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Kinetic and kinematic follow-up gait analysis in Doberman Pinschers with cervical spondylomyelopathy treated medically and surgically

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Background: The efficacy of treatment of dogs with cervical spondylomyelopathy (CSM) is commonly based on the owner's and clinician's perception of the gait, which is highly subjective and suffers from observer bias.

Hypothesis/Objectives: To compare selected kinetic and kinematic parameters before and after treatments and to correlate the findings of gait analysis to clinical outcome.

Animals: Eight Doberman Pinschers with CSM confirmed by magnetic resonsance imaging.

Methods: Patients were prospectively studied and treated with either medical management (n = 5) or surgery (n = 3). Force plate analysis and 3-D kinematic motion capture were performed at initial presentation and approximately 8 weeks later. Force plate parameters evaluated included peak vertical force (PVF). Kinematic parameters measured included number of pelvic limb strides, stifle flexion and extension, maximum and minimum thoracic limb distance, truncal sway, and thoracic limb stride duration.

Results: Kinematic analysis showed that deviation of the spine to the right (truncal sway) was significantly smaller ($P < .001$) and the degree of right stifle flexion was significantly larger ($P = .029$) after treatment. Force plate analysis indicated that PVF was significantly different after treatment ($P = .049$) and the difference of the PVF also was significantly larger ($P = .027$). However, no correlation was found with either method of gait analysis and clinical recovery.

Conclusions and Clinical Importance: Kinetic and kinematic gait analysis were able to detect differences in dogs with CSM before and after treatment. A correlation of gait analysis to clinical improvement could not be determined.

KEYWORDS
cervical instability, digital motion capture, kinematic, kinetic, wobbler

Abbreviations: CSM, cervical spondylomyelopathy; CV, coefficient of variation; MRI, magnetic resonance imaging; PBF, peak braking force; PBI, peak braking impulse; PMLF, peak mediolateral force; PMLI, peak mediolateral impulse; PPF, peak propulsive force; PPI, peak propulsive impulse; PVF, peak vertical force; PVI, peak vertical impulse

1 | INTRODUCTION

Cervical spondylomyelopathy (CSM) a common disease of the cervical vertebral column in large and giant breed dogs, particularly Doberman Pinschers and Great Danes.[1,2] Gait abnormalities often are 1 of the first signs noted in dogs with CSM and are observed as a slowly progressive pelvic limb ataxia or "wobbling" of the pelvic limbs.[1,3] Thoracic limb abnormalities may manifest themselves as variable degrees of ataxia in combination with a short, stilted gait.[1,3,4] The disease is secondary to a collection of disorders affecting primarily the caudal cervical vertebrae and intervertebral discs resulting in clinical signs of spinal cord or nerve root compression or both including neurologic deficits, cervical hyperesthesia, or both.[3,5] The cause of the spinal cord compression often is multifactorial and can be caused by vertebral canal stenosis (relative or absolute), intervertebral disc protrusion, or hypertrophy of the ligamentum flavum.[1] Based on the multifactorial pathogenesis of this disease process, treatment recommendations are highly variable. Thus, the standard method for evaluating response to treatment is based on subjective interpretation of both the clinician and client's perception. For this reason, objective parameters are needed that can be correlated to clinical findings.

Kinematic and kinetic gait analyses are being used more frequently in veterinary medicine. Specifically, gait analysis has been used for evaluation of orthopedic diseases including cranial cruciate ligament disease, hip dysplasia, and treatment outcomes after surgical repair of these conditions.[6–16] Gait analysis also has been used in the evaluation of neurologic diseases in animal models, including dogs, horses, and rodents.[17–29] More recently, these techniques were applied in evaluating dogs with CSM.[21,22,30]

In human medicine, gait analysis has been used routinely in the evaluation of neurologic conditions, including cervical spondylotic myelopathy, the equivalent of CSM in humans.[31–37] These techniques have been used to correlate findings on magnetic resonance imaging (MRI) with clinical signs and to determine outcomes after surgery.[32,34] A recent study evaluated both kinetic and kinematic parameters in the pelvic limbs in a group of control dogs and dogs that underwent a thoracolumbar hemilaminectomy for disc disease.[26] Although this study found significant changes between the groups, it did not correlate the abnormalities in these gait parameters with clinical neurologic status.

The purpose of our study was to compare selected force plate kinetic and digital video motion capture kinematic parameters before and after medical or surgical treatment and to correlate these parameters with clinical signs to use as markers of outcome. We hypothesized that certain kinetic and kinematic parameters such as peak vertical force (PVF), thoracic and pelvic limb distances, truncal sway (ie, spinal angles), and thoracic limb stride duration would be significantly different between the initial and post-treatment follow-up gait analyses. We also hypothesized that these parameters would be correlated with clinical outcome.

2 | MATERIALS AND METHODS

2.1 | Animals

Eight client-owned mature Doberman Pinscher dogs were prospectively enrolled. The dogs were part of a previous study for which baseline data was presented in 2 previous studies.[21,22] The study was conducted in accordance with the guidelines and approval of the Clinical Research Advisory Committee and the Institutional Animal Care and Use Committee of the Ohio State University. Written owner consent was obtained before study enrollment. Dogs were considered affected and eligible for study enrollment if they had neurologic examination findings consistent with a cervical myelopathy and were skeletally mature ($\geq$1 year of age). All affected dogs underwent physical and neurologic examinations performed by 2 of the authors (K. Foss and R. da Costa), CBC, serum biochemistry profile, cervical spinal radiographs, and MRI examination of the cervical vertebral spine. Additionally, thoracic radiographs were performed in all affected dogs $>$ 7 years of age (n = 5). Neurologic status at the time of initial examination was graded on a scale from 1 to 5 on the basis of a previously published grading scale.[5,8] Patients with cervical hyperesthesia only were classified as Grade 1. These patients were excluded from participation. Grade 2 patients were those with mild pelvic limb ataxia or paresis with mild thoracic limb involvement. Thoracic limb involvement was defined as either a short-strided or spastic gait with a floating appearance. Grade 3 patients were defined as having moderate pelvic limb ataxia or paresis with thoracic limb involvement as described in Grade 2. Grade 4 was defined as marked pelvic limb ataxia or paresis with thoracic limb involvement, and Grade 5 was defined as nonambulatory tetraparesis. Any patient with Grade 5 neurologic status also was excluded from the study. All patients were confirmed to have CSM by MRI, which confirmed evidence of spinal cord compression with or without spinal cord signal change.

2.2 | Gait analysis

All dogs underwent kinetic (force plate) and kinematic (3-D motion capture) gait analysis before beginning treatment and 8–16 weeks after initiation of treatment. Force plate gait analysis was performed in all 4 limbs of all dogs using a stationary force plate (Kistler Model 9687A force platform, Kistler Instrumente AG, Winterthur, Switzerland) and computer analysis system (Acquire 7.35, Sharon Software, Inc, Dewitt, Michigan) as previously described.[22] At least 4 runs of ipsilateral limbs were collected from all dogs. Peak vertical force was the sole kinetic parameter evaluated based on results of a previous study that showed PVF to have a significant amount of variability between normal and affected dogs with CSM.[22] Force peaks and impulses were expressed as percentage of body weight and percentage of body weight per second by normalizing the dogs' weights and multiplying by time, respectively.

Three-dimensional motion capture also was performed as previously described.[21] All dogs were fitted with a Lycra (Invista, Wichita, Kansas) bodysuit and 32 reflective markers were applied representing

specific anatomic landmarks of the head, trunk, and limbs. Three-dimensional motion capture was performed with 15 infrared cameras in a designated capture space using the Vicon8i (Vicon, Los Angeles, California) motion capture system. Kinematic parameters evaluated included number of pelvic limb strides, stifle flexion and extension, maximum and minimum thoracic limb distance, thoracic limb stride duration, truncal sway (lateral spinal deviation), and hip drop difference (pelvic limb height deviation).[21] Processing of the recorded images was carried out using Vicon iQ 2.0 (Vicon) software. The sagittal plane (viewing the dog from the side) was defined as the x-plane, the vertical plane as the y-plane, and movement toward/forward and away/backward, as the z-plane. Limb angles were determined in the x-plane, spine angle from the y-plane, limb distance in the z-plane, step cycle duration and stride length in the x-plane, and hip drop difference in the x-plane. The number of strides was recorded from each pelvic limb of every dog and counted as successive maximal x-plane positions. The angle of the stifle joints was determined by the maximum joint angle positions in both flexion and extension and measuring the maximum and minimum values for each angle during the step cycle. Stifle angles were defined as the maximum and minimum angles formed by the greater trochanter, the stifle joint, and the tarsal joint. Maximum and minimum distance between the thoracic limbs was the maximum and minimum distance recorded between the contralateral limbs in the z-plane. Thoracic limb stride duration was calculated by measuring the time elapsed between 1 maximal x-plane position and the next in the front paws. Truncal sway was calculated based on the maximum and minimum lateral deviation of the vertebral column at any given time during the walking phase. It was determined by measuring the maximum and minimum angles made from the Spine 1 marker to the greater trochanter in the y-plane. The maximum and minimal angles were the angles made between these 2 vectors in the y-plane. Lastly, hip drop, or pelvic limb height difference was calculated using the difference between maximum and minimum distance from the marker on the greater trochanter and the hind paw in the x-plane.

2.3 | Statistical analysis

All data for the 3-D motion capture were cleaned and exported using Microsoft Visual Studio 2009 (Microsoft, Redmond, Washington). All data acquired in Vicon iQ 2.0 then was transferred as numerical data into MATLAB (MathWorks, Natick, Massachusetts). A custom-written script was used to extract the data points of interest. The resulting data then was analyzed by Stata 12.0 (Stata Corporation, College Station, Texas). Differences in the means for both the kinetic and kinematic data were tested using a random effects linear regression model with significance level set at $P < .05$. Regression analyses were performed because multiple observations were nested within each dog. For the kinetic gait analysis, PVF was evaluated by regression analysis using the mean values from each limb in all dogs and using the mean values from all 4 limbs in all dogs. Significance levels again were set at $P < .05$.

The clinical assessment for each dog was correlated to the gait analysis parameters to determine if any measurement could predict improvement. For each dog at each visit, the mean of the technical replicates was calculated for each of the 17 paremeters, and the difference of the means was calculated. A logistic regression model was fitted for each of the 17 possible predictor parameters (using the difference of the means), with the outcome being clinical improvement.

3 | RESULTS

3.1 | Clinical findings

Eight dogs were enrolled, 6 males and 2 females between the ages of 3 and 12 years (mean, 6.7 years; standard deviation [SD], 2.87 years; median, 7 years). Initial clinical signs included mild pelvic limb ataxia or paresis with thoracic limb involvement (Grade 2; n = 4), moderate pelvic limb ataxia or paresis with thoracic limb involvement (Grade 3; n = 2), and marked pelvic limb ataxia or paresis with thoracic limb involvement (Grade 4; n = 2). Four of the 8 dogs were more affected on the right side based on neurologic examination, 3 were slightly worse on the left, and 1 did not show lateralization on the neurologic examination. The body weight of the dogs ranged from 27.2 to 55.7 kg (mean, 32.6 kg; SD, 8.33; median, 34.5 kg). All CSM-affected dogs had spinal cord compression located in the caudal cervical vertebral column as identified by MRI. The main compression was located at C5-6 in 3 dogs, and at C6-7 in 5 dogs. The degree of compression was considered to be mild in 6 dogs (2 with compression at C5-C6 and 4 at C6-C7), moderate in 1 one dog with compression at C5-C6, and severe in 1 dog with compression at C6-C7. Four dogs had lateralized compression based on the MRI with 3 having more compression on the right, and 1 with more compression on the left. The compression was considered to be mild in all dogs with lateralization based on MRI. The main cause of spinal cord compression was disc-associated in all dogs, with or without ligamentous compression. Five of the 8 dogs were treated medically using either a combination of nonsteroidal anti-inflammatory and pain medications or a tapering course of corticosteroids and additional pain control. The remaining 3 dogs underwent cervical disc arthroplasty at C6-C7.

Mean time between initial and follow-up kinetic and kinematic gait analysis was 2.3 months (range 2–4 months). On re-evaluation, 2 dogs were considered to be improved based on gait assessment. One dog had improved to normal gait from grade 2 on initial examination; the other dog improved from grade of 3 to grade of 2. Five dogs remained the same (2 remained grade 4; 1 remained grade 3 and 1 grade 2) and 1 dog decreased a neurologic grade (grade 2 to grade 3).

3.2 | Gait analysis

The mean number of valid passes collected during kinetic gait analysis was 4.5 (range, 3–6). Observations for each dog from the kinematic gait analysis ranged from 13 to 20 (mean, 22.75) in the affected dogs. Detailed results of the kinetic and kinematic gait analysis are presented in Tables 1 and 2. Maximum and minimum thoracic limb distance was found to be larger after treatment with the maximum thoracic distance increasing from 190.1 to 203.1 mm and the minimum increasing from

TABLE 1 Initial and follow-up data for Doberman Pinchers with CSM before and after treatment

Parameter	Initial	Follow-up	Difference	*P* value
Number of strides/10 s LH	3.34	3.17	−0.17	.649
Number of strides/10 s RH	2.58	3.17	−0.22	.554
Right stifle flexion (degrees)	102.2	107.1	4.94	*.029
Right stifle extension (degrees)	138.5	142.6	4.07	.036
Left stifle flexion (degrees)	106.0	101.9	−4.16	.499
Left stifle extension (degrees)	138.9	136.9	−2.00	.480
Max thoracic limb distance (mm)	190.1	203.1	12.95[a]	.080
Min thoracic limb distance	130.2	140.6	10.41[a]	.110
Stride duration LF (seconds)	0.75	0.76	0.01	.675
Stride duration RF (seconds)	0.74	0.75	0.01	.748
Max right spinal deviation (degrees)	10.8	10.4	0.4	*<.001
Min right spinal deviation (degrees)	8.9	9.05	0.15	.158
Max left spinal deviation (degrees)	9.82	9.83	0.01	.176
Left pelvic limb hip drop (mm)	14.6	16.9	2.3	.071
Right pelvic limb hip drop (mm)	17.8	17.3	0.5	.786

*$P < .05$ while not found to statistically different, there still is a large increase in the maximum and minimum thoracic limb distance after treatment.[a]

130.2 to 140.6 mm. However, the differences were not found to be statistically significant ($P = .08$; $P = .110$, respectively). Maximum truncal sway to the right was found to be significantly smaller after treatment ($P < .001$) but no other changes in truncal sway were significantly different (Table 1). When comparing the means from each limb of all dogs with force plate analysis, PVF was significantly different in all dogs after treatment ($P = .049$). When using the mean values from all limbs combined for all dogs before and after treatment the difference between PVF was significantly larger ($P = .027$; Table 2). The other parameters analyzed were nonsignificant. When correlating clinical outcome to gait analysis parameters, no predictor variable approached statistically significant correlation with recovery.

TABLE 2 Regression analysis of PVF using the means from each limb and means from all limbs of all dogs at the initial and follow-up visit

Parameter	Limb	Initial	Follow-up	Difference	95% CI		*P* value
PVF	LF	69.82	73.71	3.89	0.02	7.75	.049
	LH	47.44	51.33	3.89	0.02	7.75	
	RF	67.40	71.29	3.89	0.02	7.75	
	RH	48.89	52.77	3.88	0.02	7.75	
PVF	ALL	58.36	63.32	3.96	0.44	7.48	.027

Abbreviations: LF, left front limb; LH, left hind limb; RF, right front limb; RH, right hind limb.

4 | DISCUSSION

Our study was designed to use specific kinetic and kinematic gait parameters to detect consistent differences in Doberman Pinchers with CSM after medical or surgical treatment and to correlate these findings with clinical status. The results supported our hypothesis that PVF would be significantly different from initial presentation to follow-up. We found PVF to be significantly larger after treatment and it remained higher in the thoracic limbs. In patients suffering from orthopedic disease, a lower PVF indicates lameness or impaired function. Therefore, an increase in PVF in our patients after treatment would be indicative of improvement.[38] This finding could indicate potential improvement in strength in our patient population. It was also noted that PVF in the thoracic limbs remained higher than in the pelvic limbs, even after treatment. This finding is not surprising because it is generally assumed that dogs carry approximately 60% of their body weight in the thoracic limbs and approximately 40% in the pelvic limbs.[39]

We also found our hypothesis was partially correct in regard to truncal sway because this parameter was noted to be smaller after treatment. It is interesting that truncal sway to the right was improved but the truncal sway to the left was not significantly different. This finding may be a consequence of the fact that in our patient population, 50% (4/8) of dogs were neurologically more affected on the right side, whereas in the remaining dogs, 3 were worse on the left and 1 did not show lateralization. Additionally, in those dogs that had lateralized compression on MRI, 75% (3/4) had more severe compression on the right. This finding may not be unusual because mild asymmetric signs are seen in approximately 50% of dogs with CSM.[1,40] In 1 study, it was observed that Dachshunds suffering from thoracolumbar disc disease had more pronounced asymmetric changes on the affected side of the body and it was theorized that patients with uncoordinated gait may be falling to the more affected side or limb because of lack of control on that side.[26] Another study also showed greater thoracolumbar lateral angulation in the direction of the affected limb in dogs without visually detectable lameness.[41] A finding we did not expect was the increased flexion of the right stifle at follow-up. The decreased flexion on presentation is likely explained by spastic paresis, but we would expect an improvement in both pelvic limbs. The explanation again may be associated with the fact that half of the dogs were affected on the right side and also may be explained by another study in which dogs affected with myelopathic disease tend to fall towards 1 side more than the other.[26] Therefore, reduction in truncal sway actually may indicate an improvement in mild, asymmetric ataxia, and the increased stifle flexion may indicate mild improvement in weakness. The other explanation for the finding of asymmetrical truncal sway (right versus the left) could be that of soft tissue artifact (STA). Soft tissue artifact is a common source of error in gait analysis of humans and horses by and is caused by movement of the skin being recorded instead of the underlying skeletal structures when using skin markers.

Algorithms have been proposed to correct for STA in horses but none exist yet for dogs.[42]

We were not able to show a correlation in clinical outcome with the gait analysis parameters. Despite the fact that a correlation was not identified, all 3 dogs in which clinical improvement was noted showed corresponding changes in the kinetic and kinematic parameters. All 3 dogs experienced a decrease in truncal sway and an increase in right stifle flexion. Because of small sample size, we cannot draw a conclusion from these results, but they do suggest further investigation, especially into using truncal sway and spine angles as outcome measures. This finding also is similar to that of another study in which pelvic sway range of motion was found to be a more sensitive indicator of myelopathy as compared to pelvic limb joint range of motion.[26]

The reliability of 3-D gait analysis is evaluated in multiple ways, 1 of which is performing multiple walking trials within a single session. The variability among these trials is classified as "intrinsic" and reflects the inherent variation within either unimpaired individuals or those with underlying pathology. Intrinsic variations reflect intraindividual variations that arise naturally, either from trial-to-trial or subject-to-subject variability. Usually, these variations can be overcome by collection of data from many walking trials during the same session.[43–45] In our study, multiple trials and observations were performed for each patient for both the kinetic and kinematic gait analysis with an average of 4.5 valid trials and 22.75 observations, respectively. Extrinsic factors also account for variability and typically are from procedural errors, with marker placement being a key factor.[43] A main issue with the use of skin markers is accurate and repeatable placement of the markers. One study found that accurate and reproducible marker placement was difficult in dogs because it required the dogs in the study to stand completely still in a neutral position.[26] In our study, Lycra body suits were used on the patients as an attempt to provided repeatable marker placement.

Limitations of our study include small sample size, which may lead to Type II error. A post-hoc power analysis was performed, and to correlate clinical recovery with PVF (with 80% power and 95% confidence) a sample size of 226 would be needed. For the other measures, sample sizes from 12 to 1193 would be needed. Therefore, it would take a substantial amount of time to obtain enough cases, especially when looking at a specific disease process in a specific breed of dog. There also is the potential for STA as well as inconsistent marker placement, as discussed above. We attempted to avoid STA by using the Lycra body suits. However, doing so still requires the marker to be on the skin and not the targeted osseous structure. In regard to any variability that may have occurred secondary to marker placement, we attempted to keep marker placement constant by using the same size Lycra suit for both gait trials but there is always the potential for some shifting of the body suit, and thus even a small change in the marker location. Unfortunately, the best way to minimize STA and ensure repeatable marker placement would be to place the markers into the bony landmarks, which is unethical in the living patient.

One concern with gait analysis is how body size may affect the results. In our study, we were evaluating only 1 breed with similar body conformation. Although body weight was variable, we did not anticipate this variation to affect our results because gait data are rescaled to dimension-less values such that inertial and gravitational forces scale in proportion, and the direction of the resultant force vector does not change with body size.[46] A study assessing whether kinetic data, in particular ground reaction forces and stance time, were dependent on dog breed and body confirmation did find significant differences in force plate data among different breeds and indeed recommended that group comparisons should be made only when breeds of similar body confirmation are used.[46] In regard to the kinematic parameters, larger dogs may have had a longer stride length and duration than smaller dogs. However, for our study, the dogs were grouped together and the data averaged when comparing pre- and post-treatment and, when assessing clinical response, dogs were compared with themselves. The other parameters (eg, flexion, extension, and truncal sway) should not be affected because they were expressed in degrees. Additionally, hip drop was the difference from the maximum hip height to the minimum and therefore size should not be a factor. During the kinematic gait analysis, we did not have any way to monitor each patient's speed, which could contribute to variability within the parameters. One way to control speed is to use a treadmill, as has been reported previously.[28] However, we chose to walk the dogs in a large, open space as it is more representative of a typical gait assessment and we felt doing so may show more gait differences. For the kinetic gait analysis, the speed could be monitored and any trial with a speed > 1.5 or < 0.5 m/s was excluded.

The type of surface also can affect a patient's gait, in particular a surface with less traction may make it more difficult for a weak or ataxic patient to walk.[47] The motion capture space consisted of rubber mats making it easy for the patients to walk. The force plate walkway was made of linoleum but the speed at which the dogs were walked did not cause any problems with ambulation. Lastly, the data collection time varied substantially in duration but did not seem to be correlated with neurologic status. Overall, the collection time for the kinetic gait analysis took 1–2 hours and the collection time for the kinematic data ranged from 45 minutes to 3 hours. We found that some dogs took longer based on their behavior when walked on a leash. In particular for the kinematic gait analysis, data collection had to be stopped and the process restarted any time a marker was dislodged, which also added a substantial amount of time to the process. Overall, the time and technique for both methods were not ideal given they took a substantial amount of time and required equipment that is not readily available and can be very expensive. More recently, a study using a pressure-sensitive walkway also found significant differences in the thoracic limbs and PVF of Doberman Pinchers with and without CSM.[30] This method of gait assessment also may be beneficial for evaluating the response of a patient with CSM to treatment because it is more commercially available than options for 3-D motion capture and less time-consuming compared to digital motion capture and force plate analysis.

In conclusion, kinetic and kinematic gait analysis detected differences in dogs with CSM before and after treatment. Unfortunately, correlation of gait analysis to clinical improvement could not be determined. Future, larger scale studies are warranted using these and other

computerized gait analysis techniques to determine if these methods can be used to evaluate response to treatment in dogs with CSM.

CONFLICT OF INTEREST DECLARATION

The authors declare that they have no conflict of interest with the contents of this article.

OFF-LABEL ANTIMICROBIAL DECLARATION

Authors declare no off-label use of antimicrobials.

INSTITUTIONAL ANIMAL CARE AND USE COMMITTEE (IACUC) OR OTHER APPROVAL DECLARATION

Authors declare no IACUC or other approval was needed. IACUC approval was obtained and is stated in the materials and methods.

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