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Short communication

Stride frequency derived from GPS speed fluctuations in galloping horses

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ABSTRACT

Changes in gallop stride parameters prior to injury have been documented previously in Thoroughbred racehorses. Validating solutions for quantification of fundamental stride parameters is important for large scale studies investigating injury related factors. This study describes a fast Fourier transformation-based method for extracting stride frequency (SF) values from speed fluctuations recorded with a standalone GPS-logger suitable for galloping horses. Limits of agreement with SF values derived from inertial measurement unit (IMU) pitch data are presented. Twelve Thoroughbred horses were instrumented with a GPS-logger (Vbox sport, Racelogic, 10 Hz samplerate) and a IMU-logger (Xsens DOT, Xsens, 120 Hz samplerate), both attached to the saddlecloth in the midline caudal to the saddle and time synchronized by minimizing root mean square error between differentiated GPS and IMU heading. Each horse performed three gallop trials with a target speed of 36 miles per hour (16.1 ms^{-1}) on a dirt racetrack. Average speed was 16.48 ms^{-1} ranging from 16.1 to 17.4 ms^{-1} between horses. Limits of agreement between GPS- and IMU-derived SF had a bias of 0.0032 Hz and a sample-by-sample precision of +/−0.027 Hz calculated over N = 2196 values. The stride length uncertainty related to the trial-by-trial SF precision of 0.0091 Hz achieved across 100 m gallop sections is smaller than the 10 cm decrease in stride length that has been associated with an increased risk of musculoskeletal injury. This suggests that the described method is suitable for calculating fundamental stride parameters in the context of injury prevention in galloping horses.

1. Introduction

Morbidity and mortality associated with musculoskeletal injury (MSI) is a major issue in racehorses (Verheyen, 2013). A recent study analyzed stride characteristics during racing together with race outcome and injury data and identified an association between a decrease in speed and stride length (SL) – but not stride frequency (SF) – and an increased risk of MSI, with stride characteristics markedly changing approximately 6 races prior to injury (Wong et al., 2022). Specifically, an increased risk of MSI by a factor of 1.18 was found per 0.1 m/s decrease in speed and of 1.11 per 10 cm decrease in SL. Stride characteristics were extracted with a combination of a global positioning system (GPS) receiver and an inertial measurement unit (IMU) (Wong et al., 2022): typically GPS speed sampled with a low update rate (e.g. 5 Hz) is combined with SF data calculated from high update rate IMU data (e.g. 800 Hz) by extracting the periodicity of one of the IMU's signals (Morrice-West et al., 2020). When average speed and SF are known, SL can be calculated according to.

(1) speed = SF × SL.

In a galloping horse, the fundamental signal frequency, i.e. the frequency that allows identifying a repetitive pattern in acceleration, velocity and displacement signals (see for example (Pfau et al., 2006) is the SF. SF in a galloping horse reaches average values up to approximately 3 Hz (Vergara-Hernandez et al., 2022). Based on the Shannon-Nyquist theorem, a sample frequency of > 6 Hz (double the signal frequency of interest) is needed to accurately extract SF. In practice, often higher sample rates are required, for example when aiming to calculate movement asymmetry values from equine inertial sensor data (Pfau and Reilly, 2020). However, with appropriate signal processing it appears feasible to extract SF from modern GPS receivers sampling at 10 Hz or above.

The aim of this short communication is to describe a practical

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method – aimed at deployment in daily training – for extracting SF from speed fluctuations across gallop strides recorded via a commercial GPS-logger (Vbox Sport, Racelogic, USA)) with 10 Hz update rate and to calculate limits of agreement (Bland and Altman, 1986) between sample-by-sample and trial-by-trial SF values calculated from the GPS-derived speed values and from a commercial IMU-logger (Xsens DOT 2nd generation, Xsens, The Netherlands) with 120 Hz update rate. Here, we investigate whether a fast Fourier transformation (FFT) based method can identify SF from GPS speed with sufficient precision in the context of predicting MSI.

2. Materials and methods

Animal care and use approval for this study was obtained from the University of Calgary Animal Care Committee (AC21-0231). Informed, written consent was obtained from the owners/trainers of the horses prior to data collection.

2.1. Animals and data collection equipment

Twelve Thoroughbred geldings (age 8–15 years, body mass 456–554 kg) were equipped with a VBox Sport (Racelogic, USA, 130 g, 104.5 mm × 72.8 mm × 25.1 mm) GPS-logger sampling data at an update rate of 10 Hz onto a 8 GB SD storage card and a 2nd generation Xsens DOT IMU-logger (11.2 g, 36 × 30 × 11 mm, Xsens, The Netherlands, +/−2000 degrees/s, +/−16 g, +/−8 Gauss) sampling tri-axial linear accelerations, angular velocities, and Euler angles. The DOT sensor was configured via the Xsens DOT app running on an iPhone12 (Apple Inc, USA) to log data streams at 120 Hz update rate and to use the 'dynamic' version of the sensor fusion algorithm. Data logging was initiated approximately simultaneously for the GPS, by pressing the logging button, and for the IMU, via the iOS app; more accurate synchronization between the modalities was achieved through a root mean square error-based approach (described below); both loggers were then taped to the saddle cloth just caudal to the saddle. The jockey was equipped with a Garmin (fēnix 6) multisport GPS watch, which was set to display speed to allow the jockey to ride to an approximate target speed.

2.2. Data collection protocol

Each of the twelve horses was galloped by the experienced jockey along an oval track (Stampede grounds, Calgary) initiating the gallop at the apex of the curve and accelerating throughout the curve aiming to reach a target speed of 16.1 ms^{-1}, using the miles per hour speed display of the GPS watch (36 miles per hour) as a guideline, on the straight-line portion of the track. As part of a separate study, the dirt racing surface of the track had been prepared in three parallel lanes harrowed to different depths. Each horse performed three consecutive runs, one on each lane, in randomized order. After the last run, data logging was stopped and both loggers were transferred to the next horse. Data for different surface preparations were included here in an attempt to increase the range of SF values observed.

2.3. Data processing

GPS and IMU data were downloaded onto a laptop computer, using an SD card reader and a micro-USB cable plus the Xsens DOT data exporter for Windows software (Xsens, The Netherlands), respectively. GPS data were exported in text files with speed (in kmh^{-1}) with two decimal places and heading (in degrees) with one decimal place. IMU data were exported with Euler angles (in degrees) with 8 decimal places derived from 16-bit values of tri-axial acceleration (+/−16 times gravitational acceleration), tri-axial rate of turn (+/−2000 degrees s^{-1}) and tri-axial magnetic field data (+/−8 Gauss). Data processing then followed these steps in MATLAB (The Mathworks Inc., USA):

1. GPS and IMU data were time-synchronized by down-sampling IMU data (using a polyphase anti-aliasing filter) to match the 10 Hz GPS update rate, unwrapping and then differentiating heading data from both sensors (removing potential heading offsets between GPS and IMU) using a 1-second time window (10 samples) and then calculating the root mean square error between differentiated GPS and time-shifted differentiated IMU heading data over a range of time-shifts from −30 to + 30 s and identifying the best match (lowest root mean square error).
2. Based on the identified time-shift (step 1), matching portions of GPS and IMU data were identified. GPS location (latitude and longitude) and GPS speed information was used to identify a 6-second portion of straight-line gallop data. GPS latitude and longitude were plotted with GPS speed. A portion of the GPS data was selected where the location represented a progression of the horse in an approximately straight line and speed was found to be around the target speed. Then the matching IMU data were extracted using the time-shift between the two modalities.
3. Power spectrograms (windowed fast Fourier transformation, FFT) were used to localize the signal frequency with the maximum signal power in the frequency bands between 1.5 and 3 Hz (estimate of SF for galloping horses (Vergara-Hernandez et al., 2022)). The following settings were used:
   - o GPS speed spectrograms (Fig. 1a): a Hamming window of 64 samples (6.4 s @ 10 Hz) was shifted sample by sample over the 6-second GPS speed data (augmented by the 32 samples preceding and the 32 samples following the signal of interest). Please see Fig. 1d for an example of GPS speed data for one run of horse 12. A 1024-point FFT was implemented generating 513 power frequency values from 0 Hz to the Nyquist rate of 5 Hz resulting in a frequency resolution of approximately 0.0097 Hz. For each time window, the frequency band containing the maximum value for power frequency was determined and labelled as GPS-derived SF for each sample.
   - o IMU spectrograms (Fig. 1b-c): a Hamming window of 768 samples (6.4 s @ 120 Hz) was shifted sample by sample over the 6-second IMU pitch data (augmented by the 384 samples preceding and the 384 samples following the signal of interest). Please see Fig. 1e and Fig. 1f for an example of IMU acceleration and IMU orientation data channels for one run of horse 12. A 16384-point FFT was implemented generating 8193 power frequency values from 0 Hz to the Nyquist rate of 60 Hz resulting in a frequency resolution of approximately 0.007 Hz. For each time window, the frequency band containing the maximum value for power frequency was determined. Temporal resolution of the vector containing SF values over time was subsequently down sampled to 10 Hz to match the GPS update rate. The sub-sampled frequency band values were labelled as IMU-derived SF.

2.4. Data analysis

Average of GPS speed- and IMU-derived SF values were plotted against their differences and bias, and precision (Bland and Altman, 1986) calculated based on the differences between the GPS speed- and IMU-derived SF values as the mean difference value and mean difference value +/−1.96 × standard deviation of the differences, respectively. This was implemented on a sample-by-sample basis as well as for mean values calculated over each 6-second run (i.e. trial-by-trial).

3. Results

Average speed from GPS data across horses and track lanes – see Fig. 1d for GPS speed for one run of one horse – was 16.48 ms^{-1} (36.86 miles per hour), averaging 16.4 ms^{-1} on the inside and middle lanes and 16.6 ms^{-1} on the outside lane, ranging from 16.1 ms^{-1} to 17.4 ms^{-1} between horses (Table 1).

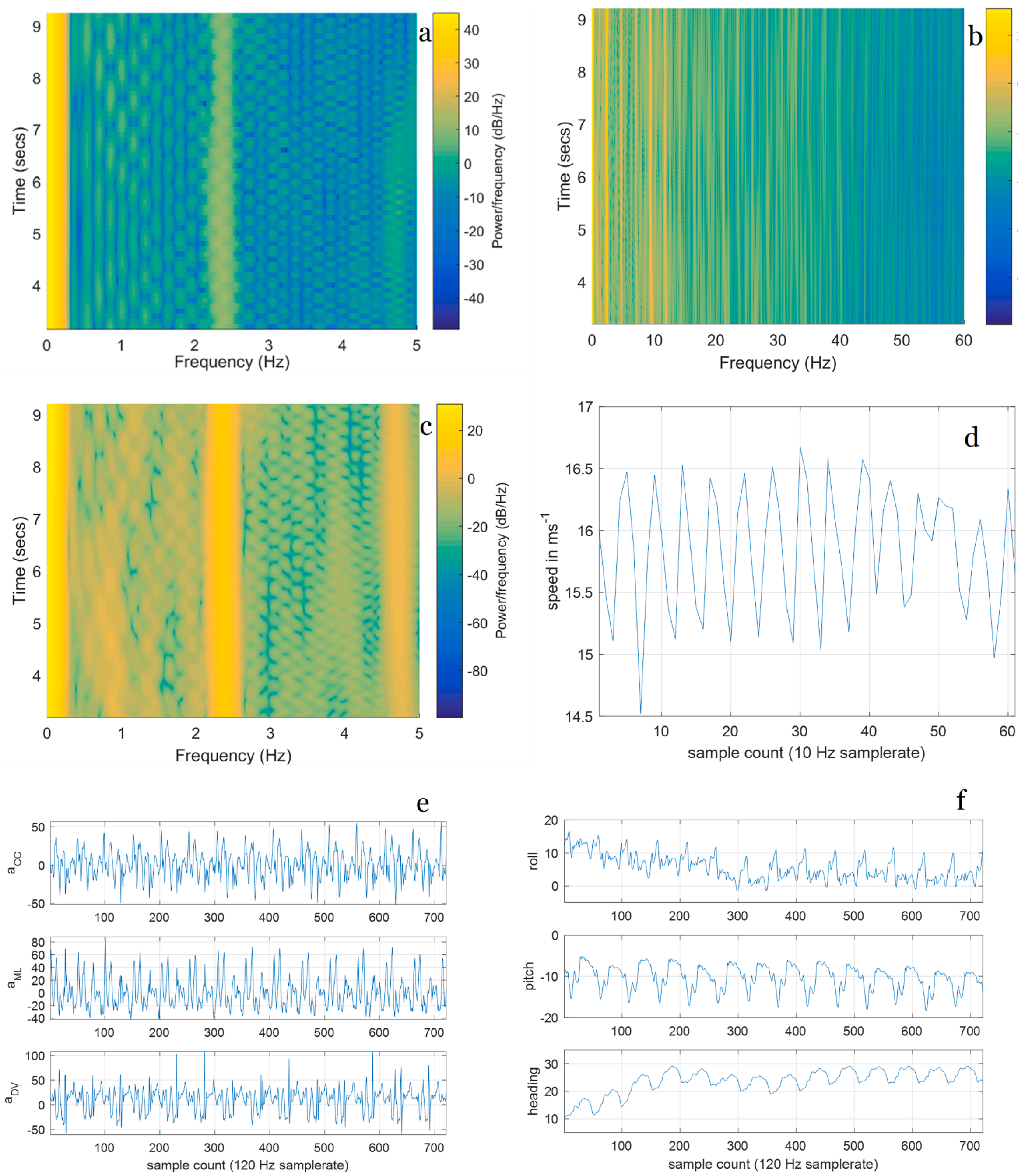

Fig. 1. Spectrogram for (a) GPS speed (b) IMU pitch data (both presented up to the Nyquist rate (5 Hz respectively 60 Hz) and (c) zoomed in version for IMU pitch data up to 5 Hz. (d) GPS speed over the time period corresponding to the GPS spectrogram y-axis in (a). (e) IMU acceleration in ms^{-2} (a_{CC}: craniocaudal, a_{ML}: mediolateral, a_{DV}: dorsoventral). (f) IMU orientation in degrees (roll: rotation CC axis, pitch: rotation around ML axis, heading: rotation around DV axis). Both (e) and (f) are plotted over the time period corresponding to the IMU spectrogram y-axes in (b) and (c). The spectrograms (a-c) provide an overview over the frequency-time distribution (x-axis: frequency, y-axis: time) of signal power (color coded from blue (lowest power) to yellow (highest) for 6-second signal portions (trials) collected during near constant speed, straight-line gallop on a dirt racetrack. At each time point, the frequency band, at which the maximum signal power is found within the frequency band ranging from 1.5 to 3 Hz (see materials and methods), corresponds to the SF value used for further analysis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Average SF across horses and track lanes was 2.46 Hz, averaging 2.48 Hz on the inside lane, 2.44 Hz on the middle lane and 2.45 Hz on the outside lane, ranging from 2.36 Hz to 2.64 Hz between horses (Table 2).

Average SL (Equation 1) across horses and track lanes was 6.72 m, averaging 6.63 m on the inside lane, 6.74 m on the middle lane and 6.80 m on the outside lane, ranging from 6.18 m to 7.29 m between horses (Table 3).

A total of N = 2196 values (61 values for 12 horses and 3 runs per horse) were used to calculate limits of agreement. Bias for GPS speed-derived SF was + 0.0032 Hz (positive sign indicating higher values for GPS speed-derived SF), sample-by-sample precision was 0.0271 Hz resulting in a lower limit of agreement of −0.0498 Hz and an upper limit of agreement of + 0.0562 Hz (Fig. 2). Trial-by-trail precision calculated from average SF values across 6 s (60 samples) or approximately 100 m of gallop exercise was 0.0091 Hz.

Table 1
Average speed in ms^{-1} for N = 12 horses performing one gallop run on each of three lanes (inside, middle, outside) harrowed to different depths on a dirt-type racing surface to a target speed of 16.1 ms^{-1}.

horse	inside	middle	outside	*average*
1	16.03	15.93	16.60	*16.19*
2	16.45	15.96	16.67	*16.36*
3	15.87	16.75	16.38	*16.33*
4	15.71	16.91	16.10	*16.24*
5	15.90	15.92	16.45	*16.09*
6	16.55	16.10	16.16	*16.27*
7	16.64	16.66	17.06	*16.78*
8	16.76	16.54	16.92	*16.74*
9	16.34	16.72	16.70	*16.58*
10	17.51	17.25	17.31	*17.35*
11	16.86	16.42	16.74	*16.68*
12	16.14	15.96	16.30	*16.13*
average	*16.40*	*16.43*	*16.62*	***16.48***

Table 2
Average SF in Hz for N = 12 horses performing one gallop run on each of three lanes (inside, middle, outside) harrowed to different depths on a dirt-type racing surface to a target speed of 16.1 ms^{-1}.

Horse	inside	middle	outside	*Average*
1	2.50	2.40	2.47	*2.46*
2	2.67	2.61	2.65	*2.64*
3	2.42	2.48	2.38	*2.43*
4	2.40	2.47	2.39	*2.42*
5	2.62	2.54	2.66	*2.61*
6	2.38	2.34	2.35	*2.36*
7	2.53	2.47	2.45	*2.48*
8	2.54	2.48	2.53	*2.52*
9	2.39	2.35	2.37	*2.37*
10	2.42	2.37	2.36	*2.38*
11	2.47	2.37	2.38	*2.41*
12	2.40	2.40	2.39	*2.40*
average	2.48	2.44	2.45	***2.46***

Table 3
Average SL in m for N = 12 horses performing one gallop run on each of three lanes (inside, middle, outside) harrowed to different depths on a dirt-type racing surface to a target speed of 16.1 ms^{-1}.

horse	inside	middle	outside	*average*
1	6.41	6.63	6.72	*6.59*
2	6.16	6.12	6.29	*6.19*
3	6.56	6.76	6.88	*6.73*
4	6.56	6.84	6.75	*6.72*
5	6.07	6.29	6.18	*6.18*
6	6.96	6.87	6.89	*6.91*
7	6.58	6.75	6.97	*6.77*
8	6.59	6.66	6.68	*6.65*
9	6.84	7.11	7.05	*7.00*
10	7.25	7.28	7.33	*7.29*
11	6.84	6.93	7.03	*6.93*
12	6.72	6.66	6.81	*6.73*
average	*6.63*	*6.74*	*6.80*	***6.72***

4. Discussion

This study is presenting a method for extracting SF data from GPS speed recorded with a commercial GPS-logger sampling data at a 10 Hz update rate. Sample-by-sample agreement between the GPS speed-derived SF values and IMU-derived SF values from a commercial IMU-logger providing IMU data at an update rate of 120 Hz indicate a low bias of 0.0032 Hz (a 0.13 % error at the average SF of 2.46 Hz), a precision of 0.027 Hz (or 1.1 % around the average of 2.46 Hz) and a lower and upper limit of agreement of −0.0498 and + 0.0562 Hz. No apparent increase or decrease in agreement over the range of SF values (approximately 2.2 to 2.7 Hz) was observed.

As always with limits of agreement analysis (Bland and Altman, 1986), the limits of agreement need to be put into the context of the size of relevant 'effects' of for example clinical or biological significance. As an example, at the average speed of 16.48 ms^{-1} a deviation by +/−0.027 Hz (the sample-by-sample precision of our method) around the average value of 2.46 Hz results in SL varying around the average of 6.70 m between 6.63 m and 6.77 m, i.e. by +/−7 cm or just above 1 %. Since each horse contributes multiple, non-independent, values to the data set, the calculated precision values are an underestimation (Bland and Altman, 2007). However, calculating ten SF values per second (i.e. at the GPS sample rate) is not a realistic requirement for many applications. For example, a study which has associated SL and speed changes with injury (Wong et al., 2022) utilized data summarized over the final 200 m segment during racing. When calculating agreement trial-by-trial (i.e. averaged over 6 s (60 samples) or just under 100 m of gallop), the precision for GPS speed-derived SF decreased to 0.0091 Hz (0.4 %) associated with an SL uncertainty of +/−2.5 cm. In comparison to the reported decrease of 10 cm (Wong et al., 2022), the 10 Hz GPS-logger used here provides sufficiently precise stride parameter estimates for injury monitoring utilizing GPS speed fluctuations to estimate SF.

Accuracy of GPS speed also needs to be considered. At comparatively low constant speed, errors of 0.07+/−0.01 ms^{-1} have been reported with a 7 Hz GPS logger (Akkamis et al., 2021). Under more variable conditions (cross-country skiing track, including curves, inclines and speed changes), errors of 0.38 ms^{-1} were reported with a 10 Hz GPS unit. Further experiments should quantify the limits of agreement (Bland and Altman, 1986) between GPS speed and a gold standard device under the exact conditions investigated here, i.e. for gallop at constant average speed over multiple seconds. A 'practical validation' of calcuated stride parameters using GPS speed (sampled at 5 Hz) and accelerometer data (sampled at 800 Hz) (Morrice-West et al., 2020; Wong et al., 2022) shows that, under similar conditions, changes in stride parameters over race progression or for predicting injuries across multiple races can be extracted.

In contrast to previous work investigating variation of stride parameters from a combination of GPS and IMUs (Morrice-West et al., 2020), with the present approach, no IMU is needed. When choosing a GPS-logger, an update rate of at least 6 Hz is required for the presented approach, since the maximum detectable SF is limited by the Shannon-Nyquist theorem to half the sample rate and SF values of up to just under 3 Hz have been reported (Vergara-Hernandez et al., 2022). Accuracy and precision of GPS speed depend on average speed, speed profile (constant speed, net acceleration, net deceleration), satellite numbers and their constellation and sample rate (Akkamis et al., 2021; Gløersen et al., 2018; Witte and Wilson, 2004). Since errors decrease with increasing sample rate (Akkamis et al., 2021; Gløersen et al., 2018), a logger exceeding the sample rate required by the Shannon-Nyquist theorem appears advantageous. Monitoring the number of satellites (here averaging 11.98 satellites across all recordings) is also important, since average errors increase with decreasing satellite numbers (Witte and Wilson, 2004).

Adding an IMU for validation purposes is not difficult though, and here we used a simple root mean square error method to synchronize differentiated GPS and IMU data. We used IMU pitch data for calculating SF and comparing GPS and IMU-based SF values. Likely, any of the accelerometer or orientation data channels of the IMU would have resulted in similar results since all IMU channels show a similar periodicity (see Fig. 1e and 1f). However, this was not further investigated.

IMU data were sampled at 120 Hz, allowing extraction of signal components up to 60 Hz and thus clearly exceeding gallop stride frequencies (Vergara-Hernandez et al., 2022). Discrepancies between the internal IMU clocking and GPS clocking could have contributed to the bias of 0.0032 Hz since frequency estimates depend on the exact sample frequency. GPS calculations are inherently relying on timing differences between multiple signals, hence, it appears likely that GPS clocking is

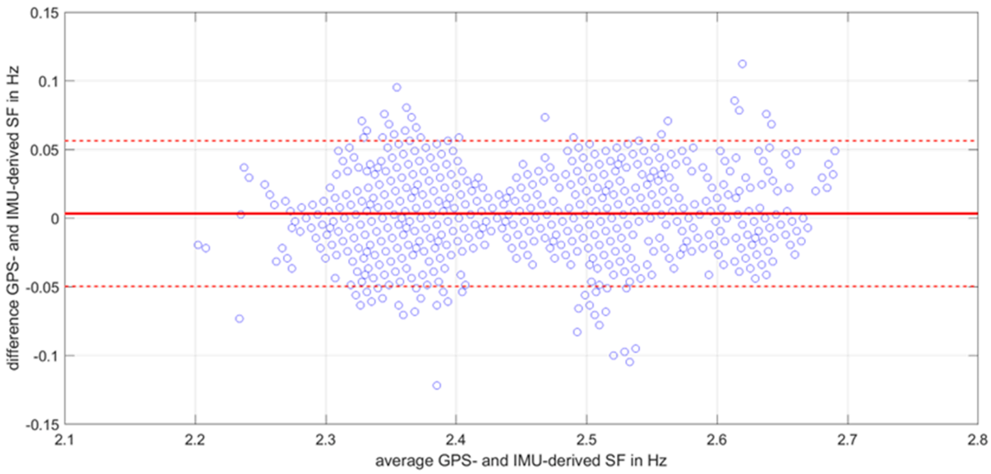

Fig. 2. Scatter plot of average and difference (Bland and Altman, 1986) for sample-by-sample GPS- and IMU-derived SF values calculated for three gallop runs of twelve horses on a dirt racing surface. Presented are N = 2196 SF data points resulting in a bias of 0.0032 Hz (red solid line), a precision (standard deviation of differences) of 0.027 Hz and lower and upper limits of agreement (red dashed lines) of −0.0498 and +0.0562 Hz. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

accurate.

CRediT authorship contribution statement

Thilo Pfau: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, study design, data collection and critical revision of the manuscript, implemented data analysis and has drafted the initial version of the manuscript. **Olivia Bruce:** Writing – review & editing, Data curation, Conceptualization, study design, data collection and critical revision of the manuscript. **W. Brent Edwards:** Writing – review & editing, Data curation, Conceptualization, study design, data collection and critical revision of the manuscript. **Renaud Leguillette:** Writing – review & editing, Data curation, Conceptualization, study design, data collection and critical revision of the manuscript.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: TP is co-owner of EquiGait Ltd, a company providing equine gait analysis products and services. The remaining authors have no conflicts of interest to declare.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2022.111364.

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