The full details of the published version of the article are as follows:

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

AUTHORS: Charlotte Brighton, Emil Olsen, and Thilo Pfau

JOURNAL TITLE: Computer Methods In Biomechanics And Biomedical Engineering

PUBLISHER: Taylor & Francis

PUBLICATION DATE: August 2014 (online)

DOI: 10.1080/10255842.2013.819857

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

Charlotte Brighton[1], Emil Olsen[1,2], Thilo Pfau[1,]*

cbrighton@rvc.ac.uk, eolsen@rvc.ac.uk, tpfau@rvc.ac.uk

[1]*Department of Clinical Sciences and Services, The Royal Veterinary College, University of London, Hatfield, UK*

[2]*Department of Large Animal Sciences, Faculty of Health and Medical Science, University of Copenhagen, Hojbakkegaard Alle 5, 2630 Taastrup, Denmark*

*Dr.-Ing. Thilo Pfau

Lecturer in Bio-Engineering, Dept. of Clinical Sciences and Services

The Royal Veterinary College, University of London

Hawkshead Lane, North Mymms, Hatfield, AL9 7TA, UK

email: tpfau@rvc.ac.uk

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 = +/-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.

References:

Barrey E, Hermelin M, Vaudelin JL, Poirel D, Valette JP. 1994. Utilisation of an accelerometric device in equine gait analysis, Equine Vet J Suppl., 17, 7–12.

Bland JM, Altman DG. 1986. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet, 1(8476), 307–310.

Bland JM, Altman DG. 1999. Measuring agreement in method comparison studies, Statistical methods in medical research, 8, 135-160.

Blue Cross. 2011. New survey reveals UK's current equine healthcare problems http://www.bluecross.org.uk/2000-84227/new-survey-reveals-uks-current-equine-healthcare-problems-.html

Buchner HH, Savelberg HH, Schamhardt HC, Barneveld A. 1996. Head and trunk movement adaptations in horses with experimentally induced fore- or hindlimb lameness. Equine Vet J, 28(1), 71–76.

Chateau H, Robin D, Camus M, Holden L, Falala S, Ravary B, Denoix JM, Pourcelot P, Crevier-Denoix N. 2011. Use of a dynamometric horseshoe for the measurement of ground reaction force and moments in horses trotting on right and left circles on different surfaces, Proceedings. International Society of Biomechanics, Bruxelles, Belgium.

Dunbar DC, Macpherson JM, Simmons RW, Zarcades A. 2008. Stabilization and mobility of the head, neck and trunk in horses during overground locomotion: comparisons with humans and other primates. J Exp Biol, 211, 3889–3907.

Egenvall A, Lönnell C, Roepstorff L. 2009. Analysis of morbidity and mortality data in riding school horses, with special regard to locomotor problems. Preventive Veterinary Medicine 88, 193-204.

Forner-Cordero A, Mateu-Arce M, Forner-Cordero I, Alcántara E, Moreno JC, Pons JL. 2008. Study of the motion artefacts of skin-mounted inertial sensors under different attachment conditions, Physiol. Meas. 29 N21, doi:10.1088/0967-3334/29/4/N01.

Geffré A, Friedrichs K, Harr K, Concordet D, Trumel1 C, Braun JP. 2009. Reference values: a review, Vet Clin Pathol, 38/3, 288–298

Goff L, vanWeeren PR., Jeffcott L, Condie P, McGowan C. 2010. Quantification of equine sacral and iliac motion during gait: A comparison between motion capture with skin-mounted and bone-fixated sensors. Equine Vet J 42, 468-474.

Halling Thomsen M, Tolver Jensen A, Sørensen H, Lindegaard C, Andersen PH. 2010. Symmetry indices based on accelerometric data in trotting horses. J Biomech., 43(13), 2608–2612.

Kaneene JB, Ross WA, Miller R. 1997. The Michigan equine monitoring system: II. Frequencies and impact of selected health problems. Preventive Veterinary Medicine 29, 277-292.

Keegan KG, Pai PF, Wilson DA, Smith BK. 2001. Signal decomposition method of evaluating head movement to measure induced forelimb lameness in horses trotting on a treadmill. Equine Vet J, 33(5), 446–451.

Keegan KG, Yonezawa Y, Pai PF, Wilson DA, Kramer J. 2004. Evaluation of a sensor-based system of motion analysis for detection and quantification of forelimb and hind limb lameness in horses. Am J Vet Res, 65(5), 665–670.

Keegan KG, Satterley JM, Skubic M, Yonezawa Y, Cooley JM, Wilson DA, Kramer J. 2005. Use of gyroscopic sensors for objective evaluation of trimming and shoeing to alter time between heel and toe lift-off at end of the stance phase in horses walking and trotting on a treadmill. Am J Vet Res, 66(12), 2046-2054.

Keegan KG, Dent EV, Wilson DA, Janicek J, Kramer J, Lacarrubba A, Walsh DM, Cassells MW, Esther TM, Schiltz P, et al. 2010. Repeatability of subjective evaluation of lameness in horses. Equine Vet J, 42(2), 92–97.

Keegan KG, MacAllister CG, Wilson DA, Gedon CA, Kramer J, Yonezawa Y, Maki H, Pai PF. 2012. Comparison of an inertial sensor system with a stationary force plate for evaluation of horses with bilateral forelimb lameness. Am J Vet Res, 73(3), 368-374.

Kramer J, Keegan KG, Kelmer G, Wilson DA. 2004. Objective determination of pelvic movement during hind limb lameness and pelvic height differences. Am J Vet Res, 65(6), 741–747.

Luinge HJ, Veltink PH, Baten CTM, 1999, Estimation of orientation with gyroscopes and accelerometers, Proc. First Joint Engineering in Medicine and Biology 21st Annual Conf and the 1999 Annual Fall Meeting of the Biomedical Engineering Soc BMES/EMBS Conference, Vol. 2, p. 844.

Madgwick SOH, Harrison AJL; Vaidyanathan R. 2011. Estimation of IMU and MARG orientation using a gradient descent algorithm. Proc. IEEE Int. Conf. Rehab. Robotics (ICORR), pp 1-7.

May SA, Wyn-Jones G. 1987. Identification of hindleg lameness. Equine Vet J, 19(3), 185-188.

McCracken MJ, Kramer J, Keegan KG, Lopes M, Wilson DA, Reed SK, LaCarrubba A, Rasch M, 2012. Comparison of an inertial sensor system of lameness quantification with subjective lameness evaluation. Equine Vet J, 44, 652–656.

Olsen E, Andersen, PH, Pfau T, 2012. Accuracy and Precision of Equine Gait Event Detection during Walking with Limb and Trunk Mounted Inertial Sensors. Sensors, 12(6), 8145-8156;

Pfau T, Witte TH, Wilson AM. 2005. A method for deriving displacement data during cyclical movement using an inertial sensor. J Exp Biol, 208, 2503–2514.

Pfau T, Robilliard JJ, Weller R, Jespers K, Eliashar E, Wilson AM. 2007. Assessment of mild hindlimb lameness during over ground locomotion using linear discriminant analysis of inertial sensor data. Equine Vet J, 39, 407–413.

Pfau T, Stubbs NC, Kaiser LJ, Brown LE, Clayton HM. 2012. Effect of trotting speed and circle radius on movement symmetry in horses during lunging on a soft surface. American Journal of Veterinary Research 73, 1890-1899.

Rhodin M, Roepstorff L, Roethlisberger-Holm K, French A, Keegan K, Egenvall A. 2010. Evaluation of the motion pattern of the horse at lunging. Poster session presented at: International Conference on Equine Exercise Physiology, Cape Town, South Africa.

Sloan JA. 2005. Assessing the Minimally Clinically Significant Difference: Scientific Considerations, Challenges and Solutions. COPD: Journal of Chronic Obstructive Pulmonary Disease, 2, 57–62

Smith RKW, Pfau T. 2010. How subjective is the detection of lameness and nerve block results in horses? Proceedings WVOC 2010, Bologna, Italy, 250-251.

Starke SD, Willems E, Head M, May SA, Pfau T. 2012a. Proximal hindlimb flexion in
the horse: effect on movement symmetry and implications for defining soundness.
Equine Vet J. 44(6), 657-663.

Starke SD, Witte TH, May SA, Pfau T. 2012b. Accuracy and precision of hind limb
foot contact timings of horses determined using a pelvis-mounted inertial
measurement unit. J Biomech. 45(8):1522-1528.

Starke SD, Willems E, May SA, Pfau T. 2012c. Vertical head and trunk movement
adaptations of sound horses trotting in a circle on a hard surface. Vet J. 193(1),
73-80.

Turner D, Schünemann HJ, Griffith LE, Beaton DE, Griffiths AM, Critch JN, Guyatt
GH. 2010. The minimal detectable change cannot reliably replace the minimal
important difference. J Clin Epidemiology 63, 28-36.

Walker AM, Wilson AM, Pfau T. 2010. Comparison of kinematic symmetry index
calculations and the effects of straight and circular trotting. Equine Vet J, 42
Suppl 3, 482–487.

Warner SM, Koch TO, Pfau T. 2010. Inertial sensors for assessment of back movement
in horses during locomotion over ground. Equine Vet J, 42 Suppl 3, 417–424.

Witte TH, Knill K, Wilson AM. 2004. Determination of peak vertical ground reaction
force from duty factor in the horse (Equus caballus), J Exp Biol 207, 3639-3648.

Xsens Technologies B.V. 2009. MTi and MTx User Manual and Technical
Documentation. Pantheon 6a, 7521 PR Enschede, The Netherlands.

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.

Horse	straight		circle	
	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:
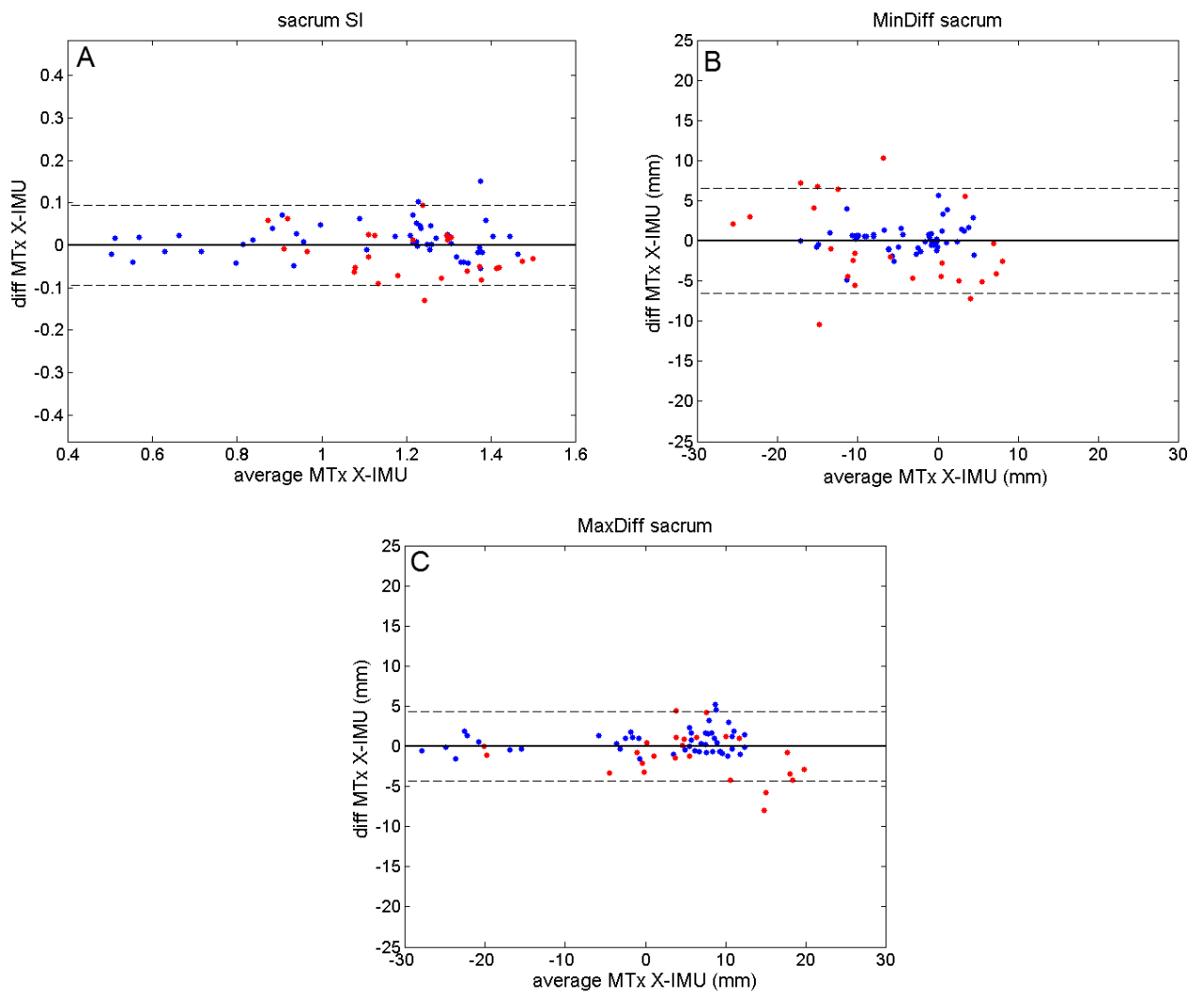MinDiff, C: MaxDiff.

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.