Use of a wireless, inertial sensor-based system to objectively evaluate flexion tests in the horse

J. F. MARSHALL*, D. G. LUND and L. C. VOUTE

Weipers Centre Equine Hospital, School of Veterinary Medicine, College of Medical, Veterinary and Life Sciences, University of Glasgow, Glasgow, UK.

*Correspondence email: john.f.marshall@glasgow.ac.uk; Received: 29.02.12; Accepted: 06.06.12

Summary

Objectives: A wireless, inertial sensor-based system has previously been validated for evaluation of equine lameness. However, threshold values have not been determined for the assessment of responses to flexion tests. The aim of this investigation was to evaluate a sensor-based system for objective assessment of the response to flexion.

Methods: Healthy adult horses (n = 17) in work were recruited prospectively. Horses were instrumented with sensors on the head (accelerometer), pelvis (accelerometer) and right forelimb (gyroscope), before trotting in a straight line (minimum 25 strides) for 2 consecutive trials. Sensors measured 1) vertical pelvic movement asymmetry (PMA) for both right and left hindlimb strides and 2) average difference in maximum and minimum pelvic height (PDMax and PDMin) between right and left hindlimb strides in millimetres. A hindlimb was randomly selected for proximal flexion (60 s), after which the horse trotted a minimum of 10 strides. Response to flexion was blindly assessed as negative or positive by an experienced observer. Changes in PMA, PDMax and PDMin between baseline and flexion examinations were calculated for each test. Statistical analysis consisted of a Pearson’s product moment test and linear regression on baseline trials, Mann–Whitney rank sum test for effect of flexion and receiver operator curve (ROC) analysis of test parameters.

Results: There was a strong correlation between trials for PMA, PDMin and PDMax measurements (P < 0.001). A positive flexion test resulted in a significant increase in PMA (P = 0.021) and PDMax (P = 0.03) only. Receiver–operator curve analysis established cut-off values for change in PMA and PDMax of 0.068 and 4.47 mm, respectively (sensitivity = 0.71, specificity = 0.65) to indicate a positive response to flexion.

Conclusions: A positive response to flexion resulted in significant changes to objective measurements of pelvic symmetry.

Potential relevance: Findings support the use of inertial sensor systems to objectively assess response to flexion tests. Further investigation is warranted to establish cut-off values for objective assessment of other diagnostic procedures.

Keywords: horse; lameness; accelerometer; flexion test

Introduction

Lameness remains a major problem in working horses and can have serious consequences for both animals and owners, including shortened working careers and financial loss. Early and accurate assessment of the lame limb or limbs, including the severity of the lameness, is essential to ensure timely and effective treatment. Routine clinical lameness examinations generally consist of initial palpation of the limbs and visual evaluation of the horse at rest, followed by observation of the horse in motion at the walk and trot, ideally over a hard, level surface. The horse may also be assessed moving in a circle, usually on the lunge, or may be assessed while ridden. Severity of lameness is graded based on a discrete subjective scale, such as the AAEP lameness scale [1]. Despite being the routine method of lameness examination, multiple studies have demonstrated a low agreement between visual lameness evaluations by equine veterinarians [2,3]. Furthermore, in cases of mild lameness, low repeatability for subjective lameness evaluation of horses has been shown regardless of the conditions of evaluation [3].

Flexion tests are routinely used as part of the lameness examination to exacerbate lameness. Applying pressure to a joint in this way often accentuates problems that would not be otherwise readily apparent. However, the interpretation of flexion tests is inherently subjective and considerable variation exists between observers [4].

Methods of objective lameness analysis are therefore highly relevant in the clinical setting and multiple systems have been developed to quantify lameness. Stationary force-plate analysis techniques are highly sensitive and repeatable, but time-consuming and labour-intensive. Force-measuring shoes and treadmills have also been devised in an attempt to refine the data collection process and measure contiguous strides, but these have yet to be adequately developed for routine clinical use. Video-based kinematic analysis has been commonly described but clinical application has been limited by equipment requirements [5,6]. However, video-based motion analysis techniques have been used to validate a wireless inertial sensor-based system for measurement of motion in the trotting horse [5].

Wireless sensor-based systems are ideal for clinical lameness investigations because they are noninvasive, do not affect the horse's natural movement and can be easily attached to the body. These systems are also advantageous in terms of data collection as they measure lameness on a continuous scale in real-time. Data are analysed rapidly, using algorithms for the detection of asymmetry, which have a high degree of accuracy and repeatability between trials [7].

Furthermore, threshold values have been determined for the test parameters used in inertial sensor-based analysis that can be applied to routine clinical examinations. These include values calculated over each trial for the asymmetry of vertical head and pelvic movement for the fore- and hindlimbs, and for the average difference in maximum and minimum head (forelimbs) and pelvic (hindlimbs) height in millimetres between the horse’s left and right sides.

However, specific guidelines and threshold values have yet to be established for the objective evaluation of flexion tests. Therefore, the aim of this investigation was to assess the use of an inertial sensor-based accelerometric system to evaluate flexion tests in the horse and determine whether clinically useful test values could be identified.

Materials and methods

Sample population

All procedures were performed with owner consent following a standard hospital lameness examination protocol and approved by the Faculty Ethics and Welfare Committee, School of Veterinary Medicine, University of Glasgow. Healthy adult large breed horses (n = 17) in routine work but with owner concerns of poor performance, including 11 geldings and 6 mares (mean age 13.7 years, s.d. 1.4 range 4–20 years), were recruited for this study. Breeds included draught cross (n = 7), Irish Sport Horse (n = 6) and Warmblood (n = 4). Horses included in this study were shod on all 4 feet.

Each horse was physically examined and its height was measured in centimetres using an aluminium measuring stick as described in the FEI guidelines (mean ± s.d., 174.7 ± 4.7 cm).
assessed as negative or positive by the observer. This was then repeated for the other limb. The observer was blinded to acelerometric results throughout the baseline and flexion test examinations.

Sensors
The commercially available sensors used were comprised of either a single-axis accelerometer or gyroscope, a radio transceiver (Bluetooth® Class 1) and antenna, 4.2 V lithium-polymer battery, microcontroller and circuitry, all contained within an epoxy case (Lameness Locator®). Sensors made up a local area network of a master node located on the tablet computer and 3 slave nodes to which it is connected wirelessly. Data were digitally recorded (8 bits) in real time at 200 Hz. A 5 ns per sample timing accuracy is achieved by synchronising the 3 channels using an onboard 40 MHz crystal with an accuracy of 10 ppm.

Accelerometry data
Data were analysed using commercially available software® as previously described [7]. Briefly, vertical head and pelvic movement were analysed by measuring patterns obtained from the head and pelvic acceleration and right forelimb pastern angular velocity data recorded by the sensors. Collected data were double-integrated and processed with a moving window, integration error correction algorithm. The signals produced were separated into 2 harmonic components and a random component, the latter component removed. The 2 harmonic components were summed in order to establish the gross vertical head and pelvic movement.

Stride rate and stance data were recorded by the right pastern gyroscopic sensor and used to determine the temporal relationships of the gross vertical movement of the head and pelvis to the stride sequence.

Measured values recorded in this study were the mean difference in millimetres in minimum and maximum pelvic height between the right and left hindlimb strides, PDMIn and PDMax respectively, and the vertical pelvic movement asymmetry (PMA) right and left hindlimb strides. The PDMax and PDMin values obtained for left hindlimb flexion tests were multiplied by \( -1 \) before analysis to remove the influence of negative values.

Data analysis
All statistical analyses were performed using commercially available software®. Linear regression and correlation analysis was performed to assess the repeatability of PMA, PDMIn and PDMax measurements. Correlation between the 2 baseline trials was determined using Pearson’s product moment test.

For all measured values, the difference between the baseline examination immediately prior to flexion and each flexion test was calculated. The effect of flexion on the PMA, PDMIn and PDMax of the flexed limb was analysed using a Mann–Whitney rank sum test. Statistical significance was set at \( P<0.05 \).

Receiver-operator curves (ROC) were generated for both PMA and PDMax to generate cut-off values for each parameter, which may be used to differentiate between positive and negative responses to flexion. Receiver-operator curve area values were used to determine the quality of each test parameter as a diagnostic discriminant.

Results
A total of 34 flexion tests were performed and responses categorised as positive (\( n=17 \)) or negative (\( n=17 \)) by the observer. There was a strong and significant correlation between baseline trials 1 and 2 for PMA (left hindlimb \( r=0.98 \), right hindlimb \( r=0.94 \)), PDMIn (\( r=0.98 \)) and PDMax (\( r=0.97 \)) values (\( P<0.001 \)).

Flexion tests categorised as positive (median 0.10, IQR 0.05–0.21) had a significantly greater change in PMA of the flexed limb than flexion tests categorised as negative (median 0.05, IQR 0.006–0.09) (Fig 2, \( P=0.021 \)). Flexion tests categorised as positive (median 5.54 mm, IQR 3.48–7.97 mm) had a significantly greater change in PDMax than flexion tests categorised as negative (median 3.20, IQR 1.94–5.20) (Fig 3, \( P=0.05 \)). There was no significant effect of flexion on PDMin (Fig 4).

Receiver-operator analysis determined that the change in PMA ratio of the flexed limb and change in PDMax are useful diagnostic tests (Fig 4, 44, Suppl. 43 (2012) 8–11 © 2012 EVI Ltd

Fig 1: Photograph of a horse instrumented with inertial sensors on the head (A, accelerometer), pelvis (B, accelerometer) and right forelimb (C, gyroscope). For examination purposes sensors were secured with additional adhesive tape.
AUC = 0.73 and 0.70, respectively. A change in PMA of 0.068 was determined to have a sensitivity of 0.71 and a specificity of 0.65 (Fig 5). A change in PDMax of 4.47 mm was determined to also have a sensitivity of 0.71 and a specificity of 0.65 (Fig 4).

**Discussion**

This investigation was focused exclusively on evaluating the use of an inertial sensor-based system for objective assessment of proximal flexion tests of hindlimbs. This system has been previously evaluated and validated for the assessment of lameness in horses [7]. The first objective of this study was to determine whether the changes observed during a positive response to flexion would be identified and measured by the sensor system. For this reason, the measured parameters relating to pelvic movement (PMA, PDMax, PDMin) were selected for further analysis. As a flexion test is a comparison between a horse’s movement before and after flexion of a limb, the difference between measured parameters for a baseline examination and following flexion was determined. In those flexion tests categorised as positive by observation, a significant increase in PMA and PDMax was identified by the sensor system. The PMA values are determined for each limb and represent the level of symmetry of pelvic movement [7]. As the PDMax is determined by measuring the difference in maximum pelvic height between the right and left strides, perfectly symmetrical pelvic movement would result in a value of 0 mm. An increase in PDMax would suggest an asymmetric upward movement of the pelvis at the end of the hindlimb stance phase [7]. Therefore, it appears that a positive response to a flexion test results in a decrease in the rise of the pelvis, most likely after push-off of the flexed limb, resulting in a greater difference in the maximum pelvic height between left and right limb strides. In contrast to PDMax, PDMin is determined by measuring the difference in

**Fig 2:** Box plot of the change in pelvic movement asymmetry (ΔPMA) for positive and negative flexion tests. For each plot, the box represents the 25th and 75th percentiles, the horizontal line represents the median, whiskers represent the 10th and 90th percentiles and black circles represent outliers. The change in PMA is significantly greater for positive flexion tests (*P* = 0.021).

**Fig 3:** Box plot of the change in difference in maximum pelvic height between right and left limbs (ΔPDMax) for positive and negative flexion tests. The change in PDMax is significantly greater for positive flexion tests (*P* = 0.05).

**Fig 4:** Box plot of the change in difference in minimum pelvic height between right and left limbs (ΔPDMin) for positive and negative flexion tests. There is no significant difference in the change in PDMin for positive and negative flexion tests.

**Fig 5:** Receiver-operator analysis curves for the change in pelvic movement asymmetry (ΔPMA, black line) and change in maximum pelvic height between right and left limbs (ΔPDMax, red line).
minimum pelvic height between the right and left hindlimbs during the stance phase of the stride [7]. Similar to PDMax, perfectly symmetrical pelvic movement would result in a value of 0 mm. An increase in PDMin in response to flexion would indicate a decrease in the fall of the pelvis during the stance phase of flexed limb. It may then be unexpected that a positive response to flexion did not result in a change in PDMin in this study. Therefore, the increase in pelvic movement asymmetry observed and measured (PMA) during a positive response to flexion appears to be due to a decrease in push-off of the flexed limb, which may be described by an observer as an increase in ‘hip drop’.

The second objective of this study was to determine whether the inertial sensor-based system could be used to differentiate negative and positive flexion tests. The changes in PMA and PDMax between baseline examination and flexion tests were identified as suitable test parameters based on ROC analysis. Using the change in PMA following flexion, a cut-off value of 0.068 had a sensitivity of 71% and a specificity of 65% for identifying a positive response. Similarly, a cut-off value of 4.47 mm for the change in PDMax also had a sensitivity of 71% and a specificity of 65% for identifying a positive response. However, the response to each flexion test was categorised as negative or positive by a single individual for the purposes of data analysis, and it is on this interpretation that the cut-off values are based. A previous study identified a high degree of variability between individuals when assessing the response to flexion tests, and it was therefore decided to use a single live observation for the purposes of comparison [4]. As the interpretation of the response to flexion does vary between individuals, the cut-off values established by this study may not be directly applicable to other individuals. The horse population in this study was chosen as it reflects the horses commonly presented to our practice, and all horses were similar in terms of age, breed and height. However, the horse population utilised in this study may not reflect that of other equine practices and further study may be warranted with different horse populations. Overall, these results show that this inertial sensor-based system can identify significant changes in a horse’s movement as the result of flexion testing, thereby providing the basis for the development of objective diagnostic techniques for assessment of lameness.

The strong correlation between baseline trials for all measured parameters indicates excellent repeatability, a necessary prerequisite for any diagnostic test to be considered clinically relevant. These results are consistent with the findings of a recent repeatability assessment of the same inertial sensor-based system for use in lameness evaluations, which also reported strong correlation between successive trials [7].

Horses used in this study were in regular work at the time of observation, but 7 horses were determined to have hindlimb lameness (AAEP Grade 1–3). The use of flexion tests to identify lame limbs was outside the scope of this project and was not investigated, but represents a potential future use of this objective method.

In conclusion, this study has shown that the changes in pelvic movement associated with a positive flexion test can be objectively measured using a wireless inertial sensor-based system. Using this method, it is possible to determine diagnostic cut-off values to aid in the interpretation of flexion tests.

Conflicts of interest
No competing interests have been declared.

Sources of funding
This study was funded by the Chancellor’s Fund and the School of Veterinary Medicine, University of Glasgow.

Acknowledgements
The authors would like to acknowledge the contribution of the staff and students of the Weipers Centre Equine Hospital that helped make this study possible.

Authorship
J.M. conceived the study and J.M., D.L. and L.V. designed the study. J.M. and D.L. completed the study design and data analysis. J.M., D.L. and L.V. interpreted the data and prepared the manuscript.

Manufacturers’ addresses
aShurtape Technologies LLC, Hickory, North Carolina, USA.
bEquinosis LLC, Columbia, Missouri, USA.
cSigmaPlot 11.2, Systat Software Inc, Chicago, Illinois, USA.

References