responsible for increased signal intensity in the deep digital flexor tendons on all feet on T1-weighted and proton density images. Changes in signal intensity with positional rotation of the foot were present in the lateral collateral ligament of the distal interphalangeal joint in feet with mediolateral hoof imbalance. The dependence of the signal intensity on the position of the foot relative to the magnetic field is characteristic for a manifestation of the magic angle effect (Erickson et al. 1993; Bydder et al. 2007).

Similar changes have been reported previously with a low field MR system used with horses under general anaesthesia (Spriet et al. 2007; Spriet and McKnight 2009). The orientation of the magnetic field relative to the limb in those studies is equivalent to the equine standing MR system used in this study, which accounts for the similar changes observed with the 2 systems. However, the change in signal intensity observed with the recumbent MR system is due to angulation of the long axis of the limb in the dorsal plane (Spriet et al. 2007; Spriet and McKnight 2009). Such a change in position is unlikely to occur with a standing MR system due to the inherent weight bearing position. These results show that the rotation of the foot of a standing horse in the solar plane can induce the same type of changes in the deep digital flexor tendon. The relative orientation between the magnetic field and the long axis of the tendon has to be considered in 3 dimensions. Changes in position in different planes can be responsible for similar results.

The change in signal intensity at the distal aspect of the deep digital flexor tendon appears as a linear hyperintense signal at the palmar aspect of one of the lobes of the tendon, often associated with a linear hyperintense signal at the dorsal aspect of the other lobe. The focal appearance of the magic angle effect in these areas can be explained by the specific orientation on some of the collagen fibres of the deep digital flexor tendon. At the distal aspect of the deep digital flexor tendon, groups of fibres have a different orientation from the long axis of the tendon. The collagen fibres at the palmar aspect of the tendon are diverging from proximal to distal, whereas those at the dorsal aspect of the tendon are converging (Spriet and McKnight 2009). With rotation of the foot, some of these fibres are oriented at 55° relative to the magnetic field, which explains the focal manifestation of the magic angle effect.

Three of the 6 feet imaged in this study presented increased signal intensity at the palmar aspect of the lateral lobe of the deep digital flexor tendon on the 0° position. These 3 feet presented a toe-out conformation that resulted in a slight external rotation of the foot on the 0° position, as the alignment of the limb relative to the magnetic field was based on the metacarpal area. This explained the hyperintense signal observed at the palmar aspect of the lateral lobe of the deep digital flexor tendon on the 0° position. There was no foot with toe-in conformation imaged in this study. It is probable that such a foot would have presented increased signal intensity at the palmar aspect of the medial lobe of the deep digital flexor tendon on a 0° position.

The 4 feet that presented increased signal intensity in one of the collateral ligaments of the distal interphalangeal joint all had some degree of foot imbalance. On the 2 feet with a good conformation, change in signal intensity was not present in the collateral ligaments of the distal interphalangeal joint in any position. This suggests that a change in signal intensity in a collateral ligament is primarily related to mediolateral imbalance of the foot. Mild mediolateral hoof imbalance is enough to induce changes in signal intensity in one of the collateral ligaments. An angle of only 3° was present between the articular surface of the distal phalanx and the solar surface of the hoof in one of the feet presenting increased signal intensity within the lateral collateral ligament.

Increased signal intensity in a collateral ligament was only seen in the lateral collateral ligament in this study. This correlates with the finding that 4 feet had mediolateral hoof imbalance with a higher lateral coronary band. As a result, the medial collateral ligament acquires a more vertical orientation in the standing horse and the lateral collateral leans more at an angle. The orientation between this ligament and the main magnetic field reaches 55 ± 10°, area of occurrence of the magic angle effect, in a similar way as when angulation of the long axis of the limb is present on a horse under general anaesthesia with a low field magnet (Spriet et al. 2007).

The increased signal intensity in the collateral ligament, associated with the mediolateral hoof imbalance, varied depending on the rotation of the foot. Increased signal intensity was always present in the lateral collateral ligament of the feet with a higher lateral coronary band with external rotation of 15° and higher, whereas the signal intensity was not always increased with internal rotation. External rotation of the foot seemed to enhance signal intensity changes present in the lateral collateral ligament due to mediolateral hoof imbalance. Changes were not observed in this study in the medial collateral ligament. This is probably due to the conformation of the feet used. It is likely that a foot with mediolateral hoof imbalance with a higher medial coronary band would present increased signal intensity in the medial collateral ligament and that this change in signal intensity would be more prominent with internal rotation of the foot. The presence of increased signal intensity in one of the collateral ligaments of the distal interphalangeal joint depends on the combination of the mediolateral balance and the position of the foot. The mediolateral balance is the primary determinant factor but the position modulates the presence and intensity of the change.

The limbs used in this study were isolated and not loaded. This represents a limit to the application of the present results to clinical cases. The limbs were isolated at the level of mid-radius in order to keep the accessory ligament of the deep digital flexor tendon intact and maintain a better position of the deep digital flexor tendon compared with section through mid metacarpus.

The conformation of the foot is an important element with standing MR in order to predict, recognise or prevent the occurrence of the magic angle effect. With a well-balanced foot, the magic angle effect does not occur if the horse is properly positioned with the sagittal plane of the limb perpendicular to the magnetic field. However, if the limb is rotated, for example if the horse is oblique within the stocks, artifactual changes can be expected in the deep digital flexor tendon with as little as 7.5° of rotation. The collateral ligaments of the distal interphalangeal joint do not present any changes if the foot has a normal mediolateral balance.

Feet that are poorly balanced present a more complex problem. Even if the horse is properly positioned with the sagittal plane of the limb perpendicular to the magnetic field, a palmar hyperintense signal appears in the lateral lobe of the deep digital flexor tendon with toe-out conformation. It is likely that the reciprocal is also true: a palmar hyperintense signal would appear in the medial lobe of the deep digital flexor tendon with toe-in conformation. This can be prevented by voluntarily positioning toe-out feet with a mild degree of internal rotation and toe-in feet with a mild degree of external rotation in order to realign the foot itself with the magnetic field. If increased signal intensity is observed on a T1-weighted image of a collateral ligament, the balance of the foot should be assessed. Changes in signal intensity in the collateral ligaments of the distal interphalangeal joint due to mediolateral hoof imbalance may be prevented with the use of graded blocks or hoof trimming.

In conclusion, during MR imaging with the horse standing, the position and conformation of the foot influence the signal intensity in the deep digital flexor tendon and in the collateral ligaments of the distal interphalangeal joint.

Acknowledgements

Manufacturer's address

[1]Hallmarq Veterinary Imaging Ltd, Guildford, Surrey, UK.

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