How low can we go?

Influence of sample rate on equine pelvic displacement calculated from inertial sensor data

Keywords: horse, upper body movement, inertial measurement unit, sample rate, Nyquist, accuracy, precision

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Summary:

Background: Low-cost sensor devices are often limited in terms of sample rate. Based on signal periodicity, the Nyquist theorem allows determining the minimum theoretical sample rate required to adequately capture cyclical events, such as pelvic movement in trotting horses . *Objectives*: To quantify the magnitude of errors arising with reduced sample rates when capturing biological signals using the example of pelvic time-displacement series and derived minima and maxima used to quantify movement asymmetry in lame horses. *Study Design*: Data comparison. *Methods*: Root mean square (RMS) errors between the 'reference' time-displacement series, captured with a validated inertial sensor at 100 Hz sample rate, and down-sampled time-series (8 Hz to 50 Hz) are calculated. Accuracy and precision are determined for maxima and minima derived from the time-displacement series. *Results*: Average RMS errors are <2 mm at 50 Hz sample rate, <4 mm at 40 Hz, <7 mm between 25 and 35 Hz, and increase to up to 20 mm at 20 Hz and below. Accuracy for maxima and minima is generally below 1mm. Precision is 1 mm at 50 Hz sample rate, 3 mm at 40Hz and >=9 mm at 20 Hz and below. *Main limitations*: Only sample rate, no other sensor parameters were investigated. *Conclusions*: Sample rate related errors for inertial sensor derived time-displacement series of pelvic movement are <2mm at 50 Hz, a rate that many low-cost loggers, smartphones or wireless sensors can sustain hence rendering these devices valid options for quantifying parameters relevant for lameness examinations in horses.

Introduction:

When choosing a suitable technological solution for the quantification of dynamic parameters, i.e. a time-variant measurement, it is important to take the fundamental principles of signal processing into account. The most important principle in this context is the Nyquist theorem, which stipulates, that the sample rate, i.e. the number of measurements per time unit, needs to be above twice the value of the maximally 'expected frequency' in the time-series signal.

When it comes to quantifying upper body movement symmetry in the horse, the last few decades have resulted in a clear understanding of the expected movements. In the trotting horse, the most relevant condition for the lameness examination, stride frequency is typically observed in the region of up to 2 Hz (2 strides per second) [1]. During each stride cycle, the body moves up and down twice, related to the ground contact and subsequent aerial phase of each diagonal pair of limbs. Assuming a perfectly sinusoidal movement in the vertical plane, this would result in a maximal 'expected frequency' of 4 Hz. In order to calculate the movement amplitude of a 'perfect' 4 Hz sine wave, the Nyquist theorem indicates that a sample rate of just above 8 Hz is required.

Biological phenomena, such as animal movement, rarely result in 'perfect' sine waves. Hence, time series signals of vertical upper body movement also contain higher frequency signals. Audigie and colleagues [2] have applied Fourier analysis (decomposing the time-series signal into sine and cosine waves) to reconstructing vertical movement signals of landmarks along the back of trotting horses. This shows, that in excess of 99% of the time-series signal can be captured with only the first two harmonics, i.e. making use of the amplitudes and phases of sine waves with periods equivalent to the stride cycle and half the stride cycle. This suggests, that for a trotting horse a minimum sample rate of 8 Hz could be considered for quantifying the time-series signal of vertical upper body movement according to the Nyquist theorem.

Recent advances in processing power of smartphones combined with sensor miniaturization mean that inertial sensor data can now be recorded without specialist equipment and have been validated and are being used for gait analysis in humans (e.g. [3–9]) In horses, a comparison has been conducted between a specialist inertial sensor and a sensor integrated into a smartphone for asymmetry assessment in horses [10]. While in theory, it is possible with these consumer grade devices to record data at sample rates of around 100 Hz (e.g. http://sensorlog.berndthomas.net/ used in [10]), a sample rate also used in a previous validation study in horses with specialist inertial sensors [11]. However, in comparison with specialist data logging devices which provide very accurate sample rates, smartphone based logging can lead to missing data points or inconsistencies in sample rate particularly with increasing sample rates.

In the following we will quantify the effect of reducing the sample rate, from a ‘reference’ sample rate of 100 Hz (i.e. well above the postulated minimum Nyquist rate) to sample rates between 50 and 8 Hz, when calculating vertical displacement from a validated inertial measurement unit (MTw, Xsens, The Netherlands). This example is of specific relevance for quantifying movement symmetry during the equine lameness exam, a topic of recent discussions [12–15]. As a consequence, errors resulting from a reduction in sample rate will be assessed in relation to published repeatability values and movement asymmetry thresholds suggested for the lameness exam.

Materials and Methods

Data collection: Data from four horses, assessed with 5 MTw[a] inertial measurement units at poll, withers, sacrum and left and right tuber coxae, as part of routine lameness investigations, were retrospectively chosen for this technical comparison study. The retrospective study was given approval by the Royal Veterinary College Social Sciences Research Ethical Review Board (SSRERB) (URN SR2020-0212). From each horse, one data file, from the sacrum mounted sensor, was chosen from the baseline assessment. Each data file contained >20 seconds (2000 samples) of data recorded at a sample rate of 100 Hz per individual data channel, consisting of tri-axial acceleration, tri-axial rate of turn, tri-axial magnetic field and 3D orientation data (Euler angles). These data were transmitted wirelessly via an Awinda[a] transceiver to a nearby Windows[b] (v10 Pro) laptop computer running MTManager[a] software. Data processing was implemented in MATLAB[c]. Data files were chosen based on the requirement to contain a minimum of 20 seconds (2000 samples) of data to avoid potential boundary effects of subsequent processing steps such as filtering. Hence files analysed here represent data collected from lungeing or ridden exercise (as opposed to straight line trials where often shorter time periods are collected). The pelvic sensors was chosen as a representative of vertical upper body movement which shows similar characteristics across body landmarks with generally >99% percentage reconstruction with only the first two Fourier harmonics [2] and also due the tighter movement asymmetry thresholds suggested for this landmark in comparison to for example the poll sensor [16].

Effect of sample rate: ten copies were created of each data file, with each copy containing a down-sampled version at the following sample rates: 8, 10, 15, 20, 25, 30, 35, 40, 45 and 50 Hz in addition to the original copy at 100 Hz. Time-series data were down-sampled using the built-in MATLAB[c] function 'resample' implementing a polyphase anti-aliasing filter to avoid side effects occurring when the sample rate is below the Nyquist rate of twice the highest signal frequency (Nyquist frequency). Down-sampled tri-axial acceleration and orientation time-series were then re-upsampled to 100 Hz and fed into the validated process that first rotates tri-axial acceleration in the sensor reference frame into a horse-based reference frame and then highpass filters and numerically double-integrates from vertical acceleration to vertical displacement [11,17]. Re-upsampling results in time-series signals with the same number of data points as the original 100 Hz-signal and avoids differences in the numerical double-integration process simply related to a lower temporal resolution of the down-sampled signals.

Spectrograms (windowed fast-Fourier transformation) were plotted for the 100 Hz reference signals to illustrate the frequency content in the time-series acceleration signal prior to down-sampling. Spectrograms were calculated with 128 points fast-Fourier transform from Hamming windows representing 640 ms of vertical acceleration data each (approximately the length of a stride period in a trotting horse), each window shifted by 4ms along the time axis between adjacent windows. The power spectral density in dB was colour-coded for graphical display.

Root mean square errors were calculated comparing the time-series signals of vertical displacement for each of the nine down-sampled signals to the original time-series signal. The first and last 200 samples of each data file were excluded from analysis to avoid boundary effects of the 1 Hz highpass filter used during the integration process influencing the comparison as documented previously [18].

In addition, accuracy (mean difference) and precision (standard deviation of differences) [19] were calculated for 50 displacement minima and maxima identified from each displacement-time-series signal to document the influence of sample rate on parameters commonly assessed in trotting horses in a clinical context.

Results

The four data files contained time-series of N=[2284, 2267, 2162, 2623] samples recorded at the original sample rate of 100 Hz. Figure 1 shows the vertical pelvis displacement (first 2000 samples, i.e. first 20 seconds) for each horse illustrating the cyclical nature of the data interspersed with some non-cyclical events (e.g. horse 2: around sample 700 and between 1400 and 1600 or horse 4: at around sample 1000 and 1200), which are related to imperfect cyclical movements, e.g. variations in footfall patterns or changes in speed, which are common in kinematic recordings of animal movement. Movement asymmetry values of the four horses showed mean (standard deviation) values of 5.2 (4.0) mm, 10.4 (8.5) mm, 21.5 (11.3) mm and 17.6 (11.7) mm for horses 1 to 4 for absolute differences between subsequent displacement maxima and values of 11.5 (6.2) mm, 14.5 (10.5) mm, 12.1 (5.1) mm and 8.5 (6.5) mm for absolute difference between subsequent displacement minima.

From Figure 2, it can be appreciated, that the majority of signal power (yellow and orange colour) is limited to frequency bands below approximately 10 Hz. This suggests that differences between the original time-series signal and down-sampled versions can be expected to increase when the sample rate is reduced below the Nyquist rate of 20 Hz for signal components at 10 Hz or below.

Table 1 shows the RMS errors obtained when comparing time-series of down-sampled signals between 8 and 50 Hz to the original 100 Hz signal. With rates of 40 Hz, the errors of 1.6 to 3.5 mm, are in the region of previously suggested asymmetry thresholds of 3 mm for pelvic movement asymmetry in lame horses [16], which coincide with values obtained for repeat assessments and with values of stride-to-stride variability in trotting horses [20]. Figure 3 further illustrates the RMS error as a function of reduced sample rate and specifically highlights a step increase in RMS error for sample rates of 20 Hz and below with a major increase observable between 15 Hz and 10 Hz.

Table 2 provides values for accuracy and precision [19] between the minima and maxima identified in the original 100 Hz time-series and the minima and maxima identified from the down-sampled signals. Accuracy is – with the exception of 8 Hz sample rate – consistently below 1 mm. Precision shows a reduction from values above 10 mm, observed at the lower sample rates to values of approximately 5 mm at 25 Hz and to below 3 mm at 40 Hz and above.

Discussion:

Reference sample rate

This technical note quantifies the errors related to a reduction in sample rate when processing time-series data of a pelvis mounted inertial measurement unit. With a rate of 100 Hz, the sample rate is well above the maximum signal frequency of interest of 4 Hz, i.e. the estimated maximum value of step frequency assuming a trot stride frequencies of up to 2Hz [1]. It is also well above the theoretical minimum sample rate of 8 Hz for capturing a 4 Hz signal component according to the Nyquist theorem.

The sample rate of 100 Hz used here, is however only half the value of the commonly used sample rate of 200 Hz for accelerometer based asymmetry measurement in trotting horses [16,20]. Should we hence have used a higher sample rate as our reference rate? Previous validation studies indicate reasonable agreement with sensor based measurements and optical motion capture when conducted at 50-100 Hz [6–8,11]. In addition, published evidence suggests that time-series signals of vertical upper body position across the back of trotting horses can be reconstructed with very high accuracy (>99%) with only the first two harmonics of a Fourier decomposition [2]. Thus, a sample rate of 100 Hz is well above what is needed for an accurate signal representation. In support of this, here, a windowed fast-Fourier analysis (see Figure 2) of the reference acceleration time-series signal illustrates that approximately 95% of the signal power is located in frequency bands up to 10 Hz. A sample rate above the Nyquist rate of 20 Hz for a 10 Hz signal component should hence capture the major signal components. This is confirmed by the observed step change in RMS error when reducing the sample rate from 25 Hz to 20 Hz (Figure 3, Table 1). As such our reference sample rate of 100 Hz is adequate.

<u>Origin of 4 to 10 Hz signals</u>

Based on the spectrograms (Figure 2), it is clear that considerable amounts of signal power are contained in frequency bands above 4z. Where do these signals with frequencies above the step frequency originate from?

First, biological signals generally deviate from perfectly cyclical, sine wave like signals which can be clearly seen in Figure 1. Deviations from a perfectly cyclical signal can only be reconstructed with higher frequency sine waves: symmetry indices derived from frequency analysis of trunk-mounted tri-axial accelerometers indicate that 8-10 harmonics are needed to characterize asymmetry parameters (adding further harmonics does not increase the quality of the reconstruction [21]). Assuming a maximum stride frequency of around 2 Hz [1], the first ten harmonics capture signal frequencies of up to 20 Hz. Our data indicate the first step change in RMS error when reducing the sample rate to 20 Hz, indicating that frequencies up to approximately 10 Hz, i.e. lower than indicated previously [21], are critical components relating to the shape of the signal.

Second, attachment of the sensor to the skin as well as skin movement itself may also contribute frequency components above the step frequency. Quantitative analysis of skin movement (in limb-mounted markers) shows signal shapes with more than the two minima and maxima per stride cycle [22] that would be expected as a results of step frequency. Here, the sensor was mounted more proximal (over the sacrum) and further studies need to investigate to what extent skin movement and attachment may contribute to higher frequency components.

Finally, internal sensor noise may also be present [9].

<u>What is the minimum sample rate required?</u>

The most interesting question in the context of sample rate appears to be: how much error is too much error? This depends on the clinical or research question that needs answering. Here we concentrate on the sacrum, a popular location for quantifying movement symmetry in the context of lameness [10,16,20,23,24].

When reducing the sample rate to 50 Hz, a sample rate that is well within the reach of many consumer grade devices such as smartphones used for gait analysis in horses and humans [3–7,10], values of 1-2 mm were reported here for RMS errors of the time-series signal as well as for the precision of maxima and minima. These values are within the reported values in the region of 3 mm for 95% confidence intervals for repeat assessments, stride-to-stride variability and asymmetry thresholds for lame horses established with a commonly used accelerometer based system [16,20]. Our results thus suggest that reducing the sample rate to 50 Hz has very minor consequences.

A further reduction in the data rate to 40 Hz increases the error to up to 4mm. This value is above the 3 mm threshold [16] for mild lameness suggesting that the influence of such reduced sample rates needs to be considered carefully when dealing with horses displaying mild asymmetries However, the values are still smaller than for example within- or between-day variation in Thoroughbred racehorses in training and asymmetry values identified in Thoroughbred racehorses with lameness [23,24]. It is thus important to consider the intended application when considering whether a specific sample rate, which may be the maximum rate a particular device can achieve, is indeed sufficient.

Finally, error rates increase further when reducing the sample rate below 40 Hz and undergo a step change when the sample rate is reduced to 20 Hz, then resulting in unacceptably high error rates even for less ‘stringent’ applications [23,24].

Beyond sample rate

It is worth mentioning that in general appropriate filtering techniques also need to be considered to remove low frequency components from the signal, ideally minimizing edge effects, i.e. signal distortions occurring near the beginning and the end of a time-series signal [18]. Here we have used a 1 Hz highpass filter as previously validated and used in a comparison study between the sensors used here and a smartphone sensor [10,11].

The human eye

Clinically, lameness is commonly assessed “by eye”. Can we compare the temporal resolution of the human eye with the sample rate of digital devices? The human eye-brain combination is not a digital system: as such the Nyquist theorem does not apply. The temporal resolution of the human eye is best described by the critical flicker fusion frequency (CFF), i.e. the frequency below which we can perceive a flickering image as such. This is not a constant value and is influenced by many variables, such as colour, intensity, retinal location etc [25,26]. The CFF ranges from approximately 20 to 60 Hz. This suggests that human visual perception is becoming ‘blurry’ (in a temporal sense) for movements with components above the relevant CFF value. This is a ‘desired effect’ in television screens, where the image frequency (frame rate) is above the CFF so we cannot perceive the flickering.

With our reference sample rate of 100 Hz, which resolves frequency components of up to 50 Hz in our digital system, we are operating in an area that is similar to the temporal resolution of the human visual system under ‘ideal’ conditions (CFF up to 60 Hz). The fact, that the first step change in error when reducing the sample rate occurs at a sample rate of around 20 Hz, indicates that components up to approximately 10 Hz are important contributors to the signal shape. This is clearly below the CFF of the human eye, even in non-optimal conditions, and suggests that the temporal resolution of the human eye is not a limiting factor in visual lameness assessment. Other factors, such as the spatial resolution may be more important with previous studies suggesting a value of 20-25% movement asymmetry being required for a reliable detection [27].

Conclusion:

We have shown that reducing the sample rate from 100 Hz to 50 Hz results in negligible time-series RMS errors and acceptable precision of signal minima and maxima. The values of 1 to 2 mm are smaller than previously suggested asymmetry thresholds and stride-to-stride and between-trial variability. Hence, consumer-grade smartphones or other devices capable of sustained 50 Hz sampling of accelerometer data may be appropriate for quantifying clinically relevant upper body movement (here: pelvic movement) asymmetries in trotting horses. Of course, in addition to sample rate, other factors such as the accuracy and precision of the calibrated acceleration range of a sensor plays a role when calculating displacement from acceleration and this needs to be investigated. A further reduction in sample rate to below 50 Hz may be considered on a case by case basis depending on the required accuracy and precision for each intended application: in the 4 horses investigated here, mean RMS errors then increase to 3 mm or more questioning the use of sample rates below 50 Hz for quantifying movement asymmetry in mildly lame horses. Sample rates of 20 Hz and below generally appear inadequate for most animal movement related applications.

A comparison of the measured signal frequencies to the critical flicker fusion frequency of the human eye indicates that temporal resolution of the human eye may not be the limiting factor in visual assessment of lameness.

Manufacturer Addresses

[a] Xsens, Enschede, The Netherlands

[b] Microsoft, Redmond, WA, USA

[c] The Mathworks Inc, Natick, MA, USA

Figure legends

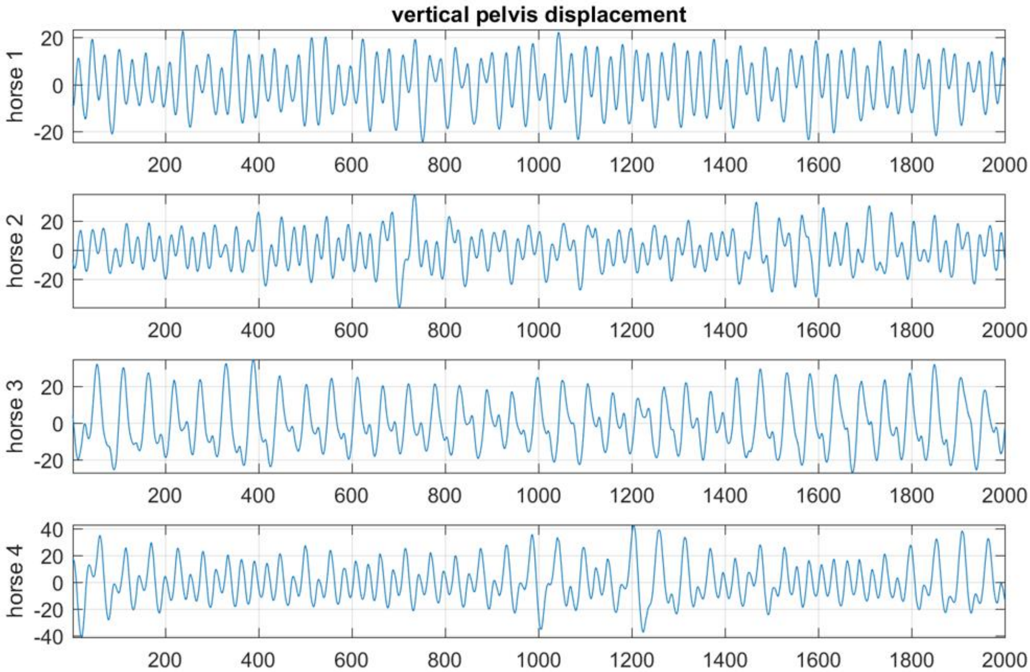

Figure 1: Vertical pelvis displacement (in mm) of four trotting horses calculated from tri-axial acceleration and 3D orientation data (from sensor fusion of IMU data streams) recorded with a wireless inertial sensor (MTw, Xsens) following established protocols at a sample rate of 100 Hz [17].

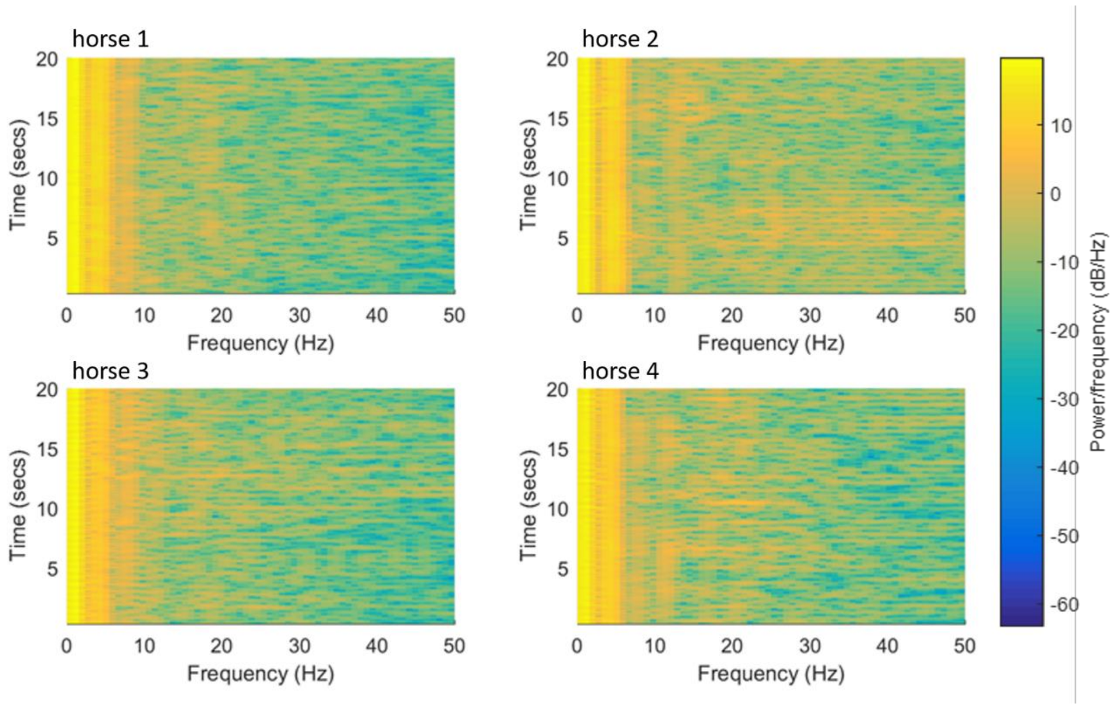

Figure 2: Spectrograms of the first 20 seconds (2000 samples) of the vertical acceleration signal measured from a pelvis-mounted inertial sensor (MTw, Xsens) recorded at 100 Hz from four trotting

horses. The power spectral density in dB (see legend for colour-code is given between 0 and 20 seconds and frequency bands between 0 and 50 Hz. Each panel represents data from one horse (top left: horse 1, top right: horse 2, bottom left: horse 3, bottom right: horse 4), with each horse showing somewhat different movement patterns and amounts of movement symmetry.

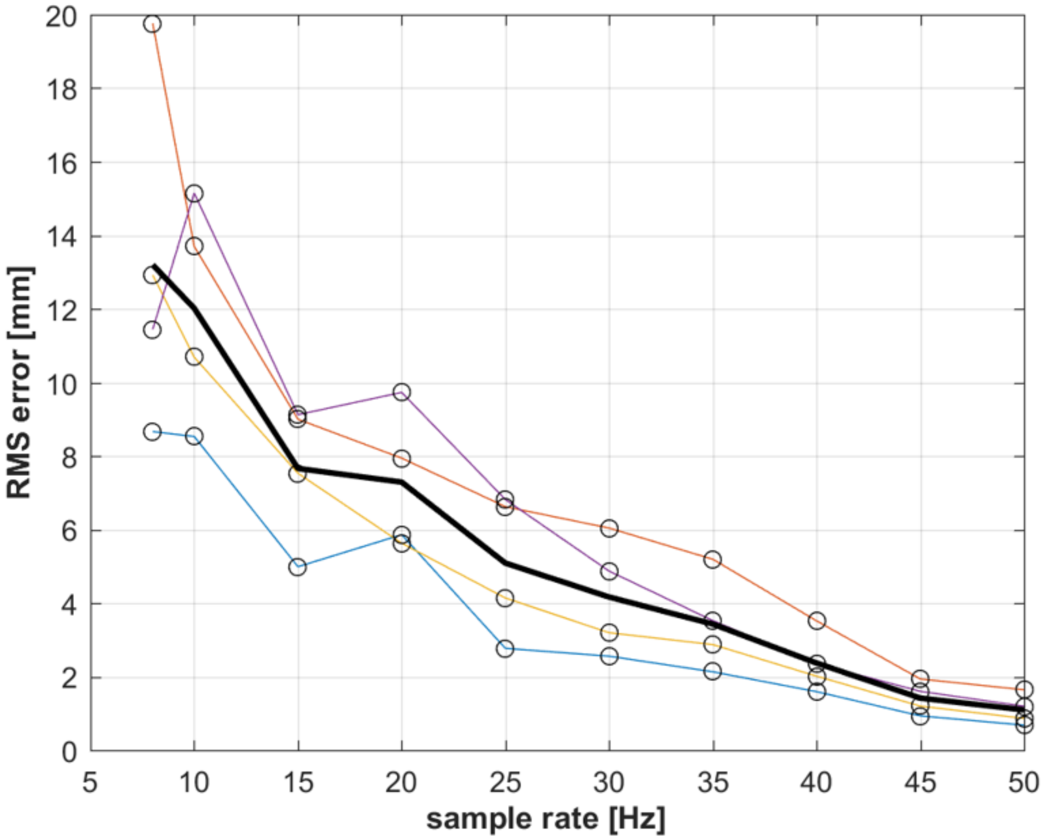

Figure 3: Root mean square (RMS) error in mm as a function of sub-sampling rate achieved for calculation of vertical pelvic movement from inertial sensor data sampled at 100 Hz. A clear increase in RMS error can be observed when the sample rate drops to values of 20 Hz and below.

Tables:

Table 1: Root mean square (RMS, standard deviation of the differences between the original and the down sampled signal) errors (in mm) between the vertical displacement calculated from down-sampled signals compared to the original signal sampled at 100Hz. Given are the RMS values for each data set as well as the mean and the standard deviation across the four horses: H1-H4: horse 1 to 4.

	8 Hz	**10 Hz**	**15 Hz**	**20 Hz**	**25 Hz**	**30 Hz**	**35 Hz**	**40 Hz**	**45 Hz**	**50 Hz**

H1	8.7	8.5	5.0	5.9	2.8	2.6	2.1	1.6	0.9	0.7
H2	19.8	13.7	9.0	7.9	6.6	6.0	5.2	3.5	1.9	1.6
H3	12.9	10.7	7.5	5.6	4.1	3.2	2.9	2.0	1.2	0.9
H4	11.4	15.1	9.1	9.7	6.8	4.9	3.5	2.3	1.6	1.2
Mean (SD)	13.2 (4.7)	12.0 (3.0)	7.7 (1.9)	7.3 (1.9)	5.1 (2.0)	4.2 (1,6)	3.4 (1.8)	2.4 (0.8)	1.4 (0.4)	1.1 (0.4)

Table 2: Accuracy (Acc., mean difference in mm) and precision (Prec., standard deviation of differences in mm) for maxima (max) (or minima (min)) determined from data sampled at 100 Hz subtracted from down-sampled data at rates between 8 and 50 Hz (column headers labelled with sample rate values used during down sampling). Values (in mm) are based on N=200 minima and maxima withthe 200 values originating from N=50 values per horse.

		8 Hz	**10 Hz**	**15 Hz**	**20 Hz**	**25 Hz**	**30 Hz**	**35 Hz**	**40 Hz**	**45 Hz**	**50 Hz**
min	Acc.	3.2	-0.2	0.3	-0.3	-0.03	0.2	0.1	-0.04	0.04	-0.05
	Prec.	11.4	11.2	6.7	6.0	4.2	4.0	3.0	2.0	1.2	0.9
max	Acc.	-3.9	-0.5	0.1	0.2	0.02	0.03	0.03	-0.07	-0.02	0.08
	Prec.	13.9	14.1	9.2	8.9	6.5	5.4	4.1	2.8	1.6	1.2

List of References

1. Hoyt, D.F., Wickler, S.J., Dutto, D.J., Catterfeld, G.E. and Johnsen, D. (2006) What are the relations between mechanics, gait parameters, and energetics in terrestrial locomotion? *J. Exp. Zool.* **305A**, 912–922.

2. Audigié, F., Pourcelot, P., Degueurce, C., Geiger, D. and Denoix, J.M. (2002) Fourier analysis of trunk displacements: a method to identify the lame limb in trotting horses. *Journal of biomechanics* **35**, 1173–1182.

3. Manor, B., Yu, W., Zhu, H., Harrison, R., Lo, O.-Y., Lipsitz, L., Travison, T., Pascual-Leone, A. and Zhou, J. (2018) Smartphone App–Based Assessment of Gait During Normal and Dual-Task Walking: Demonstration of Validity and Reliability. *JMIR Mhealth Uhealth* **6**, e36.

4. Ellis, R.J., Ng, Y.S., Zhu, S., Tan, D.M., Anderson, B., Schlaug, G. and Wang, Y. (2015) A Validated Smartphone-Based Assessment of Gait and Gait Variability in Parkinson's Disease. *PLoS ONE* **10**, e0141694.

5. Nishiguchi, S., Yamada, M., Nagai, K., Mori, S., Kajiwara, Y., Sonoda, T., Yoshimura, K., Yoshitomi, H., Ito, H., Okamoto, K., Ito, T., Muto, S., Ishihara, T. and Aoyama, T. (2012) Reliability and Validity of Gait Analysis by Android-Based Smartphone. *Telemedicine and e-Health* **18**, 292–296.

6. Furrer, M., Bichsel, L., Niederer, M., Baur, H. and Schmid, S. (2015) Validation of a smartphone-based measurement tool for the quantification of level walking. *Gait & Posture* **42**, 289–294.

7. Steins, D., Sheret, I., Dawes, H., Esser, P. and Collett, J. (2014) A smart device inertial-sensing method for gait analysis. *Journal of Biomechanics* **47**, 3780–3785.

8. Mourcou, Q., Fleury, A., Franco, C., Klopcic, F. and Vuillerme, N. (2015) Performance Evaluation of Smartphone Inertial Sensors Measurement for Range of Motion. *Sensors* **15**, 23168–23187.

9. Jarchi, D., Pope, J., Lee, T.K.M., Tamjidi, L., Mirzaei, A. and Sanei, S. (2018) A Review on Accelerometry-Based Gait Analysis and Emerging Clinical Applications. *IEEE Rev. Biomed. Eng.* **11**, 177–194.

10. Pfau, T. and Weller, R. (2017) Comparison of a standalone consumer grade smartphone to a specialist inertial measurement unit for quantification of movement symmetry in the trotting horse. *Equine Veterinary Journal* **49**, 124–129.

11. Warner, S.M., Koch, T.O. and Pfau, T. (2010) Inertial sensors for assessment of back movement in horses during locomotion over ground. *Equine Veterinary Journal* **42 Suppl 3**, 417–424.

12. van Weeren, P.R., Pfau, T., Rhodin, M., Roepstorff, L., Serra Bragança, F. and Weishaupt, M.A. (2017) Do we have to redefine lameness in the era of quantitative gait analysis? *Equine Veterinary Journal* **49**, 567–569.

13. Bathe, A., Judy, C.E. and Dyson, S.J. (2018) Letter to the Editor : Do we have to redefine lameness in the era of quantitative gait analysis ? *Equine Veterinary Journal* **50**, 273.

14. Adair, S., Baus, M., Belknap, J., Bell, R., Boero, M., Bussy, C., Cardenas, F., Casey, T., Castro, J., Davis, W., Erskine, M., Farr, R., Fischer, T., Forbes, B., Ford, T., Genovese, R., Gottschalk, R., Hoge, M., Honnas, C., Hunter, G., Joyce, J., Kaneps, A., Keegan, K., Kramer, J., Lischer, C., Marshall, J., Oosterlinck, M., Radue, P., Redding, R., Reed, S.K., Rick, M., Santschi, E., Schoonover, M., Schramme, M., Schumacher, J., Stephenson, R., Thaler, R., Vedding Neilsen, J. and Wilson, D.A. (2018) Response to Letter to the Editor : Do we have to redefine lameness in the era of quantitative gait analysis. *Equine Veterinary Journal* **50**, 415–417.

15. van Weeren, R. (2019) Letter to the Editor: On the origin of lameness - do opinions differ less than it might appear at first glance? *Equine Vet J.* **51**, 557–558.

16. McCracken, M.J., Kramer, J., Keegan, K.G., Lopes, M., Wilson, D.A., Reed, S.K., LaCarrubba, A. and Rasch, M. (2012) Comparison of an inertial sensor system of lameness quantification with subjective lameness evaluation. *Equine Veterinary Journal* **44**, 652–656.

17. Pfau, T., Witte, T.H. and Wilson, A.M. (2005) A method for deriving displacement data during cyclical movement using an inertial sensor. *The Journal of experimental biology* **208**, 2503–2514.

18. Serra Bragança, F.M., Roepstorff, C., Rhodin, M., Pfau, T., van Weeren, P.R. and Roepstorff, L. (2020) Quantitative lameness assessment in the horse based on upper body movement symmetry: The effect of different filtering techniques on the quantification of motion symmetry. *Biomedical Signal Processing and Control* **57**, 101674.

19. Bland, J.M. and Altman, D.G. (1986) Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* **1**, 307–10.

20. Keegan, K.G., Kramer, J., Yonezawa, Y., Maki, H., Pai, P.F., Dent, E.V., Kellerman, T.E., Wilson, D.A. and Reed, S.K. (2011) Assessment of repeatability of a wireless inertial sensor-based lameness evaluation system for horses. *American Journal of Veterinary Research* **72**, 1156–1163.

21. Halling Thomsen, M., Tolver Jensen, A., Sørensen, H., Lindegaard, C. and Haubro Andersen, P. (2010) Symmetry indices based on accelerometric data in trotting horses. *Journal of biomechanics* **43**, 2608–12.

22. van Weeren, P.R., van den Bogert, A.J. and Barneveld, A. (1990) A quantitative analysis of skin displacement in the trotting horse. *Equine Veterinary Journal. Supplement* **22**, 101–109.

23. Pfau, T., Caviedes, M.F.S., Mccarthy, R., Cheetham, L., Forbes, B. and Rhodin, M. (2018) Comparison of visual lameness scores to gait asymmetry in racing Thoroughbreds during trot in-hand. *Equine Veterinary Education* **32**, 191–198.

24. Sepulveda Caviedes, M.F., Forbes, B.S. and Pfau, T. (2018) Repeatability of gait analysis measurements in Thoroughbreds in training. *Equine Veterinary Journal* 1–6.

25. Brenton, R.S., Thompson, H.S. and Maxner, C. (1989) Critical Flicker Frequency: A New Look at an Old Test. In: *New Methods of Sensory Visual Testing*, Eds: M. Wall and A.A. Sadun, Springer New York, New York, NY. pp 29–52. https://doi.org/10.1007/978-1-4613-8835-7_3.

26. Hecht, Selig and Shlaer, Simon (1936) Intermittent stimulation by light: the relation between intensity and critical frequency for different parts of the spectrum. *J. Gen. Physiol.* **19**, 965–977.

27. Parkes, R.S.V., Weller, R., Groth, a. M., May, S. and Pfau, T. (2009) Evidence of the development of 'domain-restricted' expertise in the recognition of asymmetric motion characteristics of hindlimb lameness in the horse. *Equine Veterinary Journal* **41**, 112–117.