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Original Article

Gait analysis in French bulldogs with and without vertebral kyphosis

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Abstract

The study objective was to compare temporal-spatial and kinetic gait variables in neurologically normal French bulldogs with and without vertebral kyphosis. French bulldogs presented to a dedicated brachycephalic clinic were prospectively enrolled. All dogs underwent general physical, orthopaedic, and neurological examination prior to study inclusion. The presence of vertebral kyphosis was evaluated by computed tomography and kyphosis was defined as a Cobb angle exceeding 10°. Gait variables were collected using a pressure-sensitive GAITRite walkway with GAITFour software and included measurement of total pressure index (TPI) defined as the sum of peak pressure values recorded from each activated sensor by a paw during mat contact.

Fifteen French bulldogs with (n = 8) and without kyphosis (n = 7) were included. Cobb angle in kyphotic dogs ranged from 14.9° to 39.5°. Univariate analyses were initially performed to examine the association between kyphosis and 16 gait variables. When those variables found to be associated ($P < 0.2$) were taken forward into multivariate generalised linear mixed models (accounting for dog, velocity and side), kyphosis had a significant effect upon TPI of the forelimbs and TPI symmetry ratio ($P < 0.05$); however, the size of these effects was small. Although vertebral kyphosis is rarely associated with neurological deficits, it was associated with subtle alterations in kinetic gait variables (TPI forelimbs and TPI symmetry ratio). Further studies are needed to evaluate the clinical importance of altered gait variables in French bulldogs with kyphosis.

Keywords: Biomechanics; Brachycephalic; Hemivertebra; Spinal

Introduction

Kyphosis is defined as an abnormal dorsal curvature of the vertebral column which is a common sequela to congenital vertebral malformations such as hemivertebra (Guevar et al., 2014, Dewey et al., 2016). Hemivertebra are a common finding in French bulldogs with a reported prevalence of 78% to 93.5% in neurologically unaffected animals (Moissonnier et al., 2011, Schlensker and Distl, 2013, Ryan et al., 2017). Although vertebral kyphosis can result in neurological abnormalities and spinal cord dysfunction, in most dogs it is not associated with clinical signs and is generally considered an incidental finding on imaging studies of the vertebral column (Moissonnier et al., 2011, Dewey et al., 2016).

In a small number of dogs however, vertebral kyphosis is directly linked to repetitive and progressive spinal cord injury (Aikawa et al., 2014, Charalambous et al., 2014). This is often multifactorial in nature with dynamic and static factors involved including vertebral instability, vertebral subluxation, and vertebral canal stenosis (Lorenz et al., 2011, Dewey et al., 2016).
In addition to neurological dysfunction, kyphosis may also be linked to secondary biomechanical changes of the vertebral column (Faller et al., 2014). This can be manifested as altered gait variables, which are challenging to detect and accurately quantify on visual assessment alone (Carr and Dycus, 2016). Pressure-sensitive gait analysis systems provide objective means for assessing gait variables and are a useful tool to improve the ability of clinicians to detect and diagnose subtle gait changes (De Camp, 1997, LeQuang et al., 2009, Carr and Dycus, 2016). Their use for assessment of temporal-spatial gait variables in both human and canine neurological patients has been previously validated (Givon et al., 2009, Gordon-Evans et al., 2009, Lima et al., 2015).

French bulldogs are predisposed to several spinal conditions including intervertebral disc extrusions (Aikawa et al., 2014, Mayousse et al., 2017). This has been linked to a high prevalence of vertebral malformations in the breed, although the exact pathophysiological mechanisms are currently unknown (Inglez de Souza et al., 2018). Identification and documentation of altered temporal-spatial and kinetic gait variables in French bulldogs with kyphosis may be important to evaluate the full spectrum of potentially important clinical consequences associated with this malformation. Therefore, the study objective was to collect and compare gait variables in French bulldogs with and without vertebral kyphosis by use of a portable pressure-sensitive walkway system. It was hypothesised that vertebral kyphosis in clinically normal French bulldogs would have a significant effect on gait variables compared with French bulldogs without vertebral kyphosis.

Materials and methods

Animals

French bulldogs which presented to a dedicated brachycephalic clinic at the study institution were prospectively enrolled. All dogs underwent general physical, orthopaedic and neurological examination before study enrollment; only those dogs with an unremarkable neurological and orthopaedic examination were included in the study. Radiographic evaluation to further exclude orthopaedic disease was not performed. Clinical information retrieved from the medical records included: signalment, clinical history, physical examination findings, and results of diagnostic investigations including diagnostic imaging findings. The study was granted ethical approval by the Royal Veterinary College Clinical Research Ethical Review Board (Protocol number 20151393; Approval date 21 October 2015). Owners of all dogs were required to sign an informed consent form prior to inclusion (see Appendix: Supplementary File 1).

Gait analysis

Gait variables were collected using a 4.88 × 0.61 m portable walkway (GAITRite, platinum version, CIR Systems) with 16,128 embedded pressure-sensitive sensors. The walkway was connected to a laptop computer with dedicated software (GAITFour software, version 40f, CIR Systems). A camera (Logitech mega pixel web camera, Logitech) was positioned immediately adjacent to the mat at a height of 0.5 m to create digital video files of each pass along the walkway; this was automatically linked to gait data generated from each walkway trial to allow verification of walks and footfall when processing data. Prior to data analysis, paw prints were identified using the software program which replicated gait patterns previously identified by the user.

The study protocol was based on previously validated gait analysis protocols (Light et al., 2010). Each dog was allowed a habituation period of 10 min, during which they were walked freely around the study area. Dogs were then walked along the mat until three valid trials were obtained within a 30-min period, and only the first three valid trials were selected for study inclusion. A trial was considered valid when the dog walked straight ahead, at a consistent walk, with the head centered straight forward. Three gait cycles per trial were needed as a minimum. The velocity of individual gait cycles was compared to ensure variation within each pass along the walkway did not exceed 10%. Walk velocity was restricted between 0.6 to 1.0 m/s. Those walks which did not meet these criteria were excluded. All dogs were walked by one of two study authors who were experienced animal handlers and trained in the study protocol (SW, HS). Dogs were walked along the mat in both directions equally, and the side which the leash was held alternated between left and right depending on the direction of walk. All walks were completed prior to induction of general anaesthesia and completion of imaging studies.

Imaging Studies

The presence of vertebral kyphosis was evaluated based on computed tomography(CT) imaging under general anesthesia, and vertebral kyphosis was defined as a Cobb angle exceeding 10°. CT images were acquired using a 16 multi-detector row unit (Mx8000 IDT, Philips). All imaging studies were assessed using a PACS workstation DICOM viewer (Osirix Imaging Software, version 3.9.2). The degree of vertebral kyphosis was evaluated through measurement of the Cobb angle by one study author (SDD), using the automated method described by Guevar et al. (2014). Study dogs were then divided into kyphotic and non-kyphotic groups.

Gait variables

The following temporal-spatial data were extracted for each dog: (1) Stride length (the distance between two strikes of a single paw on the ground); (2) Stance time (the length of time a paw is in contact with the ground during a gait cycle); (3) Hind reach (calculated from the heel center of the hind paw to the heel center of the fore paw on the same side); (4) Number of activated sensors per paw per gait cycle; (5) Number of gait cycles per trial; and (6) Mean gait velocity. Furthermore, the kinetic variables 'total pressure index' (TPI), and TPI % were also determined. TPI was defined as 'the sum of peak pressure values recorded from each activated sensor by a paw during mat contact, represented by switching levels and reported as a scaled pressure from zero to seven for each sensor' (Light et al., 2010). TPI % represents the TPI as a percentage of all four limbs and illustrates weight distribution across all four paws.

Statistical methods

Data was exported from the gait software into a commercially available data analysis programme (Microsoft Excel 15.26, 2016) for descriptive statistics. Symmetry ratios (SR) of gait variables were calculated for each dog by dividing the forelimb value of each parameter by the hind limb value ($SR = X_{fore}/X_{hind}$). The SR metric was chosen over other measures of symmetry as it has the advantage of being easily interpreted (Patterson et al., 2010).

Further statistical analysis was performed using SPSS Statistics Desktop (V22.0, IBM) to evaluate the effect of vertebral kyphosis on individual gait variables. Generalised linear mixed models (GLMM) were constructed with individual gait variables included in models as the outcome measures, with presence of kyphosis as a binary predictor variable. Three trials were included for each dog in all analyses, with non-independence of this data accounted for by including dog ID as a random effect in all models. In initial univariate GLMM analyses, the effect of kyphosis upon all individual gait variables was investigated, with only dog ID included as an additional (random) effect. For those gait variables associated with kyphosis at the univariate level ($P < 0.2$), multivariate models were constructed where velocity and side of the dog were included as fixed effects to account for their potential impact upon other gait variables. Correlation between gait variables was checked to reduce the number of variables tested and thus the type I error. $P < 0.05$ was considered statistically significant in all tests.

To estimate the magnitude of the effect of kyphosis upon gait variables, the omega-squared (ω^2) effect size statistic was calculated for models in which kyphosis was a significant predictor of gait. Omega-squared is an estimate of how much variance in the outcome variables (gait) are accounted for by the explanatory variables (in this case, kyphosis). Magnitude of ω^2 was interpreted in line with Murphy and Myors (2004), where 0 indicates no effect, a small effect = 0.01, a medium effect = 0.06 and a large effect = 0.14.

Results

Twenty French bulldogs were initially enrolled in the study. Five dogs were excluded as they failed to produce three valid gait trials within the 30-min period. Hence, 15 French bulldogs were included in the final study. These dogs had a mean age of 21 months (range: 6–48 months) and a mean body mass of 11.2 kg (range: 7.8–15.4 kg). Twelve dogs were male (four neutered) and three were female (one neutered).

All dogs underwent CT imaging of the cervical and thoracic vertebral column for further investigation of brachycephalic obstructive airway syndrome (BOAS); seven dogs had no vertebral kyphosis while eight dogs had evidence of kyphosis (Fig. 1). Cobb angle in kyphotic dogs ranged from 14.9° to 39.5° (mean: 26.2°). Cobb angle in non-kyphotic dogs ranged from 0.5° to 6.2° (mean: 4.1°). Twelve study dogs had evidence of thoracic vertebral body malformations while only three study dogs had no obvious vertebral malformations. Of those dogs with thoracic vertebral body malformations, one dog had a single malformed vertebral body while the remaining eleven dogs had between 2 and 9 malformed vertebrae. The most commonly affected vertebra was the sixth thoracal vertebra (T6), which was abnormal in nine dogs, but affected vertebrae ranged from the second to the thirteenth thoracal vertebra (T2–T13). In those dogs with kyphosis, all vertebral malformations were associated with the kyphotic curve apex.

Three valid gait trials were collected for each dog at a walk (Table 1). The average number of gait cycles per valid trial was five. Gait velocity was 0.742 m/s (standard deviation (SD) ± 0.122) for non-kyphotic dogs and 0.793 m/s (SD ± 0.158) for kyphotic dogs. There was no statistically significant difference in gait velocity between the two groups ($P = 0.241$). In non-kyphotic dogs, the number of activated sensors in the thoracic limbs was 9.83 (SD ± 1.24) and in kyphotic dogs, it was 9.75 (SD ± 1.48). In non-kyphotic dogs, the number of activated sensors in the pelvic limbs was 5.35

(SD ± 0.71) and in kyphotic dogs was 4.83 (SD ± 1.47). Overall, there was no significant difference in the number of activated sensors in the thoracic limbs ($P = 0.847$) or pelvic limbs ($P = 0.129$) between kyphotic and non-kyphotic groups.

In univariate analyses (with dog ID accounted for as a repeated measure), seven gait variables were found to be associated with the presence of kyphosis ($P < 0.20$): Hind reach, TPI forelimbs, TPI % forelimbs, TPI hind limbs, TPI % hind limbs, TPI symmetry ratio, and TPI % symmetry ratio (see Appendix: Supplementary File 2). For non-kyphotic dogs, TPI fore limbs was 66.5 (95% CI: 64.7–68.3) and TPI hind limbs was 33.4 (95% confidence interval (CI): 31.6–35.2). For kyphotic dogs, TPI fore limbs was 69.4 (95% CI: 67.6–71.2) and TPI hind limbs was 30.8 (95% CI: 28.9–32.6). As TPI was strongly correlated with TPI % for fore and hind limbs in kyphotic and non-kyphotic dogs ($r > 0.7$ and $P < 0.001$), only TPI variables were explored in multivariate analyses, to reduce the likelihood of type I errors from multiple testing.

In multivariate analyses, kyphosis significantly affected two gait variables: TPI forelimbs and TPI symmetry ratio (Fig. 2; see Appendix: Supplementary File 3). Although significant, the effect size of kyphosis upon these two kinetic gait variables was small (TPI fore $\omega^2 = 0.004$; TPI symmetry ratio $\omega^2 = 0.003$). Velocity had a significant effect on TPI forelimbs, TPI hind limbs and TPI symmetry ratio. No effect of side was found in any model ($P > 0.05$).

Discussion

Although vertebral kyphosis is rarely associated with neurological deficits, the findings of the current study suggest an association with subtle alterations in kinetic gait variables. Dogs with kyphosis had a greater TPI in their thoracic limbs and an altered TPI symmetry ratio when compared to dogs without kyphosis. This means that dogs with vertebral kyphosis shifted weight from the pelvic limbs onto the thoracic limbs. While the effect of kyphosis was statistically significant, the numerical difference in gait variables between the study groups was relatively minor, and calculated effect sizes were small. The results should therefore be interpreted with the small magnitude of effect in mind. However, the study hypothesis was largely unsupported, as the majority of gait variables tested were not significantly different between kyphotic and non-kyphotic dogs.

Although the dogs in this study were clinically normal, altered kinetic gait variables which were not evident on visual gait assessment and only detectable using the walkway, suggest that dogs with kyphosis may undergo a compensatory adaption secondary to a structural abnormality. It is unclear if the pathophysiological basis for this compensatory adaption is due to compromise of neurological pathways involving sensory or motor tracts, or if it is simply a biomechanical adaptation. The inability to definitively differentiate between ataxia and paresis using the pressure walkway is an intrinsic limitation of the system. In the human literature, previous studies utilizing the GAITrite system attempted to correlate alterations in temporal-spatial gait variables with functional impairments using a graded scoring system, although all those patients were neurologically abnormal (Givon et al., 2009). Interestingly, in a study by Gordon-Evans et al. (2009), dogs with thoracolumbar spinal cord disease also distributed more weight on neurologically normal thoracic limbs as a result of pelvic limb ataxia compared with clinically normal dogs. In the same study, neurologically affected dogs also exhibited decreased stance time, stride time, and stride length in the thoracic limbs, and increased swing time in the pelvic limbs (Gordon-Evans et al., 2009). In contrast, kyphotic dogs in the current study distributed more weight on thoracic limbs but temporal-spatial gait variables remained unchanged; this suggests the pathophysiology of altered kinetic gait variables in kyphotic dogs may have a non-neurological mechanism and may simply represent a biomechanical adaptation rather than subclinical neurological disease.

While the clinical relevance of the study findings is currently unclear, vertebral malformations could predispose affected dogs to degenerative changes of the vertebral column. Dogs with kyphosis are more likely to have a different anatomical distribution of thoracolumbar intervertebral disc disease and earlier degeneration of adjacent intervertebral discs (Aikawa et al., 2014, Faller et al., 2014, Inglez de Souza et al., 2018). French bulldogs are known to be at risk of spinal conditions such as intervertebral disc extrusion and spinal arachnoid diverticula (Aikawa et al., 2014, Mauler et al., 2014, Mayousse et al., 2017). The pathophysiology is considered to be multifactorial with genetic, anatomic and biomechanical factors involved (Brisson, 2010, Mauler et al., 2014), but altered gait variables and vertebral loading is one possible cause. The mechanisms responsible are likely related to asymmetrical loading of vertebrae and intervertebral discs adjacent to the kyphotic vertebral segments, and secondary effects on supporting soft tissues with altered stress-loading cycles (Stokes and Iatridis, 2004, Moissonnier et al., 2011, Ortega et al., 2012, Aikawa et al., 2014, Faller et al., 2014). Therefore, while vertebral kyphosis is rarely a direct cause of clinical signs in affected dogs, it is possible that biomechanical changes associated with kyphosis could contribute to the development of spinal conditions such as intervertebral disc disease. Biomechanical changes and chronic alterations in loading of appendicular joints could also have wider implications on the health status of affected individuals, such as increased incidence of orthopaedic disease and degenerative arthropathies of thoracic limbs (Kaplan et al., 2017, Roemhildt et al., 2010, Vos et al., 2009). The study findings suggest that although thoracic vertebral malformations and spinal kyphosis are only rarely considered the direct cause of clinical signs, their occurrence should not necessarily be a benign finding. These conclusions may raise welfare issues associated with the breed conformation and could also have implications for other screw-tailed brachycephalic breeds commonly affected with vertebral kyphosis.

Temporal-spatial gait variables have been evaluated in several canine breeds to establish breed-specific reference ranges (Light et al., 2010, Lima et al., 2015). The results from non-kyphotic study dogs provide breed-specific reference values not previously reported for French bulldogs. Gait variables vary significantly between dogs of different body mass and size, which may in turn, lead to variation in the center of gravity and influence the force distribution between different limbs (Bertram et al., 2000, Voss et al., 2010). Although it is difficult to directly compare gait variables between different breeds for the reasons outlined above, comparison of symmetry ratios can be useful. In the current study, non-kyphotic dogs had a 67:33 percentage weight distribution for thoracic and pelvic limbs, respectively. This ratio is noticeably different from the previously reported 60:40 weight distribution assumed for the normal canine population at a walk (Nunamaker and Blauner, 1985; Kano et al., 2016). This suggests that this deviation of 'normal' is likely breed specific and related to conformational differences between specific canine breeds, as demonstrated in a previous study (Voss et al., 2011).

The prevalence of thoracic vertebral malformations in our study population was similar to earlier studies (Moissonnier et al., 2011, Schlensker and Distl, 2013, Ryan et al., 2017). The fact that the majority of neurologically normal French bulldogs are affected with such malformations creates some difficulty to define what is 'normal' in this breed. It would be interesting to collect gait variables in French bulldogs with neither thoracic vertebral malformations nor kyphosis to better investigate the influence of these anomalies on gait variables. Practically however, this is challenging considering up to 93.5% of French bulldogs may be affected with such malformations (Ryan et al., 2017). Future work involving data stratification based on Cobb angle measurement may focus on the correlation between gait variables and the degree of kyphosis. A vertebral angulation threshold of 10° was chosen in this study as this has previously been reported as clinically relevant in the human literature (Angevine and Deutsch, 2008). While a Cobb angle measurement of 35° or more is linked to an increased risk of neurological disease (Guevar et al., 2014), it is quite plausible that there could be clinical consequences well before this. Vertebral kyphosis has previously been classified as mild (<15°), moderate (15–60°), or severe (>60°) although no direct correlation with clinical significance was reported (Aikawa et al., 2007).

The primary limitation of the current study was the small sample size which was smaller in number than the number of gait variables examined; this could lead to type II error and restricts the possible conclusions. Nevertheless, two gait variables were significantly different between the study groups and these findings provide a basis for further research which would ideally utilize a larger sample size. The variation in handlers is another limitation; despite both handlers being experienced and trained in the study protocol, there is potential for introduction of variability (Keebaugh et al., 2015). Although previous studies by Gordon-Evans et al. (2009) and Lima et al. (2015) may allow some predictions regarding the possible effect of kyphosis on specific gait variables, this study is one of the first of its kind. Therefore, the study hypothesis was rather exploratory and examined a broad set of gait variables. This restricts the impact of the study conclusions, although the findings provide grounds on which future research hypotheses with a more specific focus may be based. Another limitation was the lack of a 'control' group of dogs. It would indeed have been valuable to recruit a population of dogs with neither evidence of vertebral kyphosis or vertebral malformations. Due to the high prevalence of vertebral malformations within the breed (Moissonnier et al., 2011, Schlensker and Distl, 2013, Ryan et al., 2017), this was not practically possible within the time constraints of the study. Finally, another study limitation was the lack of information regarding classification of each vertebral malformation in the dogs under study. While this was beyond the scope of the current study, it is possible that different vertebral malformations may have a different effect on gait variables.

Conclusions

Vertebral kyphosis was associated with subtle alterations in kinetic gait variables (TPI fore limbs and TPI symmetry ratio), with kyphotic dogs redistributing weight from pelvic limbs onto thoracic limbs. This could be linked with altered vertebral loading and potentially predispose French bulldogs to degenerative changes of the vertebral column. However, 14 of 16 gait variables tested were not significantly different between kyphotic and non-kyphotic dogs. Therefore, the study hypothesis was largely unsupported. Further studies are necessary to fully evaluate the clinical relevance of altered gait variables and its influence on spinal biomechanics.

Conflict of interest statement

This research did not receive any specific grants from funding agencies in the public, commercial, or not-for-profit sectors. None of the authors has any financial or personal relationships that could inappropriately influence or bias the content of the paper.

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Table 1. Descriptive statistics of temporal-spatial gait variables in kyphotic versus non-kyphotic dogs.

Variable	No kyphosis	Kyphosis
Hind reach (m)	0.015 ± 0.044	0.042 ± 0.044
TPI fore	33.24 ± 1.99	34.70 ± 2.14
TPI hind	16.70 ± 1.99	15.38 ± 2.18
TPI symmetry ratio	2.12 (1.67–2.32)	2.28 (1.85–3.09)
TPI fore (%)	66.49 ± 3.98	69.40 ± 4.30
TPI hind (%)	33.41 ± 3.98	30.75 ± 4.36
TPI percentage symmetry ratio	2.06 (1.76–2.25)	2.34 (1.95–2.65)
Stride length fore (m)	0.427 ± 0.053	0.423 ± 0.049
Stride length hind (m)	0.423 ± 0.052	0.421 ± 0.049
Stride length symmetry ratio	1.00 (0.99–1.02)	1.01 (0.99–1.02)
Stance time fore (s)	0.34 ± 0.07	0.31 ± 0.06
Stance time hind (s)	0.28 ± 0.09	0.26 ± 0.06
Stance time hind symmetry ratio	1.15 (1.13–1.35)	1.16 (1.08–1.28)
Stance time fore (%)	57.49 ± 4.48	56.55 ± 4.34
Stance time hind (%)	46.94 ± 8.62	46.60 ± 6.94
Stance time percentage symmetry ratio	1.15 (1.12–1.39)	1.17 (1.09–1.29)

[a]Normally distributed variables are stated as mean ± standard deviation (SD) and non-normally distributed variables as median (25th–75th percentiles).

[b]Total pressure index (TPI).

Figure 1. Saggital computed tomography (CT) images of two dogs: (A) is regarded as non-kyphotic and has a Cobb angle of 2.4°; (B) is regarded as kyphotic and has a Cobb angle of 37.5°.

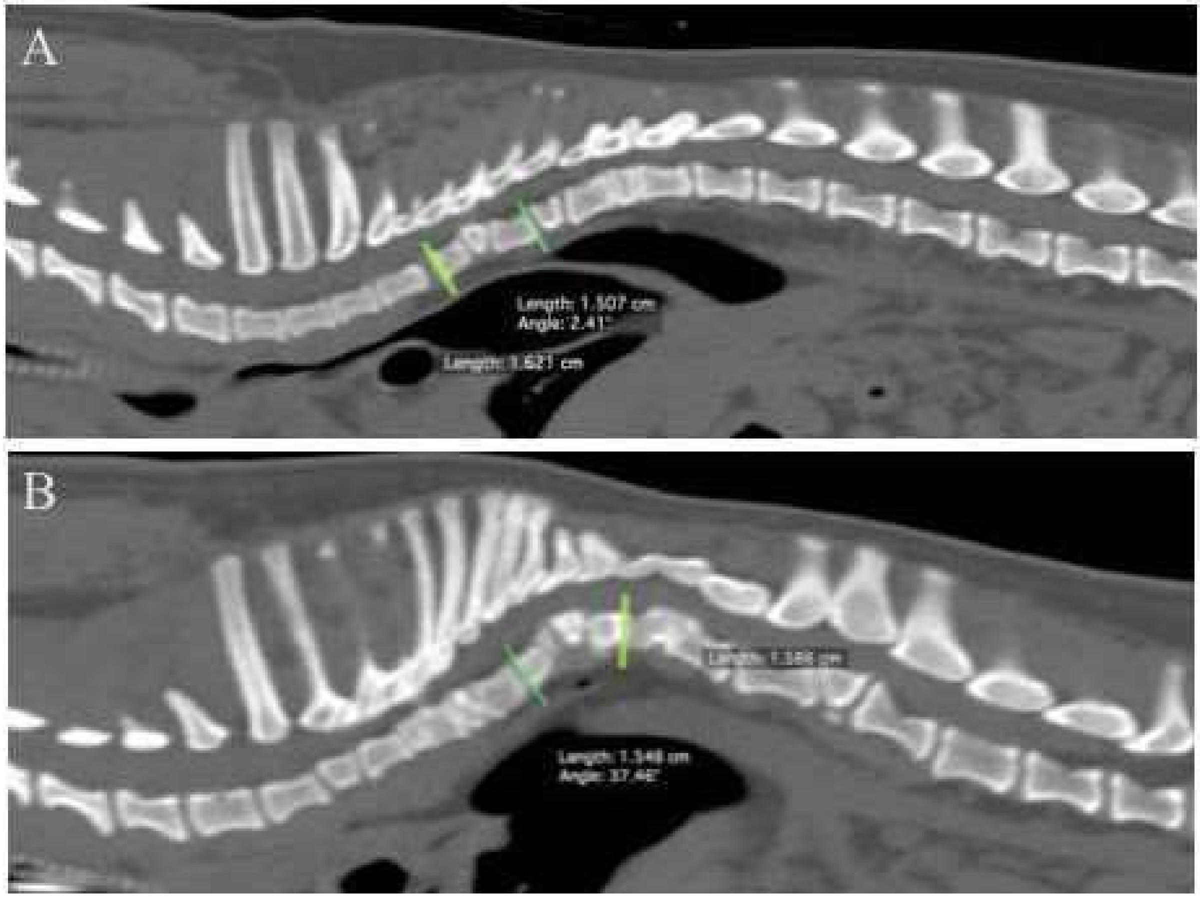

Figure 2. Graphical illustration of data for total pressure index (TPI) of the forelimbs and the TPI symmetry ratio in kyphotic and non-kyphotic dogs.