Literature

Keegan KG, Pai PF, Wilson DA, Smith BK. A curve-fitting technique for evaluating head movement to measure forelimb lameness in horses. *Biomedical Sciences Instrumentation*, 36 (ISA [International Society for Measurement and Control volume 395]:239-244, 2000. PMID: 10834239

Abstract: Evaluation of the asymmetry of vertical head movement is used during kinematic evaluation of forelimb lameness in horses. For mild lameness, absolute translational measurements are not sensitive enough to detect small differences in the asymmetry of vertical head movement. Also, conscious movement of the head by the horse, not associated with lameness, interferes with accurate measurement. We describe an improved method of evaluating vertical head movement as a measure of lameness, using a model of induced lameness in 9 horses and a time-domain processing technique of curve-fitting. The technique assumes that vertical head movement can be broken down into 3 components; the natural inertially-driven vertical head movement, the alteration of vertical head movement caused by forelimb lameness, and extraneous head movement. The technique uses data from several contiguous strides, eliminates the natural inertially-driven and extraneous head movements, and quantifies lameness as a single value. The technique is shown to more sensitive to change in lameness than absolute measurement of head height translation and to be more accurate than a previously reported frequency-domain technique.

KEEGAN, K. G., PAI, P. F., WILSON, D. A., & SMITH, B. K. (2010). Signal decomposition method of evaluating head movement to measure induced forelimb lameness in horses trotting on a treadmill. *Equine Veterinary Journal*, 33(5), 446–451. https://doi.org/10.2746/042516401776254781

Summary: In horses at a trot, the head moves up and down twice in one stride. In horses with unilateral forelimb lameness this movement is asymmetric. Computer-assisted kinematic analysis of vertical head movement can be used to quantify objectively lameness in horses in clinical trials. However, in mild lameness, absolute measurements of vertical head height may not be sensitive enough to detect small differences in lameness, and extraneous head movement by the horse due to curiosity, excitement or nervousness interferes with the accurate measurement of vertical head movement asymmetry. We describe a simple, signal-decompensation method of evaluating vertical head movement using a model of induced mild foot lameness in 9 horses. The technique assumes that the vertical head movement pattern can be broken down into 3 components; the vertical head movement caused by forelimb lameness (A_1), the amplitude of the natural biphasic vertical head movement (A_2) and extraneous head movement. Extraneous head movement is mathematically removed from the vertical head movement pat tern. A_1 and A_2 are then calculated. After induction of lameness, mean A_1 increased by 1.63 cm (range 0.10–3.33 cm, P = 0.005). Mean A_2 did not significantly change after lameness induction. Error in reproduction of the original head movement pattern was 0.3–0.5%. We calculated that a hypothetical clinical trial would require 12 subjects for testing to be 80% certain that this difference would be successfully detected using this method of lameness evaluation.

Keegan KG, Yonezawa Y, Pai PF, Wilson DA. Telemeterized accelerometer-based system for the detection of lameness in horses. *Biomedical Science Instrumentation*, 38 (ISA [International Society for Measurement and Control volume 419]:112, 2002. PMID: 12085585

Abstract: Video-based kinematic analysis of gait in horses is accurate for quantification of lameness and reliable for identification of the affected limb. Algorithms for the measurement of the vertical head and pelvic displacement and phase correlation with vertical displacement of one forelimb and hindlimb foot have been developed for this purpose. However, because of camera field-of-view limitations, video-based analysis of gait can only be reliably accomplished with the horse constrained to move on a treadmill. This paper describes the use of 2 single-axis accelerometers and 2 gyroscopic transducers

as a measurement system for the identification and quantification of forelimb and hindlimb lameness in horses. Vertical head and pelvic acceleration are converted to displacement, lameness is quantified from previously developed algorithms, and affected limb is determined by correlation of head and pelvic signals with gyroscopic signals from the right forelimb and hindlimb feet. Signals from the 4 transducers are telemeterized at 200 Hz and collected to a receiver connected to a lap top computer, freeing the horse from the constraints of a treadmill laboratory setting. In this paper we describe the reliability of this new accelerometer-based system in horses with induced lameness while trotting on a treadmill and freely outside overground.

Keegan, K. G., Arafat, S., Skubic, M., Wilson, D. A., & Kramer, J. (2003). Detection of lameness and determination of the affected forelimb in horses by use of continuous wavelet transformation and neural network classification of kinematic data. *American Journal of Veterinary Research*, 64(11), 1376–1381. https://doi.org/10.2460/ajvr.2003.64.1376

Objective - To investigate continuous wavelet transformation and neural network classification of gait data for detecting forelimb lameness in horses. **Animals** - 12 adult horses with mild forelimb lameness. **Procedure** - Position of the head and right forelimb foot, metacarpophalangeal (ie, fetlock), carpal, and elbow joints was determined by use of kinematic analysis before and after palmar digital nerve blocks. We obtained 8 recordings from horses without lameness, 8 with right forelimb lameness, and 8 with left forelimb lameness. Vertical and horizontal position of the head and vertical position of the foot, fetlock, carpal, and elbow joints were processed by continuous wavelet transformation. Feature vectors were created from the transformed signals and a neural network trained with data from 6 horses, which was then tested on the remaining 2 horses for each category until each horse was used twice for training and testing. Correct classification percentage (CCP) was calculated for each combination of gait signals tested. **Results** - Wavelet-transformed vertical position of the head and right forelimb foot had greater CCP (85%) than untransformed data (21%). Adding data from the fetlock, carpal, or elbow joints did not improve CCP over that for the head and foot alone. **Conclusions and Clinical Relevance** - Wavelet transformation of gait data extracts information that is important for the detection and differentiation of forelimb lameness of horses. All of the necessary information to detect lameness and differentiate the side of lameness can be obtained by observation of vertical head movement in concert with movement of the foot of 1 forelimb.

Keegan, K. G., Yonezawa, Y., Pai, P. F., Wilson, D. A., & Kramer, J. (2004). Evaluation of a sensor-based system of motion analysis for detection and quantification of forelimb and hind limb lameness in horses. *American Journal of Veterinary Research,* 65(5), 665–670. https://doi.org/10.2460/ajvr.2004.65.665

Objective - To compare a sensor-based accelerometer-gyroscopic (A-G) system with a video-based motion analysis system (VMAS) technique for detection and quantification of lameness in horses. **Animals** - 8 adult horses. **Procedure** - 2 horses were evaluated once, 2 had navicular disease and were evaluated before and after nerve blocks, and 4 had 2 levels of shoe-induced lameness, alternatively, in each of 4 limbs. Horses were instrumented with an accelerometer transducer on the head and pelvis, a gyroscopic transducer on the right forelimb and hind feet, and a receiver-transmitter. Signals from the A-G system were collected simultaneously with those from the VMAS for collection of head, pelvis, and right feet positions with horses trotting on a treadmill. Lameness was detected with an algorithm that quantified lameness as asymmetry of head and pelvic movements. Comparisons between the A-G and VMAS systems were made by use of correlation and agreement (κ value) analyses. **Results** - Correlation between the A-G and VMAS systems for quantification of lameness was linear and high (r2=0.9544 and 0.8235 for forelimb and hind limb, respectively). Quantification of hind limb lameness with the A-G system was higher than measured via VMAS. Agreement between the 2 methods for detection of lameness was excellent (κ=0.76) for the forelimb and good (κ=0.56) for the hind limb. **Conclusions and Clinical Relevance** - The A-G system detected and quantified forelimb and hind limb lameness in horses trotting on the treadmill. Because the data are collected wirelessly, this system might be used to objectively evaluate lameness in the field.

Kramer, J., Keegan, K. G., Kelmer, G., & Wilson, D. A. (2004). Objective determination of pelvic movement during hind limb lameness by use of a signal decomposition method and pelvic height differences. *American Journal of Veterinary Research*, 65(6), 741–747. https://doi.org/10.2460/ajvr.2004.65.741

Objective - To evaluate pelvic movement over a large number of strides in sound horses and in horses with induced hind limb lameness by applying methods to the pelvis that have been described for evaluating vertical head movement in horses with induced forelimb lameness. **Animals** - 17 adult horses. **Procedure** - Horses were filmed while trotting on a treadmill before and after induction of transient mild and moderate hind limb lamenesses. Vertical pelvic movement was measured by a signal decomposition method. The vertical pelvic signal was decomposed into a periodic component (A1) that occurred at half the stride frequency (representing vertical pelvic movement caused by lameness) and another periodic component (A2) that occurred at stride frequency (representing normal vertical pelvic movement of a trotting horse). Vertical pelvic and foot positions were correlated for each stride to compare the difference between the minimum and maximum heights of the pelvis during and after stance of the right hind limb to the minimum and maximum heights of the pelvis during and after stance of the left hind limb. **Results** - Maximum pelvic height difference and lameness amplitude (A1) differed significantly between sound and mild or moderate hind limb lameness conditions. Mean A1 value for vertical pelvic movement in sound horses was less than that previously reported for vertical head movement. **Conclusion and Clinical Relevance** - Pelvic height differences and signal decomposition of pelvic movement can be used to objectively evaluate hind limb lameness in horses over a large number of strides in clinical and research settings.

Keegan, K. G. (2007). Evidence-Based Lameness Detection and Quantification. *Veterinary Clinics of North America: Equine Practice*, *23*(2), 403–423. https://doi.org/10.1016/j.cveq.2007.04.008

Summary - Kinematic and kinetic gait analysis potentially offers veterinarians an objective method of determining equine limb lameness. Subjective analyses have been shown to be somewhat flawed, and there does not seem to be a high degree of interobserver agreement when evaluating individual horses. In addition, recognition of the compensatory effects of primary lameness may be helpful for the practicing equine veterinarian.

Keegan, K. G.; Dent, E. V.; Wilson, D. A.; Janicek, J.; Kramer, J.; LaCarrubba, A.; Walsh, D. M.; Cassels, M. W.; Ester, T. M.; Schiltz, P.; Frees, K. E.; Wilhite, C. L.; Clark, J. M.; Pollitt, C. C.; Shaw, R.; Norris, T.; Werner, H. W.; Agreement among veterinarians for subjective evaluation of lameness in horses. American Association of Equine Practitioners (AAEP), Lexington, USA, Proceedings of the 54th Annual Convention of the American Association of Equine Practitioners, San Diego, California, USA, 6-10 December 2008, 2008, pp 260.

KEEGAN, K. G., DENT, E. V., WILSON, D. A., JANICEK, J., KRAMER, J., LACARRUBBA, A., … NORRIS, T. (2010). Repeatability of subjective evaluation of lameness in horses. *Equine Veterinary Journal*, 42(2), 92–97. https://doi.org/10.2746/042516409x479568

Reasons for performing study: Previous studies have suggested that agreement between equine veterinarians subjectively evaluating lameness in horses is low. These studies were limited to small numbers of horses, evaluating movement on the

treadmill or to evaluating previously-recorded videotape. **Objectives:** To estimate agreement between equine practitioners performing lameness evaluations in horses in the live, over ground setting. **Methods:** 131 mature horses were evaluated for lameness by 2–5 clinicians (mean 3.2) with a weighted-average of 18.7 years of experience. Clinicians graded each limb using the AAEP lameness scale by first watching the horse trot in a straight line only and then after full lameness evaluation. Agreement was estimated by calculation of Fleiss' (κ). Evaluators agreed if they picked the same limb as lame or not lame regardless of the severity of perceived lameness. **Results:** After only evaluating the horse trot in a straight line clinicians agreed whether a limb was lame or not 76.6% of the time (κ= 0.44). After full lameness evaluation clinicians agreed whether a limb was lame or not 72.9% of the time (κ= 0.45). Agreement on forelimb lameness was slightly higher than on hindlimb lameness. When the mean AAEP lameness score was >1.5 clinicians agreed whether or not a limb was lame 93.1% of the time (κ= 0.86), but when the mean score was ≤1.5 they agreed 61.9% (κ= 0.23) of the time. When given the task of picking whether or not the horse was lame and picking the worst limb after full lameness evaluation, clinicians agreed 51.6% (κ= 0.37) of the time. **Conclusions:** For horses with mild lameness subjective evaluation of lameness is not very reliable. **Potential relevance:** A search for and the development of more objective and reliable methods of lameness evaluation is justified and should be encouraged and supported.

Adams OR, Baxter GM, Keegan K. Objective assessment of lameness. *Adams and Stashak's Lameness in Horses.* 6th ed. Chichester, West Sussex; Ames, Iowa: Wiley-Blackwell; 2011:154-164, 19 ref.

Adams OR, Baxter GM, Keegan K. Kinematics/kinetics. *Adams and Stashak's Lameness in Horses.* 6th ed. Chichester, West Sussex; Ames, Iowa: Wiley-Blackwell; 2011:165-172, 17 ref.

Keegan, K. G., Kramer, J., Yonezawa, Y., Maki, H., Pai, P. F., Dent, E. V., … Reed, S. K. (2011). Assessment of repeatability of a wireless, inertial sensor–based lameness evaluation system for horses. *American Journal of Veterinary Research*, 72(9), 1156–1163. https://doi.org/10.2460/ajvr.72.9.1156

Objective—To determine repeatability of a wireless, inertial sensor–based lameness evaluation system in horses. **Animals**—236 horses. **Procedures**—Horses were from 2 to 29 years of age and of various breeds and lameness disposition. All horses were instrumented with a wireless, inertial sensor-based motion analysis system on the head (accelerometer), pelvis (midline croup region [accelerometer]), and right forelimb (gyroscope) before evaluation in 2 consecutive trials, approximately 5 minutes apart, as the horse was trotted in a straight line. Signal-processing algorithms generated overall trial asymmetry measures for vertical head and pelvic movement and stride-by-stride differences in head and pelvic maximum and minimum positions between right and left sides of each stride. Repeatability was determined, and trial difference was determined for groups of horses with various numbers of strides for which data were collected per trial. **Results**—Inertial sensor–based measures of torso movement asymmetry were repeatable. Repeatability for measures of torso asymmetry for determination of hind limb lameness was slightly greater than that for forelimb lameness. Collecting large numbers of strides degraded stride-to-stride repeatability but did not degrade intertrial repeatability. **Conclusions and Clinical Relevance**—The inertial sensor system used to measure asymmetry of head and pelvic movement as an aid in the detection and evaluation of lameness in horses trotting in a straight line was sufficiently repeatable to investigate for clinical use.

Keegan, K. G., MacAllister, C. G., Wilson, D. A., Gedon, C. A., Kramer, J., Yonezawa, Y., … Pai, P. F. (2012). Comparison of an inertial sensor system with a stationary force plate for evaluation of horses with bilateral forelimb lameness. *American Journal of Veterinary Research*, 73(3), 368–374. https://doi.org/10.2460/ajvr.73.3.368

Objective—To assess the analytic sensitivity of an inertial sensor system for detection of the more severely affected forelimb in horses with bilateral lameness. **Animals**—18 adult horses with forelimb lameness. **Procedures**—Horses were fitted with inertial sensors and evaluated for lameness with a stationary force plate as they were trotted in a straight line. Inertial sensor-derived measurements for vertical head movement asymmetry (HMA) and vector sum (VS) of maximum and minimum head height differences between right and left halves of the stride were used to predict differences in mean peak vertical force (PVF) as a percentage of body weight between the right and left forelimbs. Repeatability was compared by calculation of the intraclass correlation coefficient (ICC) for each variable. Correct classification percentages for the lamer forelimb were determined by use of a stationary force plate as the standard. **Results**—SEs of the prediction of difference in PVF between the right and left forelimbs from HMA and VS were 6.1% and 5.2%, respectively. Head movement asymmetry (ICC, 0.72) was less repeatable than PVF (ICC, 0.86) and VS (ICC, 0.84). Associations were positive and significant between HMA (R2 = 0.73) and VS (R2 = 0.81) and the difference in PVF between the right and left forelimbs. Correct classification percentages for HMA and VS for detecting the lamer forelimb were 83.3% and 77.8%, respectively. **Conclusions and Clinical Relevance**—Results suggested that an inertial sensor system to measure vertical asymmetry (HMA and VS) due to forelimb lameness in horses trotting in a straight line has adequate analytic sensitivity for clinical use. Additional studies are required to assess specificity of the system.

McCracken, M. J., Kramer, J., Keegan, K. G., Lopes, M., Wilson, D. A., Reed, S. K., … Rasch, M. (2012). Comparison of an inertial sensor system of lameness quantification with subjective lameness evaluation. *Equine Veterinary Journal*, 44(6), 652–656. https://doi.org/10.1111/j.2042-3306.2012.00571.x

Reasons for performing study: Subjective evaluation of mild lameness has been shown to have poor interobserver reliability. Traditional methods of objective lameness evaluation require specialised conditions and equipment. Wireless inertial sensor systems have been developed to allow for simple, rapid, objective lameness detection in horses trotted over ground. **Objective:** The purpose of this study was to compare the sensitivities of an inertial sensor system and subjective evaluation performed by experienced equine practitioners at detecting lameness in horses. We hypothesised that the inertial sensor system would identify lameness at a lower level of sole pressure than a consensus of 3 experienced equine veterinarians. **Methods:** Fifteen horses were fitted with special shoes that allowed for lameness induction via sole pressure. Horses were simultaneously evaluated by 3 equine veterinarians and a wireless inertial sensor system. Horses were subjected to multiple trials: 1) before inserting the screw; 2) after inserting the screw to just touch the sole; and 3) after tightening the screw in half turn increments. The number of screw turns required for lameness identification in the correct limb by the inertial sensors and by consensus of 3 equine veterinarians was compared using the Wilcoxon test. **Results:** The inertial sensor system selected the limb with the induced lameness after fewer screw turns than did the 3 veterinarians ($P<0.0001$). The inertial sensor system selected the correct limb before the 3 veterinarians in 35 trials (58.33%), the evaluators selected the correct limb before the inertial sensors in 5 trials (8.33%), and in 20 trials (33.33%) they selected the correct limb at the same time. **Potential relevance:** The inertial sensor system was able to identify lameness at a lower level of sole pressure than the consensus of 3 equine veterinarians. The inertial sensor system may be an effective aid to lameness localisation in clinical cases.

Keegan, K. G., Wilson, D. A., Kramer, J., Reed, S. K., Yonezawa, Y., Maki, H., … Lopes, M. A. F. (2013). Comparison of a body-mounted inertial sensor system–based method with subjective evaluation for detection of lameness in horses. *American Journal of Veterinary Research, 74(1),* 17–24. https://doi.org/10.2460/ajvr.74.1.17

Objective—To compare data obtained with an inertial sensor system with results of subjective lameness examinations performed by 3 experienced equine veterinarians for evaluation of lameness in horses. **Animals**—106 horses. **Procedures**—Horses were evaluated for lameness with a body-mounted inertial sensor system during trotting in a straight line and via subjective evaluation by 3 experienced equine practitioners who performed complete lameness examinations including lunging in a circle and limb flexion tests. Agreement among evaluators regarding results of subjective evaluations and correlations and agreements between various inertial sensor measures and results of subjective lameness evaluations were determined via calculation of Fleiss' κ statistic, regression analysis, and calculation of 95% prediction intervals. **Results**—Evaluators agreed on classification of horses into 3 mutually exclusive lameness categories (right limb lameness severity greater than left limb lameness severity, left limb lameness severity greater than right limb lameness severity, or equal right and left limb lameness severity) for 58.8% (κ = 0.37) and 54.7% (κ = 0.31) of horses for forelimb and hind limb lameness, respectively. All inertial sensor measures for forelimb and hind limb lameness were positively and significantly correlated with results of subjective evaluations. Agreement between inertial sensors measures and results of subjective evaluations was fair to moderate for forelimb lameness and slight to fair for hind limb lameness. **Conclusions and Clinical Relevance**—Results of lameness evaluation of horses with an inertial sensor system and via subjective lameness examinations were significantly correlated but did not have strong agreement. Inertial sensor-based evaluation may augment but not replace subjective lameness examination of horses.

Bell, R. P., Reed, S. K., Schoonover, M. J., Whitfield, C. T., Yonezawa, Y., Maki, H., … Keegan, K. G. (2016). Associations of force plate and body-mounted inertial sensor measurements for identification of hind limb lameness in horses. *American Journal of Veterinary Research*, *77(4),* 337–345. https://doi.org/10.2460/ajvr.77.4.337

OBJECTIVE To investigate associations between inertial sensor and stationary force plate measurements of hind limb lameness in horses. **ANIMALS** 21 adult horses with no lameness or with mild hind limb lameness. **PROCEDURES** Horses were instrumented with inertial sensors and evaluated for lameness with a stationary force plate while trotting in a straight line. Inertial sensor–derived measurements of maximum and minimum pelvic height differences between right and left halves of the stride were compared with vertical and horizontal ground reaction forces (GRFs). Stepwise linear regression was performed to investigate the strength of association between inertial sensor measurements of hind limb lameness and amplitude, impulse, and time indices of important events in the vertical and horizontal GRF patterns. **RESULTS** Difference in minimum pelvic position was moderately (R_a^2 = 0.60) associated with the difference in peak vertical GRF but had little association with any horizontal GRF measurements. Difference in maximum pelvic position was strongly (R_a^2 = 0.77) associated with a transfer of vertical to horizontal ground reaction impulse in the second half of the stance but was not associated with difference in peak vertical GRF. **CONCLUSIONS AND CLINICAL RELEVANCE** Inertial sensor–derived measurements of asymmetric pelvic fall (difference in minimum pelvic position) indicated a decrease in vertical GRF, but similar measurements of asymmetric pelvis rise (difference in maximum pelvic position) indicated a transfer of vertical to horizontal force impulse in the second half of the stance. Evaluation of both pelvic rise and fall may be important when assessing hind limb lameness in horses.

Other Papers Utilizing the Technology for Objective Quantification of Results

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