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Is a standalone inertial measurement unit accurate and precise enough for quantification of movement symmetry in the horse?

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Short Communication

Introduction

Gait analysis with inertial measurement units (IMUs) has become common in horses (e.g. Barrey et al, 1994, Keegan et al, 2004, Pfau et al, 2007, Halling-Thomsen et al, 2010). Small sensors and wireless transmitters are unobtrusive in large animals. Consequently IMUs are ideally suited to support clinical decision making by providing objective evidence about changes in movement symmetry (MS) in conjunction with diagnostic tests, such as lunging the horse on hard and soft ground (Chateau et al, 2011, Pfau et al, 2012, Rhodin et al, 2010, Walker, et al, 2010), flexion tests (Starke et al, 2012a), and diagnostic regional analgesia (Smith and Pfau, 2010). Large-scale studies are needed to establish reference intervals (Geffré et al, 2009) for non-lame horses and minimal clinically important differences (Sloan, 2005, Turner et al, 2010) to support clinical decision making. The cost of current IMU systems prevents their widespread use by horse professionals/owners to monitor asymmetry over time.

The aim of this study was to determine whether a 'low-cost', 6 DoF IMU (X-IMU, x-io Technologies Limited, Bristol) is sufficiently accurate and precise for quantification of MS measures to assess orthopaedic movement deficits in horses. Bias and limits of agreement (Bland and Altman, 1986) were established with respect to a validated system based on multiple synchronized 6-DoF IMUs (MTx, Xsens, The Netherlands, Pfau et al, 2005, 2007, 2012, Warner et al, 2010, Starke et al, 2012a, 2012c).

Materials and Methods

Six horses from the RVC teaching herd were equipped with two X-IMU sensors (57×38×21 mm, 49 g, +/-8×gravity, +/-2000 deg/s, +/-4 Gauss) and two MTx (53×38×21 mm, 30 g, +/-18×gravity, +/-1200 deg/s, +/-750 mGauss) over sternum and sacrum. The two sternum and the two sacrum IMUs were attached as close as possible

to each other in the sagittal plane. Measurements were then conducted during straight line trot and during lunging.

X-IMU and MTx data were captured at 256 Hz (lowest common sample rate) per individual data channel. X-IMU sensors logged onto a removable microSD storage card; MTx sensors transmitted data to a computer via a dedicated Bluetooth wireless link (Xbus, Xsens).

Custom written software (MATLAB, Natick, US) was used to process data from both types of IMUs following published procedures (Pfau et al, 2005, Warner et al, 2010): calibrated acceleration data were rotated into a horse based reference frame based on sensor orientation and knowledge about orientation of the sensor mounting. Sensor orientation was calculated with the built-in sensor fusion algorithms without modifications (X-IMU: gradient descent (Madgwick et al, 2011); MTx: extended Kalman filter (Luinge et al, 1999, Xsens 2009)). Vertical acceleration was high pass filtered and double integrated to velocity and displacement. Finally, continuous sensor data were segmented into individual strides based on vertical velocity and sensor roll (sacrum) (Starke et al, 2012) or sensor heading (sternum).

Averages of MS measures were calculated from stride segmented vertical displacement during trot: (1) Symmetry index (SI: Buchner et al, 1996), (2) difference between minima (MinDiff: Kramer et al, 2004) and (3) difference between maxima (MaxDiff: Kramer et al, 2004). These quantify different components of symmetry between the two halves of a stride related to ground contact of the diagonal pairs of limbs.

Agreement analysis as described by Bland and Altman (1986) between MTx and X-IMU for all three MS measures revealed an increasing systematic error between the two systems with increasing deviation from symmetry. The regression based approach

described by Bland and Altman (1999) was chosen to correct for this systematic error. Median values were then calculated across the strides of each exercise based on MTx and corrected X-IMU data. Then mean (termed: bias or accuracy), SD (precision) and limits of agreement ($LoA = \pm 1.96 * SD$) of the differences between the sensors were calculated (Bland and Altman, 1986).

Results

From the six horses 73 trials were collected: 48 during straight line trot and 25 during lunging. On average each trial contained 22 strides (see table 1). Regression corrected bias values were close to zero for all MS measures.

For the sacrum, SI precision was 0.048, 3.36 mm for MinDiff and 2.20 mm for MaxDiff. LoA were ± 0.095 for SI, ± 6.6 mm for MinDiff and ± 4.3 mm for MaxDiff (see figure 1).

For the sternum, precision was 0.045 for SI, 2.52 mm for MinDiff, and 2.14 mm for MaxDiff resulting in LoA of ± 0.088 for SI, ± 5.02 mm for MinDiff and ± 4.18 mm for MaxDiff (see figure 2).

Discussion

Study motivation:

This study investigated a standalone ‘low-cost’ IMU (X-IMU) for assessment of MS in horses with the main focus on accurate quantification of lameness, one of the most common health problems in horses (Kaneene, 1997, Egenvall et al, 2009, BlueCross, 2011). If easy to use, such a sensor could facilitate data collection from a sufficiently large population to establish reference intervals (Geffré et al, 2009) and MID values (Turner et al, 2010). This also requires subjective assessment of gait quality (e.g. non-lame, mildly lame, moderately lame) or improvement or worsening of a given

condition. Given that agreement for subjective gait assessment even amongst expert observers is generally poor for horses with low grade lameness (Keegan et al, 2010) the required sample size is further increased emphasizing the need for a simple, cost-efficient solution.

Optimizing sensor performance:

We have compared a 'low-cost' IMU to a more expensive 'reference' system. Both systems were applied without further calibration or fine-tuning of in particular the orientation estimation routines (Madgwick et al, 2011, Luinge et al, 1999). The 'low-cost' IMU provides software access to calibration and processing routines. These routines were not utilized here implementing a 'worst-case' scenario prioritising ease-of-use (no complicated calibration or modified processing) over sensor performance, ultimately aiming at large scale studies. Future studies should investigate customised routines to further improve IMU performance.

Sensor fixation:

Due to the physical size of the two sensor types (X-IMU slightly heavier due to addition of battery) the two IMUs could not be placed at identical locations, hence at least part of the discrepancies may be related to a difference in sensor location. Ideally, the two IMUs should be used in both locations at random, however to keep statistical analysis simple the sensors were placed in consistent locations (in the sagittal plane) for all horses. In support of this decision, Warner (et al, 2010) only reports small differences in MS for sensors along the back. Direct comparison is difficult due to the different choice of symmetry measures and differences in inter-sensor distance (0.15 to 0.2m in Warner et al, 2010 and approximately 0.02 to 0.03m here). Smaller effects seem likely for smaller distances.

Both IMU types were fixed with the same attachment method: cross-elastic adhesive foam fixative (Animal Polster, Snogg, Norway) to the horse and double sided tape between this and the IMU. The IMUs hence record the movement of the skin rather than the movement of the underlying bony landmark. Skin movement is known to be an overestimation compared to bone-pin fixated IMUs in the horse (Goff et al, 2010). The soft tissue artefact between skin mounted accelerometers and underlying bony structures has been modelled with a second order mass–spring–damper e.g. applied to the human heel-drop (Forner-Cordero et al, 2008). With decreasing sensor mass, an increase in natural frequency can be observed. Accelerometer mass was an order of magnitude lower (2.8 g and 4.7 g) in that study than here, however the reported effect on natural frequency was small when sensors were strapped tightly to the limb. We cannot exclude that the higher IMU masses and the less tight fixation introduce movement artefacts. Given the identical attachment method and the similar masses, effects are likely to be similar between the two IMUs. An IMU with comparable mass (less than 30g) shows good agreement with gold standard kinetic assessment (Keegan, 2012) and with subjective assessment (McCracken et al, 2012) indicating that clinically relevant signal components are maintained in the signal using this type of fixation.

Comparison to reference data

In order to be suitable for establishing MIDs, the sensors need to be sufficiently accurate and precise to document differences between sound and mildly lame horses. At current, reference data for MS from non-lame horses during over ground locomotion are sparse. Our normal values are currently [0.83-1.17] for pelvic SI and [0.82-1.18] for head SI (Starke et al, 2012c based on Buchner et al, 1996). Thresholds of +/-3 mm for sacral MinDiff and MaxDiff and +/-6 mm for head MinDiff and MaxDiff have been proposed (McCracken et al, 2012) using uni-axial accelerometers (with different signal

processing, Keegan et al, 2001). It is not clear whether these can be directly transferred to 6 DoF IMU measurements assessing true vertical movement. Assuming displacement amplitude of approximately 60 mm (withers, trot, Pfau et al, 2005) a 3mm difference would result in SI deviating from 1 by ± 0.1 , less than our 1 ± 0.17 normal range. Out of plane rotation of the uni-axial sensor (McCracken et al, 2012) is unlikely to explain this discrepancy affecting minima, maxima and movement amplitude alike.

Are the low-cost sensors precise enough?

LoA reported here (± 0.095) for SI are approximately half of our established threshold values (1 ± 0.17 or 1 ± 0.18) indicating sufficient precision of the low-cost sensors to assess medium and long-term development of MS to determine MID. For MinDiff and MaxDiff, LoA values (± 6.6 mm or ± 4.3 mm) are of similar magnitude to the proposed thresholds (McCracken, et al, 2012): with our worst-case scenario approach without fine-tuning sensor performance, the sensors appear insufficiently precise for investigating low-grade lameness, using MinDiff and MaxDiff. However, further improvements can be expected with future IMU generations and as a result of customised processing algorithms.

The contradictory results with respect to the different lameness parameters (SI versus MinDiff and MaxDiff) also question the different proposed thresholds. Further investigations into uni-axial versus full 6DoF IMUs are required and need to establish clinically relevant thresholds based on reference intervals and MIDs between sound and mildly lame horses, ideally in a large multicentre study.

Although not investigated quantitatively, it is intriguing to note what appears to be a tendency for increasing differences between the systems for the trials collected during lunging (red data points in Figure 1 and 2). The influence of centripetal acceleration as a function of circle radius and trotting speed on body lean angle (Pfau et

al, 2012) might systematically affect the different sensor fusion algorithms when calculating sensor orientation. This needs further investigations and might result in better agreement if corrected for by implementing customised processing routines, potentially guided by additional knowledge about the horse's path, e.g. from a global positioning system.

Choice of sensor location:

The two main lameness parameters used in Veterinary practice are 'head nod' (Buchner et al, 1996) and hip hike (May and Wyn-Jones, 1987). Here, IMUs were placed over sacrum and sternum. A head mounted sensor seems more obvious to quantify front limb lameness. In order to distinguish between left and right sided lameness with a single sensor (Starke et al, 2012b), additional parameters need evaluating together with vertical movement. Head roll appears to be an unreliable indicator of the side of asymmetry since horses limit out of plane movements of the head (Dunbar et al, 2008). The sternum has been used previously (Barrey et al, 1994) and body orientation seems better suited than head orientation. In multi-sensor systems with synchronized sensors (Warner et al, 2010, Starke et al, 2012a,c, Pfau et al, 2012), the sacral sensor can be used to segment all sensor data (Starke et al, 2012b). If thoracic limb hoof contact is required, IMUs located on the distal limb (Olsen et al, 2012) or hoof mounted accelerometers or gyroscopes (Witte et al, 2004, Keegan et al 2005) provide precise results.

Conclusion

The comparison between two IMU systems for assessing equine MS has shown contradictory results for the LoA: SI indicates sufficient precision of the low-cost IMU; MinDiff and MaxDiff are less favourable without additional fine-tuning of IMU

processing. Further studies should investigate specific calibration and orientation estimation algorithms to further improve performance. Large scale, long term studies would then be feasible to revise our current lameness thresholds.

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Table 1: Number of trials per exercise condition and sensor (and average number of strides per trial in brackets) collected based on the automated stride segmentation algorithm for all six horses. Horse 2 refused to being lunged and hence no data are available for the ‘circle’ condition.

	straight		circle	
Horse	sternum	sacrum	sternum	sacrum
1	8 (22)	8 (23)	3 (34)	3 (41)
2	7 (20)	7 (19)	NA	NA
3	9 (21)	9 (20)	5 (37)	5 (35)
4	8 (19)	8 (19)	6 (27)	6 (26)
5	8 (14)	8 (15)	6 (26)	6 (24)
6	8 (14)	8 (15)	5 (24)	5 (24)

Figure legends:

Figure 1. Scatter plots showing mean of regression corrected (Bland and Altman, 1999) X-IMU and MTx derived **sacral** MS values on x-axis and difference between regression corrected X-IMU and MTx derived MS values on y-axis (Bland and Altman, 1986). Each point represents one of the 73 trials (blue: straight line assessment, red: lunging). The solid black line indicates bias and the dashed lines represent LoA. A: SI, B: MinDiff, C: MaxDiff.

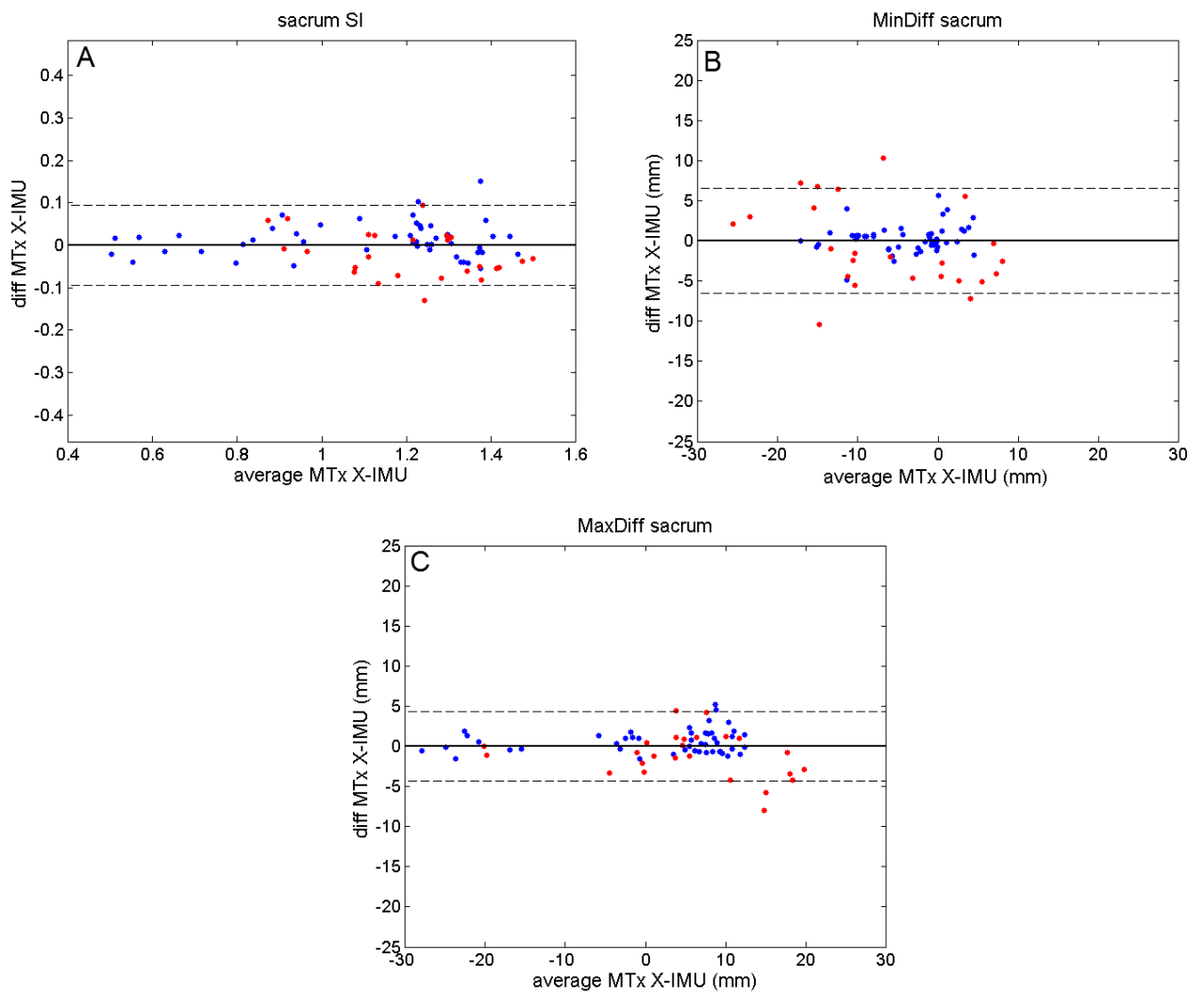


Figure 2. Scatter plots showing mean of regression corrected (Bland and Altman, 1999) X-IMU and MTx derived **sternal** MS values on x-axis and difference between regression corrected X-IMU and MTx derived MS values on y-axis (Bland and Altman, 1986). Each point represents one of the 73 trials (blue: straight line assessment, red: lunging). The solid black line indicates bias and the dashed lines represent LoA. A: SI, B: MinDiff, C: MaxDiff.

