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Original Article

Quantifying center of pressure variability in chondrodystrophoid dogs

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ABSTRACT

The center of pressure (COP) position reflects a combination of proprioceptive, motor and mechanical function. As such, it can be used to quantify and characterize neurologic dysfunction. The aim of this study was to describe and quantify the movement of COP and its variability in healthy chondrodystrophoid dogs while walking to provide a baseline for comparison to dogs with spinal cord injury due to acute intervertebral disc herniations. Fifteen healthy adult chondrodystrophoid dogs were walked on an instrumented treadmill that recorded the location of each dog's COP as it walked. Center of pressure (COP) was referenced from an anatomical marker on the dogs' back. The root mean squared (RMS) values of changes in COP location in the sagittal (y) and horizontal (x) directions were calculated to determine the range of COP variability.

Three dogs would not walk on the treadmill. One dog was too small to collect interpretable data. From the remaining 11 dogs, 206 trials were analyzed. Mean RMS for change in COPx per trial was 0.0138 (standard deviation, SD 0.0047) and for COPy was 0.0185 (SD 0.0071). Walking speed but not limb length had a significant effect on COP RMS. Repeat measurements in six dogs had high test retest consistency in the x and fair consistency in the y direction. In conclusion, COP variability can be measured consistently in dogs, and a range of COP variability for normal chondrodystrophoid dogs has been determined to provide a baseline for future studies on dogs with spinal cord injury.

Introduction

Thoracolumbar spinal cord injury is a common problem in certain breeds of dog because of acute intervertebral disc extrusion (Coates, 2000; Brisson, 2010). In chondrodystrophoid breeds, the nucleus undergoes premature degeneration resulting in acute extrusion of calcified nuclear material, which causes compression and contusion of the overlying spinal cord (Hansen, 1952; Funkquist 1962). The high frequency and serious nature of this condition have heightened interest in developing novel ways to assess both mechanisms and extent of recovery from spinal cord injury in dogs (Borgens et al., 1999; Laverty et al., 2004; Baltzer et al., 2008; Granger et al., 2012; Levine et al., 2014; Lim et al., 2014; Olby et al., 2016). There are numerous measures of outcome in this population of dogs, with a heavy focus on ordinal scales of gait (Olby et al., 2001; Levine et al., 2009) that can be applied readily in a clinical setting. However, subtle effects of neurologic injury on locomotion may be missed with these techniques and assessments are necessarily somewhat subjective.

Gait can be evaluated using kinematic analysis technology. This technique highlights the confounding influence of limb length and individual variation when attempting to measure parameters associated with stride. However, the variability of stride length, stride time, swing time, fore limb-hind limb coordination and lateral paw positioning are extremely low in normal dogs and highly variable in dogs with spinal cord injury (Hamilton et al., 2007, 2008; Gordon-Evans et al., 2009a and b). There are little data published on the use of pressure sensing technology in dogs with spinal cord injury. We were interested in identifying a single parameter that could be recorded in all dogs to reflect a combination of gait pattern and limb forces generated.

Center of gravity (COG; the three dimensional point representing the location of the average weight of a body) and center of pressure (COP; the two dimensional projection of center of gravity

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on the plane of the walking surface) have long been used in humans, and more recently in horses, to describe and quantify pathologic gaits (Cavanagh, 1983; Detrembleur et al., 2000; Massaad et al., 2004; Hobbs and Clayton, 2013; Clayton and Nauwelaerts, 2014). The position and movement of the COG and COP reflect the complex effects of proprioceptive, motor and mechanical influences on movement. As such, evaluation of changes in these parameters over time could provide insight into mechanisms of compensation and recovery and may provide an objective way to compare outcome from spinal cord injury.

The objectives of this study were to describe the movement of COP and to determine the range of variability of COP during walking in normal chondrodystrophoid dogs as a baseline for comparison to dogs with spinal cord injury. We hypothesized that a force-plate treadmill and infrared sensors could be used to quantify the variability of COP of dogs while walking and that COP variability remains consistent for individual normal dogs.

Materials and methods

Animals

Chondrodystrophoid dogs were recruited through the North Carolina State University (NCSU) College of Veterinary Medicine list serve, NCSU neurology service clients and Dodgerslist via their facebook page.[2] In order to participate, dogs had to be aged between one and 14 years and have no history of orthopedic lameness or neurologic disease. Owner consent was obtained for all participating dogs. Study protocol was reviewed and approved by the NCSU Animal Care and Use Committee, and the study was performed in compliance with institutional guidelines for research on animals (IACUC protocol number 14-022-O; approval date 14 February 2014).

Data collection

Dogs were fitted with six spherical reflective markers in specified anatomical positions. One marker was placed on the lateral surface of each forelimb and hindlimb just distal to the carpus or tarsus, respectively. Elastic tape was used to secure the marker in place without interfering with joint flexion and extension (Figs. 1 and 2). For long-haired dogs, additional bandaging was sometimes necessary to ensure hair did not block the markers. Two additional reflective markers were affixed to each dog's upper and lower back. The upper back marker was positioned between the 4th and 6th thoracic vertebrae by following the line of the point of the elbow dorsally to the midline and placing the marker just cranial to that point. Elastic and bandaging tape were used to secure the marker in this location. Only data from the upper back and right forelimb markers were used for the purposes of this study.

Trials were performed on an instrumented force-plate treadmill (Fully Instrumented Treadmill, Bertec) with six cameras with infrared sensors (mx-t020, Vicon) mounted on the ceiling surrounding the treadmill to track the location of the dogs' reflective markers. Trials were also recorded using a digital video camera (HDR-CX580V, Sony) positioned to capture all four limbs of the dogs as they walked as a reference on dog behavior during an individual trial if needed. The force-plate in the treadmill recorded the COP of each dog as it walked. COP location was recorded as a coordinate on the plane of the treadmill with system axes origin (0,0) at the left rear corner of the treadmill. The COP was computed by converting the summed effect of the forces and moments recorded by four six degree of freedom load transducers (*i.e.,* three forces (*F*'s) and three moments (*M*'s)) positioned under each of the corners of the treadmill belt into a single ground reaction force vector ($F_{x,y,z}$) and a couple, (T_z, sometimes called the 'free moment'), acting at a single point on the surface of the treadmill belt and defined as the center of pressure or COP (x_p, y_p) (Eq. (1)).

$$
\begin{aligned}
x_p &= \frac{-h \cdot F_x - M_y}{F_z} \\
y_p &= \frac{-h \cdot F_y + M_x}{F_z} \\
T_z &= M_z - x_p \cdot F_y + y_p \cdot F_x
\end{aligned}
\qquad (1)
$$

where *h* is the height difference of the treadmill belt surface from the x–y plane of the lab coordinate system. The analog force and moment signals output from the instrumented treadmill load transducers were sampled at 1000 hertz (Hz). The force and moment load ratings and (sensitivity) were 2500 N (500 N/V), 2500 N (500 N/V), and 5000 N (1000 N/V) for *F x, y* and *z*, respectively; and 4000 N-m (500 N-m/V), 1250 N-m (250 N-m/V), 2000 N-m (400 N-m/V) for *M x, y* and *z* respectively. We note the system used in this study was not optimized to be most sensitive for collecting data on small dogs, but rather average sized humans.

To express the COP location in the reference frame of the dog, during data analysis we redefined the COP location with respect to an origin positioned at the upper back marker of each dog. This allowed the coordinate system to be dynamic, moving with the dog if it shifted in position on the treadmill. COP location was assessed in the x (lateral) and y (rostrocaudal) directions (Eq. (1); Fig. 2).

Dogs were habituated to the handlers and the room for approximately five minutes by gentle examination by the handlers, placement of reflective markers and providing food treats, and their gait was evaluated to ensure they were not lame prior to starting the trials. The treadmill was set at a slow starting speed and dogs were encouraged to walk using vocal praise and/or food rewards. This was an important component of habituating the dogs to the treadmill. Treadmill speed was slowly increased until the dog maintained a steady walking pace. Once a comfortable walking speed was established, trials were recorded. One researcher, the recorder, called out the trial number and started data collection (Nexus, Vicon). Data for each trial were collected for as many step-cycles as possible with the dog walking at a steady pace. The recorder would stop data collection if the dog made an anomalous movement (such as lunging for a treat or stopping) and a new trial would begin when the dog resumed a steady pace. A second person, the observer, watched each recorded trial as it was being recorded and noted the quality of the trial as poor (stopped walking, stepped off the treadmill belt, sudden changes in speed or direction), good (walked consistently with only slight variation in gait) or excellent (walked consistently with no noticeable variation in gait). Only data from trials noted as good or excellent were processed and analyzed as part of the data set. The number and length of trials recorded for each session depended upon the cooperation of the dog on that day.

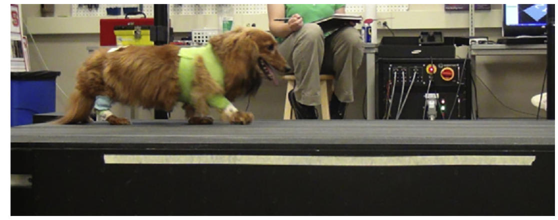

Fig. 1. A dog walking on the treadmill with reflective markers in place. The markers are spherical balls seen on the lateral aspect of the carpus and tarsus. In this dog, the colored bandaging is keeping the long hair from obscuring the markers. The observer can be seen in the background recording the quality of each trial.

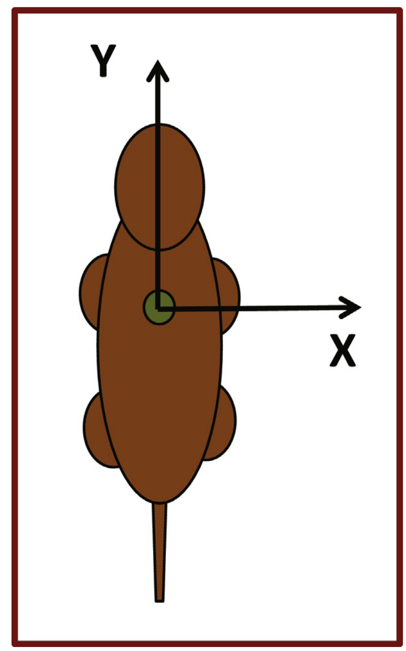

Fig. 2. Center of pressure (COP) was recorded in the X and Y direction relative to the interscapular back marker.

[2] https://www.facebook.com/Dodgerslist/

Data analysis

Center of pressure (COP) and marker location data were recorded in a spreadsheet as a .c3d file. The first data processing step involved visual inspection of the marker data using the Vicon Nexus software program to ensure that each reflective marker was accurately labeled for the anatomical location it represented throughout the entire trial. Occasionally, the infrared sensors would lose track of the spherical reflectors and pick up erroneous data. By visualizing the location of each tracked reflector over the course of each trial, the researcher could ensure that all recorded data accurately reflected the correct spherical target. If an infrared sensor did pick up erroneous data, the researcher could relocate the data captured by that infrared sensor back to the correct spherical marker although none of the datasets used for the final data analysis had any marker loss. Data files were then converted to .txt files (Visual 3D Software, C-Motion). The .txt file was then imported into MATLAB (MATLAB Software, MathWorks) to interpolate, filter, relocate, and plot data as well as to calculate COP root mean squared (RMS) values in the x and y directions using purpose-written code (see Appendix: Supplementary material).

Mean COP RMS values in the x and y directions were then calculated for each dog individually, and summary statistics for RMS values in both directions were calculated for all trials of all dogs, collectively (JMP Software, SAS). Change in right fore paw position in the y direction was plotted against time to facilitate step counting. Summary data on the number of steps per trial were generated for each dog individually and for all dogs collectively. The effect of walking speed and limb length (taken as the height of the upper back marker) on the RMS of COPx and y was investigated using logistic regression; $P \leq 0.05$ was taken as statistically significant. Test retest intersession variability for individual dogs was assessed by calculating intraclass correlation coefficients (ICC).

Results

Fifteen chondrodystrophoid dogs (12 Dachshunds, 2 Dachshund mixes, and 1 French bulldog mix) were recruited. Three dogs (20%) would not walk on the treadmill at any speed and one dog was too small to collect reliable data on the treadmill, leaving 11 dogs from which data were collected. Five dogs did one testing session, three dogs did two testing sessions, two dogs did three testing sessions and one dog did four testing sessions.

Of a total 489 trials recorded, 283 trials were classed as “poor” and not analyzed, leaving 206 trials for analysis. A total of 140 trials (out of the 206) had appropriate leg marker data and were analyzed for step cycles. Lack of leg marker data resulted from intermittent loss of camera contact with the relevant right forelimb reflective marker. A minimum of nine ‘good’ or ‘excellent’ trials (median 19; range 9–30) were recorded for each of the 11 dogs, with a minimum of two step cycles per trial (median 6; range 2–17). The median height of the reference back marker was 22.04 cm (range 19.89–28.01 cm). The median walking speed was 0.35 m/s (range 0.2–0.5 m/s).

COP data was generated for all 11 dogs. The mean COP position relative to the interscapular reference back marker was −0.34 +/− 0.12 cm in the x-direction (just left of the midline) and −8.51 cm +/−5.32 cm in the y-direction (caudal to the back marker). During a step cycle, the typical movement of the COP traced out a butterfly shape (Fig. 3). Oscillations in both x and y-directions happened twice during each step cycle (Fig. 4). Variability in COP as reported as RMS in the x and y directions was low, with a mean COPx RMS of 0.0138 (standard deviation, SD 0.0047) and mean COPy RMS of 0.0185 (SD 0.0071).

There was no significant relationship between COP measurements and back marker height in the x or y direction ($P = 0.35$ and 0.11, respectively). There was a significant relationship with treadmill speed with $P < 0.0001$ for both x and y directions.

Test retest reliability of COP RMS in the x direction was excellent (Table 1) with an ICC of 0.86. It was more variable in the y direction with an ICC of 0.46 interpreted as a fair reliability.

Discussion

We determined that a force-plate treadmill and infrared sensors can be used to describe COP of dogs while walking and to quantify its variability (RMS). The majority of dogs tested (11 out of 15) walked consistently on the treadmill and produced interpretable data. Center of pressure (COP) in the small breed dogs represented here resides approximately 8.5 cm caudal to the point of the elbow in a squared standing position and shifts laterally, forwards and backwards with stepping. Center of pressure (COP) RMS is low and is consistent for individual dogs.

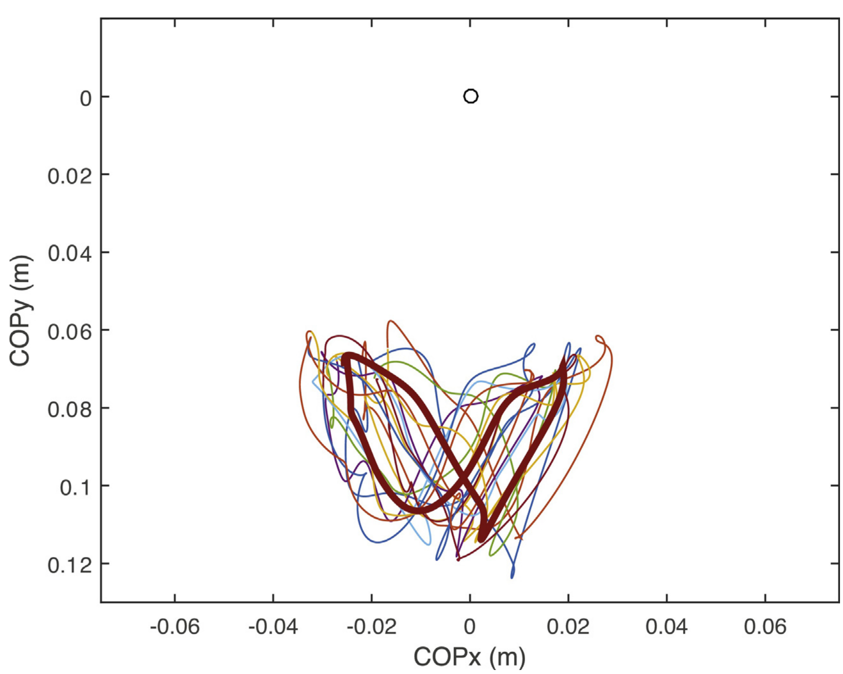

Fig. 3. Trace depicting center of pressure (COP) movements during walking in one trial from one dog. The heavy line is the mean of all the traces. The COP moves rostral and caudal (y direction) twice for each step cycle and once to each side (x direction) creating a butterfly shape.
O, interscapular marker.

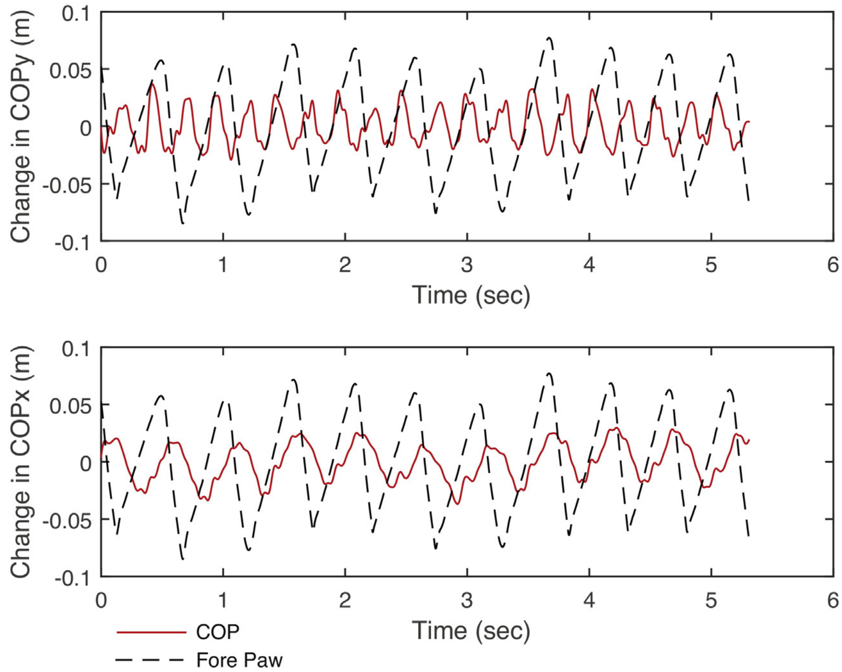

Fig. 4. Graphs of the center of pressure (COP) movements and movement of the right fore paw plotted against time in the x and y directions.

Table 1
Center of pressure (COP) root mean square (RMS) in individual dogs in repeated sessions.

Dog identification number	Session number	Mean RMS of COPx	Mean RMS of COPy	Mean velocity (m/s)	N (trials/session)
2	1	0.0209	0.0341	0.25	1
	2	0.0175	0.0209	0.40	4
	3	0.0200	0.0234	0.45	3
	4	0.0233	0.0400	0.45	11
6	1	0.0157	0.0182	0.31	8
	2	0.0144	0.0187	0.35	10
8	1	0.0096	0.0152	0.33	11
	2	0.0136	0.0230	0.50	8
	3	0.0126	0.0192	0.47	11
10	1	0.0124	0.0184	0.35	4
	2	0.0099	0.0124	0.38	6
	3	0.0135	0.0176	0.40	18
13	1	0.0160	0.0170	0.30	13
	2	0.0192	0.0198	0.35	14
14	1	0.0057	0.0100	0.26	14
	2	0.0054	0.0105	0.25	11

The movement of COG and COP is used in humans to describe stability and normal and abnormal locomotion (Whittle, 1997; Tesio et al., 1998a; Cornwall and McPoil, 2000; Detrembleur et al., 2000) and to quantify changes due to aging (Park et al., 2013), orthopedic injury (Tesio et al., 1998b; Park et al., 2016) and neurologic disease (Massaad et al., 2004; Geroin et al., 2015). It uniquely reflects the synthesis of forces generated by the subject to generate continuous data from performance of a simple task — walking. Similarly, it has been adopted for use in horses, many of which are trained to run on a treadmill, thus making data collection straight forward (Clayton and Nauwelaerts, 2014; Hobbs and Clayton, 2013). The effect of individual components on COP can be investigated specifically. For example, measurement of standing COP was used successfully to evaluate the input of vision on postural stability of the horse (Clayton and Nauwelaerts, 2014).

In this study, we evaluated the variability of COP using RMS in Dachshunds and Dachshund mixes, the breed of dog most predisposed to acute intervertebral disc herniations. Our data demonstrated that COP moves from side to side once per step cycle and rostral and caudal twice per step cycle, consistent with the foot placement in the normal lateral pattern (right fore, left hind, left fore, right hind). The mean COP sits just caudal to the interscapular region on midline. The variability from that mean position while walking, represented by RMS, is low and was not affected by limb length (represented by the height of the interscapular back marker). However, the ranges of limb length evaluated in this study were limited, and it is possible that this variable should be reconsidered if a more diverse population of dogs were studied. Walking speed did affect COP RMS and this should be taken into account either by controlling treadmill speed in a group of dogs, or by incorporating this parameter into statistical analyses if using this measurement in a research study or clinical trial. Acceleration and deceleration when walking could alter the RMS of COP, and so care was taken to start data collection when dogs were walking smoothly and to terminate it as soon as their gait or behavior started to change. In addition, sessions were categorized as to the quality of the data collection to streamline subsequent data analysis. This approach required multiple observers, but appeared to be effective as can be seen by the low test–retest variability.

Challenges included the intimidating nature of the treadmill, the variable nature of each dog and necessary adaptations to equipment designed for human research. The movement and noise of the instrumented treadmill were foreign experiences to many of the participating dogs. Three of 15 dogs recruited for this study would not walk on the treadmill while it was moving regardless of voice or treat incentive, or even the use of a loose leash to encourage them forward. Allowing more time for habituation may help to rectify this problem, but this may not be possible in pet dogs that are participating in clinical trials.

The dogs that did walk on the treadmill were quite variable in their demeanor. They required different treats to encourage forward movement, and some were very erratic in their movements, resulting in numerous attempts to obtain useful trials. Other individual characteristics may have altered COP data. For example, some dogs would wag their tails when walking while others kept their tail in a more neutral position or tucked ventrally. Some would extend their necks forward, reaching for food treats, and some held their heads in a more neutral, relaxed position. These postural differences could affect COP over individual trials, but importantly, the repeatability in individual dogs was excellent. This technology may therefore be useful to evaluate individual dogs as they recover from specific injuries.

The treadmill used for this study was designed for use in human subjects. This posed a few challenges when trying to use it for dogs. The treadmill had two belts and our canine subjects were required to walk on only one belt during data recording (whereas human subjects would straddle the belts while walking). If the dog crossed belts during a trial, that trial was graded as poor, and data from that trial was not used. Due to the much smaller size of the canine subjects as compared to humans, ambient frequency interference from lights and other machines in the laboratory were significant enough to affect data. To correct for this interference, a low-pass filter was applied during data processing to remove the effects of ambient frequencies. However, data from the smallest dog tested was not appropriately captured by the force-plate (no data was available from the Vicon software following the data collection session), demonstrating a lower weight limit for this equipment.

Conclusions

Center of pressure measurements can be obtained reliably in normal walking dogs, although not all dogs will walk on the instrumented treadmill. Center of pressure moves through a butterfly shape during normal locomotion as each limb is placed on the ground. Quantification of COP variability in the x and y direction through RMS may provide a useful measure of functional loss and recovery following spinal cord injury in dogs. Further research will investigate the RMS of COP values of dogs recovering from spinal cord injury. Comparison of data from dogs with spinal cord injury and normal dogs will allow us to determine whether COP measurements are a discriminating and effective way to quantify recovery of trunk and hind limb function.

Conflict of interest statement

There are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome. 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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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.tvjl.2017.07.001.

References

Baltzer, W.I., McMichael, M.A., Hosgood, G.L., Kerwin, S.C., Levine, J.M., Steiner, J.M., Ruaux, C.G., 2008. Randomized, blinded, placebo-controlled clinical trial of *N*-acetylcysteine in dogs with spinal cord trauma from acute intervertebral disc disease. Spine 33, 1397–1402.

Borgens, R.B., Toombs, J.P., Breur, G., Widmer, W.R., Waters, D., Harbath, A.M., March, P., Adams, L.G., 1999. An imposed oscillating electrical field improves the recovery of function in neurologically complete paraplegic dogs. Journal of Neurotrauma 16, 639–657.

Brisson, B.A., 2010. Intervertebral disc disease in dogs. Veterinary clinics of North America. Small Animal Practice 40, 829–858.

Clayton, H.M., Nauwelaerts, S., 2014. Effect of blindfolding on center of pressure variables in healthy horses during quiet standing. The Veterinary Journal 199, 365–369.

Coates, J.R., 2000. Intervertebral disk disease. Veterinary Clinics of North America. Small Animal Practice 30, 77–110.

Cornwall, M.W., McPoil, T.G., 2000. Velocity of the center of pressure during walking. Journal of the American Podiatric Medical Association 90, 334–338.

Detrembleur, C., van den Hecke, A., Dierick, F., 2000. Motion of the body center of gravity as a summary indicator of the mechanics of human pathological gait. Gait and Posture 12, 243–250.

Funkquist, B., 1962. Thoraco-lumbar disk protrusion with severe cord compression in the dog. 2. Acta Veterinaria Scandinavica 3, 317–343.

Geroin, C., Smania, N., Schena, F., Dimitrova, E., Verzini, E., Bombieri, F., Nardello, F., Tinazzi, M., Gandolfi, M., 2015. Does the Pisa syndrome affect postural control, balance, and gait in patients with Parkinson's disease? An observational cross-sectional study. Parkinsonism and Related Disorders 21, 736–741.

Gordon-Evans, W.J., Evans, R.B., Conzemius, M.G., 2009a. Accuracy of spatiotemporal variables in gait analysis of neurologic dogs. Journal of Neurotrauma 26, 1055–1060.

Gordon-Evans, W.J., Evans, R.B., Knap, K.E., Hildreth, J.M., Pinel, C.B., Imhoff, D.J., Conzemius, M.G., 2009b. Characterization of spatiotemporal gait characteristics in clinically normal dogs and dogs with spinal cord disease. American Journal of Veterinary Research 70, 1444–1449.

Granger, N., Blamires, H., Franklin, R.J.M., Jeffery, N.D., 2012. Autologous olfactory mucosal cell transplants in clinical spinal cord injury: a randomized double-blinded trial in a canine translational model. Brain 135, 3227–3237.

Hamilton, L., Franklin, R.J.M., Jeffery, N.D., 2007. Development of a universal measure of quadrupedal forelimb–hindlimb coordination using digital motion capture and computerised analysis. BMC Neuroscience 8, 77.

Hamilton, L., Franklin, R.J.M., Jeffery, N.D., 2008. Quantification of deficits in lateral paw positioning after spinal cord injury in dogs. BMC Veterinary Research 4, 47.

Hansen, H.J., 1952. A pathologic-anatomical study on disk degeneration in the dog, with special reference to the so-called enchondrosis intervertebralis. Acta Orthopaedica Scandinavica Supplement 11, 1–117.

Hobbs, S.J., Clayton, H.M., 2013. Sagittal plane ground reaction forces, center of pressure and center of mass in trotting horses. The Veterinary Journal 198, e14–e19.

Laverty, P.H., Leskovar, A., Breur, G.J., Coates, J.R., Bergman, R.L., Widmer, W.R., Toombs, J.P., Shapiro, S., Borgens, R.B., 2004. A preliminary study of intravenous surfactants in paraplegic dogs: polymer therapy in canine clinical SCI. Journal of Neurotrauma 21, 1767–1777.

Levine, G.J., Levine, J.M., Budke, C.M., Kerwin, S.C., Au, J., Vinayak, A., Hettlich, B.F., Slater, M.R., 2009. Description and repeatability of a newly developed spinal cord injury scale for dogs. Preventive Veterinary Medicine 89, 121–127.

Levine, J.M., Cohen, N.D., Heller, M., Fajt, V.R., Levine, G.J., Kerwin, S.C., Trivedi, A.A., Fandel, T.M., Werb, Z., Modestino, A., et al., 2014. Efficacy of a metalloproteinase inhibitor in spinal cord injured dogs. PLoS One 9, e96408.
Lim, J.H., Muguet-Chanoit, A.C., Smith, D.T., Laber, E., Olby, N.J., 2014. Potassium channel antagonists 4-aminopyridine and the *t*-butyl carbamate derivative of 4-aminopyridine improve hind limb function in chronically non-ambulatory dogs; a blinded, placebo-controlled trial. PLoS One 9, e116139.
Massaad, F., Dierick, F., van den Hecke, A., Detrembleur, C., 2004. Influence of gait pattern on the body's center of mass displacement in children with cerebral palsy. Developmental Medicine and Child Neurology 46, 674–680.
Olby, N.J., De Risio, L., Muñana, K.R., Wosar, M.A., Skeen, T.M., Sharp, N.J., Keene, B.W., 2001. Development of a functional scoring system in dogs with acute spinal cord injuries. American Journal of Veterinary Research 62, 1624–1628.
Olby, N.J., Muguet-Chanoit, A.C., Lim, J.H., Davidian, M., Mariani, C.L., Freeman, A.C., Platt, S.R., Humphrey, J., Kent, M., Giovanella, C., et al., 2016. A placebo-controlled, prospective, randomized clinical trial of polyethylene glycol and methylprednisolone sodium succinate in dogs with intervertebral disk herniation. Journal of Veterinary Internal Medicine 30, 206–214.
Park, S., Ko, Y.-M., Park, J.-W., 2013. The correlation between dynamic balance measures and stance sub-phase COP displacement time in older adults during obstacle crossing. Journal of Physical Therapy Science 25, 1193–1196.
Park, K.-H., Lim, J.-Y., Kim, T.-H., 2016. The effects of ankle strategy exercises on unstable surfaces on dynamic balance and changes in the COP. Journal of Physical Therapy Science 28, 456–459.
Tesio, L., Lanzi, D., Detrembleur, C., 1998a. The 3-D motion of the center of gravity of the human body during level walking. I. Normal subjects at low and intermediate walking speeds. Clinical Biomechanics (Bristol, Avon) 13, 77–82.
Tesio, L., Lanzi, D., Detrembleur, C., 1998b. The 3-D motion of the center of gravity of the human body during level walking. II. Lower limb amputees. Clinical Biomechanics (Bristol, Avon) 13, 83–90.
Whittle, M.W., 1997. Three-dimensional motion of the center of gravity of the body during walking. Human Movement Science 16, 347–355.