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Citation for published version:
Trivino Barbero, A, Davidson, C, Clements, D & Ryan, J 2023, 'Objective comparison of a sit to stand test to the walk test for the identification of unilateral lameness caused by cranial cruciate ligament disease in dogs', *Journal of Small Animal Practice*, pp. 1-6. https://doi.org/10.1111/jsap.13679

Digital Object Identifier (DOI):
10.1111/jsap.13679

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
Journal of Small Animal Practice

ORIGINAL ARTICLE

Objective comparison of a sit to stand test to the walk test for the identification of unilateral lameness caused by cranial cruciate ligament disease in dogs

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Objective: **The purpose of this study was to evaluate a sit to stand test with the walk test for the identification of unilateral cranial cruciate ligament rupture in dogs.**

Materials and Methods: **Peak vertical force and vertical impulse were measured on a pressure-sensitive walkway, during a sit to stand test and walk test, and in 10 dogs with unilateral cranial cruciate ligament rupture and 18 non-lame dogs. Data collected were used to calculate symmetry indices (SI) of ipsilateral and contralateral hindlimbs (HL), diagonal limb pairs (DLP) and ipsilateral limb pairs (ILP).**

Results: **The symmetry indices of peak vertical force of HL during the walk test and sit to stand test were 100% and 90% sensitive for discriminating lame and non-lame dogs respectively. The symmetry indices of vertical impulse of HLs during the walk test and sit to stand test were 100% and 50% sensitive for discriminating lame and non-lame dogs respectively. Analysis of ipsilateral and diagonal limb pairs did not improve the discrimination in either test. The time taken to collect data from the sit to stand test data was shorter than for the walk test.**

Clinical Significance: **Whilst the sit to stand test required a shorter time for collection of data than the walk test, it did not accurately identify all dogs with lameness associated with CCLR, and thus has relatively limited clinical utility in its tested form.**

Journal of Small Animal Practice (2023); 1–6
DOI: 10.1111/jsap.13679

Accepted: 1 October 2023

INTRODUCTION

The visual assessment of lameness in dogs is commonly used to assess the severity of disease and response to treatment, but the correlation of such assessments with objective measures of limb function is poor (Oosterlinck *et al.*, 2011; Waxman *et al.*, 2008). Kinetic gait analysis of dynamic weight-bearing is considered the gold standard objective gait assessment (Ladha *et al.*, 2017), and has been widely used to characterise the effect of medical and surgical interventions of musculoskeletal and neurological conditions in dogs (Ballagas *et al.*, 2004; Borer *et al.*, 2003; Budsberg *et al.*, 2007; Conzemius *et al.*, 2005; Grisneaux *et al.*, 2003; Karnik *et al.*, 2006; Klaveren *et al.*, 2005; Moreau *et al.*, 2003, 2007; Suwankong *et al.*, 2007; Wilson *et al.*, 2018). However, the acquisition of kinetic data from dogs during dynamic weight bearing is time consuming and thus difficult to incorporate into routine clinical practice, which has precluded its routine use.

Rising from a sitting to standing position is a complex movement requiring the recruitment of multiple muscle groups (Ellis *et al.*, 2018). Quantifying this movement, *e.g.*

with kinetic gait analysis, can allow the assessment of physical function in the form of a sit to stand test (STST) (Caplan *et al.*, 2014). In humans, the STST enables the direct quantification of lower-body functional power which demonstrates a significant correlation with measurements of functional ability such as strength, speed, endurance and agility (Gray & Paulson, 2014). The kinematic analysis of stifle movement in non-lame dogs during the STST demonstrates excellent intra- and inter-observer repeatability (Feeney *et al.*, 2007). The range of motion of the hip joint of healthy dogs is increased when compared to dogs with hip dysplasia, and this difference is accentuated with the STST when contrasted with normal walking motion (Souza *et al.*, 2019).

The accuracy of kinetic parameters of the STST to identify lameness caused by cranial cruciate ligament rupture (CCLR) has not been described or compared to other methods of quantitative gait analysis in veterinary medicine to the authors' knowledge. This study aimed to evaluate the asymmetry of weight bearing in dogs with unilateral CCLR using a simple, one stage, STST. We hypothesised that kinetic data acquired from a STST and the conventional walk test (WT) could discriminate dogs with hindlimb lameness associated with cruciate rupture from non-lame dogs, and that the STST would be quicker to complete than the WT.

MATERIALS AND METHODS

Study population

The study was approved by the Veterinary Ethical Review Committee of the Royal (Dick) School of Veterinary Studies (approval number 120.17). Non-lame dogs were recruited from staff and students working at the Hospital for Small Animals at the University of Edinburgh, and dogs with CCLR were recruited from owners presenting their pet for treatment of the disease at the same institution. Owners consented for their pet to undergo the testing procedure before commencing the study. Eighteen non-lame dogs and 10 dogs with unilateral lameness attributed to CCLR, were recruited. Non-lame dogs were ascribed as such following a complete orthopaedic examination by an ECVS diplomate. The diagnosis of CCLR was based on history, physical exam, radiography and subsequently confirmed by arthrotomy or arthroscopic evaluation of the joint.

Protocol

All dogs underwent the same testing procedure which comprised visual lameness assessment and routine orthopaedic examination confirming unilateral lameness (CCLR dogs) or subjective soundness (non-lame dogs). All dogs were weighed on an electronic scale before gait analysis to allow normalisation with pressure walkway data. All the patients included in the study were handled by a single operator (AT). All dogs were permitted to walk freely around the gait laboratory for 10 minutes and walked over the pressure-sensitive walkway (PSW) five times without recording data to permit habituation to the laboratory conditions and the PSW, before being walked over the PSW on a loose lead, a minimum of five times for acquisition of data.

A 1 m×0.5 m PSW containing 1.4 sensels per cm^2 was set up as previously described (Fanchon & Grandjean, 2007) and the data were analysed using proprietary software (Walkway v7.02; Tekscan). The walkway was calibrated as the per manufacturer's guidelines, and a proprietary equilibration file (20 PSI) was used when gathering data. The data was collected at a 60 Hz sampling rate. The PSW was placed in the middle of a 13.6 m×5.3 m room and covered with a 5 m×50 cm×2 mm rubber matt as previously described (Bockstahler *et al.*, 2009; Waxman *et al.*, 2008).

A Microsoft 1080 HD camera (Microsoft LifeCam Studio Webcam, Microsoft) was used to capture video recordings of the dogs on the PSW. The camera was synchronised with the PSW and the video recording was used to ensure the correct foot print recognition by the walkway software. The dog's velocity and acceleration during kinetic gait data collection were estimated from the video footage using five markers placed 1 m apart. The mean gait velocity of each dog was recorded as the mean velocity of the 4 velocity measurements, recorded between each marker on each trial. The two gait tests were always performed in the same order: WT then STST. The time measured to undertake each test was measured with a stopwatch. Data were exported from the proprietary gait software for each of the two tests (WT, STST) for statistical analysis.

The "walk" test

Dogs were walked on a leash, by the same handler, in a straight line across the PSW until five valid trials were achieved. Each dog was allowed to walk at its preferred velocity. A trial was considered valid when the dog walked across the full length of the PSW, in a straight line, at a gait velocity of ±0.5 m/s range, with all four paws fully contacting the plate surface as previously described (Bockstahler *et al.*, 2009; Oosterlinck *et al.*, 2011). Trials were excluded if the dog ran, trotted, paused, stopped or turned its head on the walkway. This was repeated until five valid trials were obtained. Peak vertical force (PVF), vertical impulse (VI), velocity and stance time (StT) were calculated. PVF and VI were expressed as a percent of bodyweight. The PVF and VI were recorded for all four limbs, and the average of the five trials was calculated for analysis.

Sit to stand test

Dogs were sat on the PSW and then encouraged to stand up and walk away from the PSW. Each dog was allowed to stand up and walk away at its preferred velocity. A trial was considered valid when the dog stood up on the PSW, with all four paws fully contacting the plate surface at least once. This was repeated until three valid trials were obtained. PVF and VI were expressed as a percentage of bodyweight. The PVF and VI were recorded for all four limbs, and the average of the three trials calculated for statistical analysis.

The time taken to perform each data set and individual test was recorded for each dog.

Statistical analysis

Each dataset was assessed for the normality of distribution by visual analysis of individual value plots. The mean ± 95% confidence intervals (95% CI) and range were determined for forelimbs and hindlimbs of each dog: gait velocity, StT, PVF and VI. Three measures of symmetry were calculated for each dog. The symmetry index (SI) for each variable was calculated as previously described (Bockstahler *et al.*, 2009; Fanchon & Grandjean, 2007) as follows: SI between the hindlimb pairs (HL) was calculated {=100×[(AHL−CHL)/(AHL+CHL)], where AHL is the affected hindlimb and CHL is the contralateral hindlimb}. The SI between the diagonal limb pair (DLP) was calculated {=100×[(AHL−CFL)/(AHL+CFL)], where CFL is the contralateral forelimb}. The SI between ipsilateral limb pairs (ILP) was calculated {=100×[(AHL−IFL)/(AHL + IFL)]}.

The age, weight and time taken to complete each test, for each group were assessed for normality by graphical representation, and compared by use of independent two-sample *t*-tests. The kinetic and time variables for each group were assessed for normality by graphical representation, and compared by use of an independent two-sample *t*-test, with Bonferroni correction, to identify differences between the healthy and CCLR groups. Thus, a total of 24 test conditions were assessed (comparison of SI of PVF and VI for HL, DLP and ILP during WT and STST and comparison of SI of StT for HL, DLP and ILP during WT and STST). As an optimal diagnostic test should be able to completely discriminate between non-lame and CCLR subjects, the upper range of the SI measured in the non-lame group was selected as the cut-off value to measure the sensitivity and negative predictive value of each measure (as the specificity and positive predictive value will both be 100%).

RESULTS

The non-lame group comprised of 18 dogs, 13 males and five females, all neutered, aged from 1 to 12 years (mean 5.1 years ±1.7 years) and weighing between 12 and 43 kg (24 kg ±4.1 kg). This group consisted of five crossbred dogs, two springer spaniels, three Border Collies, two Staffordshire bull terriers, one lurcher, one greyhound, one Labrador retriever, one cocker spaniel, one Dalmatian and one husky. The CCLR group comprised 10 dogs, six males and four females, all neutered, aged from 4 to 10 years (7.1 years ±1.3 years) and weighing between 17 and 72 kg (35 kg ±10.0 kg) and consisted of two Labrador retrievers, two Staffordshire bull terriers, one Border Collie, one crossbred dog, one lurcher, one rottweiler, one bullmastiff and one springer spaniel. The CCLR group was significantly heavier (P=0.03) than the non-lame group, but not significantly older (P=0.13). All dogs permitted the three trials of the STST, and five valid WT trials. The mean time taken to collect the WT dataset was 664 seconds (s) (range 449 to 1320 seconds). This was significantly longer (P=0.019) than the mean time to taken to collect the STST data (435 seconds, range 208 to 960 seconds); however, the average time to take each individual repeat was slightly longer (145 seconds per valid repeat) compared to the WT (132 seconds per valid repeat).

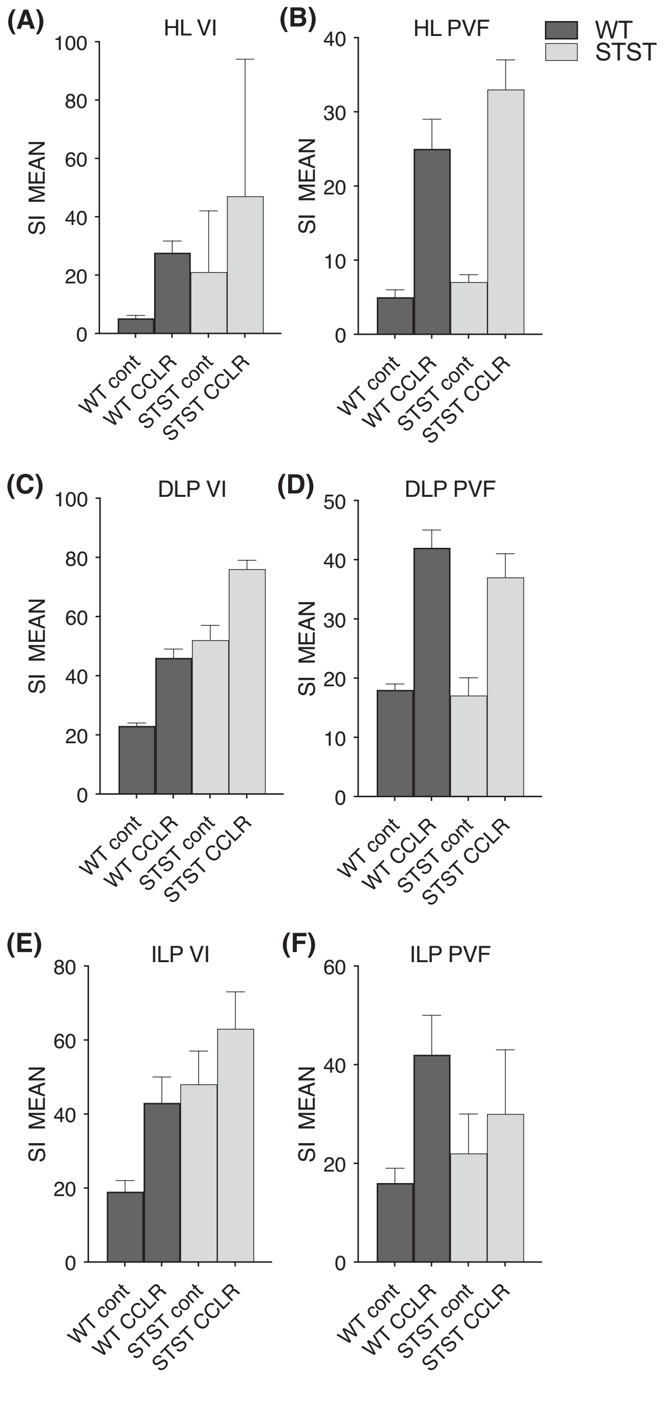

FIG 1. Mean ± 95% confidence interval (CI) values of symmetry index (SI) comparing non-lame and CCLR groups for both tests: walk test (WT) and sit to stand test (STST), corrected to mean bodyweight. Hindlimb vertical impulse (VI HL), hindlimb peak vertical force (PVF HL), diagonal limb pair vertical impulse (VI DLP), diagonal limb pair peak vertical force (PVF DLP), ipsilateral limb pair vertical impulse (VI ILP), ipsilateral limb pair peak vertical force (PVF ILP). n=18 dogs in the non-lame group, 10 dogs in CCLR group; error bars represent 95% CI

Asymmetry in StT between the non-lame and CCLR groups did not differ significantly in either test.

The mean SIs of the ground reaction forces (GRFs), HL, ILP and DLP, measured in the healthy and CCLR groups, are presented in Fig 1, and sensitivity of those measures is presented in Table S2. The SI of the HL GRFs during the WT were significantly different between the non-lame and CCLR groups (Fig 1, Table S1). The SI of the HL GRFs during the WT were 100% sensitive for classifying the non-lame and CCLR dogs (Table S2). The SIs of the DLP GRFs during the WT were 100% sensitive (PVF) and 90% sensitive (VI) for classifying the non-lame and CCLR dogs. The SI of the ILP GRFs during the WT were 100% sensitive (PVF) and 80% sensitive (VI) for classifying the non-lame and CCLR dogs.

The SI of the HL GRFs measured during the STST were 90% sensitive (PVF) and 50% sensitive (VI) for classifying non-lame and CCLR dogs. The SIs of the DLP GRFs during the STST were poorly sensitive (PVF 40%, VI 50%) for classifying the non-lame and CCLR dogs. The SIs of the ILP GRFs during the STST were 0% sensitive (PVF) and 33% sensitive (VI) for classifying non-lame and CCLR dogs.

DISCUSSION

In the present study, the clinical utility of a simple, STST was investigated, and compared to the WT (Clough *et al.*, 2018; Lascelles *et al.*, 2006; Light *et al.*, 2010; Wilson *et al.*, 2018) which is another method of quantitative gait analysis. Objective measures of lameness (SI of the GRF expressed during each test) were recorded and compared by different analysis techniques. The STST test was achievable in all patients. However, the time advantage was less than expected, and the STST did not effectively discriminate between dogs with hindlimb lameness associated with CCLR and non-lame dogs.

The SIs of PVF and VI are common kinetic gait parameters used in the diagnosis of unilateral lameness in dogs (Fanchon & Grandjean, 2007) and have been found to effectively discriminate between lame and non-lame hindlimbs (Budsberg *et al.*, 1993). Although the STST accentuated the difference in SIs between the CCLR and non-lame groups, the difference was also more variable across the three repeats assessed which reflected the observation that the dogs did not rise in the same manner on every test. This variability impacted on the ability of the test to discriminate between non-lame and dogs with lameness associated with CCLR.

Compensatory weight-shifting mechanisms in dogs with unilateral lameness are well recognised. In dogs with hindlimb lameness, compensatory load has been shown to shift to the ipsilateral forelimb when analysing PVF and VI at walk (Fischer *et al.*, 2013; Katic *et al.*, 2009) and trot (Fischer *et al.*, 2013). This is at odds with our observation that the SI of PVF and VI of DLPs was more sensitive than ILPs, but ILP and DLP were both still considerably less discriminatory for identifying lame dogs than HLs alone in the WT. The reasons for this difference with previous reports are unclear, but the nature of the hindlimb lameness, our use of a pressure platform rather than an instrumented treadmill, and the heterogeny of the breeds in our study may have contributed. The SI of PVF and VI with DLP and ILP in the STST did not improve the ability to discriminate lameness associated with CCLR when compared to the HL alone suggesting that compensatory load shifting was not occurring consistently in the STST either.

Asymmetry in StT between the lame and non-lame groups was not discriminatory for the identification of lameness in this cohort. An increase in CHL StT might be expected as a compensatory load-shifting mechanism to reduce load-bearing of the AHL as has been shown with cinematography and electrogoniometry in horses (Clayton, 1986; Ratzlaff *et al.*, 1982). In dogs however, morphometric differences such as overall body size and limb length rather than body mass, are responsible for as much as 20% of StT variance (Budsberg *et al.*, 1987; Fischer *et al.*, 2013). These variables were not controlled for in this study, and may partially explain why these differences in this measure were not observed (Abdelhadi *et al.*, 2013; Bosscher *et al.*, 2017).

The STST and the WT employ different movements and therefore some dogs with orthopaedic disease may objectively demonstrate lameness with one method but not another. The clinical application of kinetic gait analysis is challenging because it requires multiple passages across the platform to obtain enough data to reproducibly identify unilateral lameness; large variances in the data occur as a result of different stance times, velocity and/or acceleration (Hans *et al.*, 2014; Volstad *et al.*, 2016). Additionally, thus far the time burden to obtain sufficient numbers of "repeats" to obtain valid and useful data, and the space required to create a runway has precluded its use in the clinical setting. For this reason, five repeats of the WT test were undertaken and 3 repeats of the STST.

This study has several limitations. Firstly, as a pilot study of the STST, there was no prior knowledge of variance of this data upon which to select a sample size. However, the fundamental premise was that a useful test should be able to discriminate all dogs with unilateral lameness caused by CCLR from non-lame dogs, and thus five valid WT trials and three STST trials per dog were obtained in this study. Five valid WT trials is the generally accepted number to produce valid data (Torres, 2020) though the time required to collect five valid WT trials is considerable with a pressure platform 1 m in length. Increasing the number of STST trials may have reduced the variance of the SI data produced but the number of trials selected was limited to those considered acceptable by our ethical review board, and time-appropriate for the clinical setting. Rising from a prone position is considered a more painful movement than walking, and thus the number of repeats was limited for ethical reasons, as the expectation was that the lameness would be accentuated by this movement, but this will have contributed to the increased variability. The severity of lameness was not standardised for the purpose of the study, although all dogs were able to weight bear on their affected limb. No imaging of the non-lame group before enrolment into the study was performed. SI in healthy dogs should also be interpreted with caution. It is one point in time test and may not reflect the gait at home. Additionally, dogs can demonstrate significant asymmetry between healthy limbs (Torres, 2020). This natural variation can therefore result in both false positives and negatives.

In conclusion, a three repeated STST has a limited clinical utility for the identification of lameness associated with CCLR in dogs, and the SI of kinetic data of the hindlimbs alone using the WT remains the most sensitive tool for identification.

Acknowledgements

We would like to thank the HfSA staff, students and clients for consenting to their dogs taking part in this study.

Author contributions

Alexis Triviño: Data curation (equal); investigation (equal); project administration (equal); writing – review and editing (supporting). **Catherine Davidson:** Data curation (supporting); formal analysis (supporting); writing – original draft (lead); writing – review and editing (lead). **Dylan Neil Clements:** Conceptualization (lead); data curation (equal); formal analysis (lead); investigation (equal); methodology (equal); project administration (equal); supervision (lead); validation (lead); writing – review and editing (equal). **John M Ryan:** Conceptualization (equal); data curation (supporting); methodology (equal); project administration (equal); resources (equal); supervision (supporting); writing – review and editing (supporting).

Conflict of interest

None of the authors of this article has a financial or personal relationship with other people or organisations that could inappropriately influence or bias the content of the paper.

Data availability statement

Derived data supporting the findings of this study are available from the corresponding author.

References

Abdelhadi, J., Wefstaedt, P., Galindo-Zamora, V., Anders, A., Nolte, I. & Schilling, N. (2013) Load redistribution in walking and trotting beagles with induced forelimb lameness. *American Journal of Veterinary Research*, **74**, 34–39. Available from: https://doi.org/10.2460/ajvr.74.1.34

Ballagas, A.J., Montgomery, R.D., Henderson, R.A. & Gillette, R. (2004) Pre- and postoperative force plate analysis of dogs with experimentally transected cranial cruciate ligaments treated using tibial plateau levelling osteotomy. *Veterinary Surgery*, **33**, 187–190. Available from: https://doi.org/10.1111/j.1532-950x.2004.04027.x

Bockstahler, B.A., Vobornik, A., Müller, M. & Peham, C. (2009) Compensatory load redistribution in naturally occurring osteoarthritis of the elbow joint and induced weight-bearing lameness of the forelimbs compared with clinically sound dogs. *The Veterinary Journal*, **180**, 202–212. Available from: https://doi.org/10.1016/j.tvjl.2007.12.025

Borer, L.R., Peel, J.E., Seewald, W., Schawalder, P. & Spreng, D.E. (2003) Effect of carprofen, etodolac, meloxicam, or butorphanol in dogs with induced acute synovitis. *American Journal of Veterinary Research*, **64**, 1429–1437. Available from: https://doi.org/10.2460/ajvr.2003.64.1429

Bosscher, G., Tomas, A., Roe, S.C., Marcellin-Little, D.J. & Lascelles, B.D.X. (2017) Repeatability and accuracy testing of a weight distribution platform and comparison to a pressure sensitive walkway to assess static weight distribution. *Veterinary and Comparative Orthopaedics and Traumatology*, **30**, 160–164. Available from: https://doi.org/10.3415/vcot-16-09-0128

Budsberg, S.C., Verstraete, M.C. & Soutas-Little, R.W. (1987) Force plate analysis of the walking gait in healthy dogs. *American Journal of Veterinary Research*, **48**, 915–918.

Budsberg, S.C., Jevens, D.J., Brown, J., Foutz, T.L., DeCamp, C.E. & Reece, L. (1993) Evaluation of limb symmetry indices, using ground reaction forces in healthy dogs. *American Journal of Veterinary Research*, **54**, 1569–1574.

Budsberg, S., Bergh, M., Reynolds, L. & Streppa, H. (2007) Evaluation of pentosan polysulfate sodium in the postoperative recovery from cranial cruciate injury in dogs: a randomized, placebo-controlled clinical trial. *Veterinary Surgery*, **36**, 234–244. Available from: https://doi.org/10.1111/j.1532-950x.2007.00256.x

Caplan, N., Stewart, S., Kashyap, S., Banaszkiewicz, P., Gibson, A.S.C., Kader, D. et al. (2014) The effect of total hip and hip resurfacing arthroplasty on vertical ground reaction force and impulse symmetry during a sit-to-stand task. *Clinical Biomechanics (Bristol, Avon)*, **29**, 1164–1169. Available from: https://doi.org/10.1016/j.clinbiomech.2014.09.008

Clayton, H.M. (1986) Cinematographic analysis of the gait of lame horses. *Journal of Equine Veterinary Science*, **6**, 70–78. Available from: https://doi.org/10.1016/s0737-0806(86)80037-5

Clough, W., Canapp, S., Taboada, L., Dycus, D. & Leasure, C. (2018) Sensitivity and specificity of a weight distribution platform for the detection of objective lameness and orthopaedic disease. *Veterinary and Comparative Orthopaedics and Traumatology*, **31**, 391–395. Available from: https://doi.org/10.1055/s-0038-1667063

Conzemius, M.G., Evans, R.B., Besancon, M.F., Gordon, W.J., Horstman, C.L., Hoefle, W.D. et al. (2005) Effect of surgical technique on limb function after surgery for rupture of the cranial cruciate ligament in dogs. *Journal of the American Veterinary Medical Association*, **226**, 232–236. Available from: https://doi.org/10.2460/javma.2005.226.232

Ellis, R.G., Rankin, J.W. & Hutchinson, J.R. (2018) Limb kinematics, kinetics and muscle dynamics during the sit-to-stand transition in greyhounds. *Frontiers in Bioengineering and Biotechnology*, **6**, 162. Available from: https://doi.org/10.3389/fbioe.2018.00162

Fanchon, L. & Grandjean, D. (2007) Accuracy of asymmetry indices of ground reaction forces for diagnosis of hind limb lameness in dogs. *American Journal of Veterinary Research*, **68**, 1089–1094. Available from: https://doi.org/10.2460/ajvr.68.10.1089

Feeney, L.C., Lin, C.-F., Marcellin-Little, D.J., Tate, A.R., Queen, R.M. & Yu, B. (2007) Validation of two-dimensional kinematic analysis of walk and sit-to-stand motions in dogs. *American Journal of Veterinary Research*, **68**, 277–282. Available from: https://doi.org/10.2460/ajvr.68.3.277

Fischer, S., Anders, A., Nolte, I. & Schilling, N. (2013) Compensatory load redistribution in walking and trotting dogs with hind limb lameness. *The Veterinary Journal*, **197**, 746–752. Available from: https://doi.org/10.1016/j.tvjl.2013.04.009

Gray, M. & Paulson, S. (2014) Developing a measure of muscular power during a functional task for older adults. *BMC Geriatrics*, **14**, 145. Available from: https://doi.org/10.1186/1471-2318-14-145

Grisneaux, D., Dupuis, J., Pibarot, P., Bonneau, N.H., Charette, B. & Blais, D. (2003) Effects of postoperative administration of ketoprofen or carprofen on short- and long-term results of femoral head and neck excision in dogs. *Journal of the American Veterinary Medical Association*, **223**, 1006–1012. Available from: https://doi.org/10.2460/javma.2003.223.1006

Hans, E.C., Zwarthoed, B., Seliski, J., Nemke, B. & Muir, P. (2014) Variance associated with subject velocity and trial repetition during force platform gait analysis in a heterogeneous population of clinically normal dogs. *The Veterinary Journal*, **202**, 498–502. Available from: https://doi.org/10.1016/j.tvjl.2014.09.022

Karnik, P., Johnston, S., Ward, D., Broadstone, R. & Inzala, K. (2006) The effects of epidural deracoxib on the ground reaction forces in an acute stifle synovitis model. *Veterinary Surgery*, **35**, 34–42. Available from: https://doi.org/10.1111/j.1532-950x.2006.00109.x

Katic, N., Bockstahler, B.A., Mueller, M. & Peham, C. (2009) Fourier analysis of vertical ground reaction forces in dogs with unilateral hind limb lameness caused by degenerative disease of the hip joint and in dogs without lameness. *American Journal of Veterinary Research*, **70**, 118–126. Available from: https://doi.org/10.2460/ajvr.70.1.118

Klaveren, N.J., Suwankong, N., Boer, S.D., Brom, W.E., Voorhout, G., Hazewinkel, H.A.W. et al. (2005) Force plate analysis before and after dorsal decompression for treatment of degenerative lumbosacral stenosis in dogs. *Veterinary Surgery*, **34**, 450–456. Available from: https://doi.org/10.1111/j.1532-950x.2005.00068.x

Ladha, C., O'Sullivan, J., Belshaw, Z. & Asher, L. (2017) GaitKeeper: a system for measuring canine gait. *Sensors*, **17**, 309. Available from: https://doi.org/10.3390/s17020309

Lascelles, B.D.X., Roe, S.C., Smith, E., Reynolds, L., Markham, J., Marcellin-Little, D. et al. (2006) Evaluation of a pressure walkway system for measurement of vertical limb forces in clinically normal dogs. *American Journal of Veterinary Research*, **67**, 277–282. Available from: https://doi.org/10.2460/ajvr.67.2.277

Light, V.A., Steiss, J.E., Montgomery, R.D., Rumph, P.F. & Wright, J.C. (2010) Temporal-spatial gait analysis by use of a portable walkway system in healthy Labrador retrievers at a walk. *American Journal of Veterinary Research*, **71**, 997–1002. Available from: https://doi.org/10.2460/ajvr.71.9.997

Moreau, M., Dupuis, J., Bonneau, N.H. & Desnoyers, M. (2003) Clinical evaluation of a nutraceutical, carprofen and meloxicam for the treatment of dogs with osteoarthritis. *Veterinary Record*, **152**, 323–329. Available from: https://doi.org/10.1136/vr.152.11.323

Moreau, M., Lussier, B., Doucet, M., Vincent, G., Martel-Pelletier, J. & Pelletier, J.-P. (2007) Efficacy of licofelone in dogs with clinical osteoarthritis. *Veterinary Record*, **160**, 584–588. Available from: https://doi.org/10.1136/vr.160.17.584

Oosterlinck, M., Bosmans, T., Gasthuys, F., Polis, I., Ryssen, B.V., Dewulf, J. et al. (2011) Accuracy of pressure plate kinetic asymmetry indices and their correlation with visual gait assessment scores in lame and non lame dogs. *American Journal of Veterinary Research*, **72**, 820–825. Available from: https://doi.org/10.2460/ajvr.72.6.820

Ratzlaff, M.H., Grant, B.D. & Adrian, M. (1982) Quantitative evaluation of equine carpal lamenesses. *Journal of Equine Veterinary Science*, **2**, 78–88. Available from: https://doi.org/10.1016/s0737-0806(82)80010-5

Souza, A., Escobar, A., Germano, B., Farias, C., Gomes, L. & Matera, J. (2019) Kinetic and kinematic analysis of dogs suffering from hip osteoarthritis and healthy dogs across different physical activities. *Veterinary and Comparative Orthopaedics and Traumatology*, **32**, 104–111. Available from: https://doi.org/10.1055/s-0038-1677509

Suwankong, N., Meij, B., Klaveren, N.V., Wees, A.V., Meijer, E., Brom, W.V.D. et al. (2007) Assessment of decompressive surgery in dogs with degenerative lumbosacral stenosis using force plate analysis and questionnaires. *Veterinary Surgery*, **36**, 423–431. Available from: https://doi.org/10.1111/j.1532-950x.2007.00288.x

Torres, B.T. (2020) Objective gait analysis. In: Duerr, F.M. (Ed.) Canine lameness. Hoboken: John Wiley & Sons.

Volstad, N., Nemke, B. & Muir, P. (2016) Variance associated with the use of relative velocity for force platform gait analysis in a heterogeneous population of clinically normal dogs. *The Veterinary Journal*, **207**, 80–84. Available from: https://doi.org/10.1016/j.tvjl.2015.08.014

Waxman, A., Robinson, D., Evans, R., Hulse, D., Innes, J. & Conzemius, M. (2008) Relationship between objective and subjective assessment of limb function in normal dogs with an experimentally induced lameness. *Veterinary Surgery*, **37**, 241–246. Available from: https://doi.org/10.1111/j.1532-950x.2008.00372.x

Wilson, M.L., Roush, J.K. & Renberg, W.C. (2018) Comparison of the effect of dog, surgeon and surgical procedure variables on improvement in eight-week static weight-bearing following tibial plateau levelling osteotomy. *Veterinary and Comparative Orthopaedics and Traumatology*, **31**, 396–404. Available from: https://doi.org/10.1055/s-0038-1667139

Supporting Information

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

Table S1. Mean, minimum and maximum values of symmetry index (SI) (±sd), coefficients of variation (CV) and statistical analysis of kinetic data [vertical impulse (VI), peak vertical force (PVF)] for healthy and cranial cruciate ligament rupture (CCLR) groups for hindlimbs (HLs), diagonal limb pairs (DLPs), ipsilateral limb pairs (ILPs) in for both tests: walk test (WT) and sit to stand test (STST), corrected to mean bodyweight.

Table S2. Sensitivity and specificity values for symmetry index (SI) of kinetic data [vertical impulse (VI), peak vertical force (PVF)] to discriminate healthy and cranial cruciate ligament rupture groups. Hindlimbs (HLs), diagonal limb pairs (DLPs), ipsilateral limb pairs (ILPs) for both tests: walk test (WT) and sit to stand test (STST), corrected to mean bodyweight.