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Suitability of solar-powered acceleration and global positioning devices for remote monitoring of equine welfare - a case study

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A B S T R A C T

This study evaluated solar-powered GPS and accelerometer devices for monitoring equine welfare. Two devices, a research device (RD) and an ear tag-like device (ETD) originally developed for cattle, were tested on horses mounted on a halter or neck collar. The RD collects high-frequency raw data for developing behavior classification algorithms, while the ETD transmits limited daily data points for low-maintenance, long-term monitoring. Data were collected from 20 group-housed horses during winter 2023/2024, though individual animals were monitored for limited periods. Devices were compared with battery-powered GPS and accelerometer references, focusing on (1) safety and behavioral compatibility, (2) energy supply and transmission stability, and (3) behavioral evaluation. No major welfare concerns were observed; the RD occasionally interfered with natural behaviors and is unsuitable for unsupervised use, whereas the ETD was generally safe. Initial ETD data yield was low under low-light conditions but improved after pre-charging. GPS accuracy was sufficient for general positioning, although ETD showed lower temporal resolution. Accelerometry data agreed with RD and independent loggers. RD enabled locomotion classification, movement quantification, and potential detection of rare events (atonic collapses). Leg-mounted sensors classified locomotion and lying accurately, while neck-mounted sensors detected lateral but not sternal recumbency.

Combining RD data with labeled observations supports development of equine-specific algorithms. ETD is suited for herd-level monitoring, and RD enables high-resolution behavioral analysis. These results demonstrate the feasibility of adapting cattle-derived technology for equine welfare, providing a foundation for low-impact, continuous monitoring, and supporting the development of cost-effective, scalable sensor-based systems in precision livestock management.

1. Introduction

Monitoring equine welfare—which encompasses both the absence of pain and suffering and the presence of positive emotional states [1,2]—remains inherently challenging, as horses cannot verbally express discomfort. Digital technologies are increasingly used to detect subtle behavioral changes indicative of welfare shifts.

A broad range of monitoring technologies is now available, particularly for cardiac and locomotor systems, with commercial devices supporting sport horse performance optimization and assisting veterinarians in lameness detection [3]. Yet continuous, unsupervised monitoring of equine behavior remains constrained by practical limitations. Computer vision–based systems are largely unsuitable for group housing, as individual recognition and multi-area observation are not fully reliable. Energy-dependent devices face trade-offs between battery size, wearability, and long-term data acquisition [4,5]. Large batteries increase bulk, limiting continuous deployment, while limited energy autonomy restricts long-term monitoring without frequent recharging or replacement. Multiple paired devices can provide comprehensive behavioral and positional data but require guided application and supervision [6,7]. Long-term comfort and tolerance remain critical bottlenecks, and the multi-week impact of attached devices on equine welfare has not been systematically quantified. Lightweight collar-based systems combined with small ear tag–like devices (30–35 g) offer a

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promising solution.

Robust communication and device durability are critical, especially in pasture environments where transmission may be unreliable and sensors are exposed to dirt, moisture, and mechanical stress from social interactions and natural behaviors such as rolling, which can soil or displace devices in Equids more than in other livestock. Devices must also be biocompatible—lightweight, non-invasive, and comfortable—to avoid stress or injury during prolonged wear.

Continuous remote monitoring has been successfully applied in other large herbivores using multi-sensor devices [8–11]. Building on this, we evaluated the potential of a lightweight, solar-powered ear tag–like device (ETD) originally developed for cattle [12,13] for equine monitoring under real-world conditions. In addition, we tested a research device (RD) capable of collecting continuous high-frequency accelerometers and GPS data to complement ETD recordings.

This study aimed to assess ETD's functionality and practicality for horse welfare monitoring, evaluate barriers to adaptation, and explore the potential of integrating RD data for enhanced behavioral resolution and algorithm development. The goal is a scalable, minimally invasive, year-round monitoring of horse behavior and welfare, combining herd-level insights with detailed individual-level data.

2. Material and methods

2.1. Device description

The origins of the two evaluated devices can be traced back, on the one hand, to remote sensing experiments conducted by the Commonwealth Scientific and Industrial Research Organization's (CSIRO Agriculture and Food, St Lucia, Queensland, Australia) livestock division [11,12,14–16] and, on the other hand, to the initiative and vision of the start-up Ceres Tag (Ceres Tag Ltd, Lutwyche QLD 4030, Australia). The RD and ETD devices are subject to ongoing refinement and development in collaboration with the IoT specialist Embeint (Embeint Pty Ltd., Brisbane, QLD, Australia).

This technology ecosystem, which consists of RD and ETD, was explicitly designed to enable the development of behavior classification algorithms by combining high-resolution RD data with reference observations, which can subsequently be deployed on the low-resolution ETD. In cattle, this approach is implemented e.g. as the "Pasture Feed Intake (PFI)" also called "eGrazer" algorithm [12]. The possibility to adapt and deploy custom algorithms directly on the ETD represents a distinctive feature of this system compared to currently available solutions.

2.1.1. Research device (RD)

The research device (RD) weighs 0.8 kg and is mounted on the animals' neck. To transform this cattle device for the use in horses, it was necessary to build a customized horse halter, which stabilizes the unit on the horse's neck. Consequently, the counterweight of 1.8 kg, used to maintain the device's neck position on cattle, was omitted for horses, as it was deemed unsuitable for this species (Fig. 1). The RD is equipped with both an accelerometer and a Global Positioning Sensor (GPS). The device further contains a Global System for Mobile Communications (GSM) and Bluetooth Low Energy (BLE) communication units. Device temperature, humidity and altitude are also captured. Its main purpose within this study consisted of continuously recording GPS positions at 1 Hz and accelerometer data at 50 Hz. This data is saved on a local SD card and retrieved after data collection. The rechargeable lithium-ion battery supplies the device for approximately 10 days; solar panels enable recharging and thus power supply for long-term use. If required, the battery can additionally be charged via a USB-C port. RD and the ear tag-like device (ETD) carry the same basic sensors. Both device types collectively establish a device ecosystem. Hereby, RD and ETD can be operated such that raw accelerometer data at 50 Hz captured by a single ETD is streamed via a Bluetooth connection to the RD and recorded to the RD's local SD card [17]. The master device's (RD) primary tasks involve recording high-density data to model and compute symptoms or traits which, combined with adequate labeled observation data, allow for the subsequent development of detection algorithms [15]. The subordinate or pupil device (ETD) is designed for large scale deployment under typical animal husbandry conditions.

Fig. 1. Research Device (RD) mounted on halter for horses. The RD is placed on the horses' neck. The grey box on the collar contains an independent GPS unit for comparative data quality analysis.

2.1.2. Ear tag-like device (ETD)

The ear tag-like device (ETD) is developed to give farmers practical information on their herds' location and send alerts upon irregularities. The ETD weighs 30g. Energy is drawn from a small lithium battery buffer which is charged by a solar panel on the ETD. The long-term operation relies on sunlight during the day. The ETD comprises an embedded processing system (edge computing). Raw acceleration data collected at 50 Hz is processed on the device, and only the result is transmitted via satellite (GlobalStar network; up to 24 data packet transmissions per day). Transmission times from individual devices are not synchronized, leading to data from each animal at different points in time. Each data packet from the applied firmware standard contains a timestamp and a single GPS position fix, allowing up to 24 position records per ETD per day. In addition to positional data, each packet includes an accelerometer-based, cattle-derived activity index ranging from 0 to 63. Additionally, in cases of anomaly detection, the devices send alerts (including an on-demand GPS location) independent of the scheduled data transmission, based on algorithms applied to raw acceleration data. The ETD thereby establishes an individual baseline activity using a rolling six-day window, with extended periods of inactivity or excessive activity triggering alerts. Although these alert algorithms were originally developed for cattle, their design is based on deviations from an individual baseline rather than absolute activity thresholds, supporting their transferability across species. In this context, the activity index is not interpreted as an absolute measure nor linked to specific behaviors, but used comparatively within individuals, which allows its application in horses without species-specific recalibration of the scale. The ETD was originally intended to be used as an ear tag in cattle, thus ensuring the correct positioning of the solar panel with an orientation towards the sun. To use the devices on horses - and other livestock species such as small ruminants - it was necessary to design a specific fastening system adapted to their size and anatomy. We used common livestock bell collars with a fast release specification (Velcro, hook and loop fastener), as well as a counterweight (0.5kg), ensuring that the device is oriented towards the sunlight (Fig. 2). To fasten the

Fig. 2. Ear tag-like device (ETD) adapted for the use on horses via a 3D printed PUR holster mounted to bell collars and in its original form ((a) Counterweight on the bottom side of the collar to keep the ETD oriented towards the sun. (b) Clean ETD; (c) Dirt-covered ETD due to rolling behavior; (d) ETD (top) and MSR device (bottom)).

ETD on the collar it was embedded in a 3D printed holster. The holster was designed and manufactured by FreeDimension LLC of St. Petersburg FL, USA). To assess the potential for detecting locomotion and lying behavior (see Section 3.3.3), ETD were mounted in the same neoprene boots as used for the control device (Section 2.1.3).

2.1.3. Control devices (non-solar-powered)

To assess the performance of the RD and ETD devices under specific animal housing conditions, reference ("control") data was also collected using established battery-driven measurement tools.

2.1.3.1. Comparison of results obtained with RD and ETD devices to those from control devices. GPS data were recorded using a Qstarz datalogger (BT-Q1000XT, Qstarz International Co., Taipei, Taiwan, e.g., Homburger et al., 2014) resampled at 0.1 Hz and equipped with an Agroscope-customized battery extension. The Qstarz device was attached to the horse's neck using a collar fitted with a safety breakaway point (Velcro). Due to its weight, it was positioned ventrally between the mandible and the distal neck (Fig. 1). We mounted the GPS device on the same neck strap as the ETD, so that both devices were fixed simultaneously. During this deployment, a separate counterweight was not required, as the Qstarz device itself acted as a counterweight. Data was collected with the horses moving freely over two consecutive 7-day periods in January and February 2024, continuously on 19 horses.

2.1.3.2. Locomotion and lying behavior. Acceleration data were collected to compute locomotion and lying behavior (see Section 2.4.3) during one hour per day on two separate days (i.e., two hours in total) at a sampling rate of 1 Hz using an MSR data logger (MSR145, MSR Electronics GmbH, Winterthur, Switzerland, e.g., Burla et al., [18]) attached to the horse's front leg in special designed neoprene boots (custom-made by the saddlery of the Swiss National Stud, Agroscope). Data from the RD and ETD were directly compared against these MSR recordings as reference measurements.

2.2. Data flow and data processing

Data collected by the RDs were processed after completion of the field recordings. Data transmitted by the ETD was accessed via the manufacturer's API. MSR and Qstarz devices were configured (1Hz and 0.1Hz recording frequency, respectively) and their data extracted using the respective software (MSR Reader, MSR Winterthur; Qstarz Reader, Qstarz International Co., Taipei, Taiwan, respectively).

For ETD, the full dataset was retained and sub-selected by defined start and end times for specific comparisons (see sections below). No imputation or temporal regularization was applied to ETD data that deviated from the nominal 1-hour transmission interval (e.g., due to impaired device functionality). A total of 19,123 data packets were recorded from 38 of 40 deployed devices, as two did not transmit any data, of which 808 (4,05%) were excluded because the collar had fallen off or devices were removed from horses for veterinary treatment.

A total of 886 high-activity alerts and 19 inactivity alerts were recorded, excluding 109 inactivity alerts originating from two static control devices. The inactivity alerts occurred on six separate occasions and were attributable to collar loss (3 times) at the hay rack or deliberate removal when horses were taken off-site (3 times). On one occasion, an inactivity alert could not be plausibly attributed to the animal. Due to limited ground truth, inactivity alerts were not included in further analysis.

RD and control devices recorded continuously during the respective deployment periods. Devices were activated prior to and deactivated after the defined observation windows; data outside these windows were discarded. The number of data points used in specific analyses can be derived from the sampling rates and corresponding supplementary tables.

GPS positions from both RD and ETD, along with qualitative location accuracy estimates for ETD data, were included in the analysis. For accelerometry, raw values from all three axes were used as input variables. Data processing included calculation of acceleration magnitude (Euclidean norm) and application of a low-pass Butterworth filter, complemented by a sliding median filter. Filtered axis-specific signals as well as magnitude values were used for further analysis and visualization.

The dataset generated and analyzed during this study is publicly available in the Zenodo repository: https://doi.org/10.5281/zenodo.19334416.

2.3. Animals

The pilot trial included data from 20 horses. Nineteen group-housed female warmblood horses (mean age 13 ± 2.4 years, range 7–16 years) were monitored at the research site of the Swiss National Stud. In addition, data from one privately owned group-housed horse (see Section 3.3), collected by Identitas AG, were included.

The 19 horses at the Swiss National Stud were housed on a 2.5 ha site divided into four identical housing units, each accommodating groups of four (n=1 group) or five horses (n=3 groups). A housing unit consisted of a stabilized paddock trail with distinct functional areas: time-controlled covered hayrack, pasture, shelter, water dispenser and a space allowance size of 440m^2 per horse (Fig. 3). The 131-meter-long paddock trails separated the feeding area from the area with the drinking troughs and shelters (with shavings as a bedding material), encouraging the horses to exercise. The area was free from any other buildings and, thus, free from shielding. Some animals temporarily left the housing system due to medical treatment. In these cases, all devices were removed and later reattached.

Fig. 3. Experimental site and housing system for the study horses. Each of the four enclosures contains the following functional areas: a shelter, drinking area, pasture, paddock trail, time-controlled metallic hayrack, and a rolling area (from back to front).

2.4. Study description

We accustomed the horses to and assessed the acceptance and suitability for deployment of the RD and the ETD.

2.4.1. Research collar deployment

1. Six horses were systematically accustomed to wearing the RD for two one-hour periods. The purpose was to test the horse's reaction to the relatively heavy device, ensure the stability of the mounting halter and accustom animals to wearing the device. No data was analyzed from this phase (Table 1).
2. The device was then deployed on the same six horses for a three-hour period. During this time, horses' posture and behavior while wearing the devices were monitored by direct observation (continuous behavior sampling; [19]) to support the assessment of device tolerability. These observations were not subjected to formal analysis.
3. Finally, the devices were deployed on the same six horses for a duration of six hours. Hereby we sampled the behavior of horses at thirty-minute intervals, with additional mobile phone video recordings focusing on special events (atonic collapses).

2.4.2. Welfare monitoring and suitability of devices for deployment on horses

We monitored both injury occurrence and device-related behavioral patterns and abnormalities to ensure that the devices do not cause any harm to the horses through daily health checks. This evaluation aimed to determine the suitability of the devices for deployment in equine settings by assessing their impact on both equine welfare and the applicability of their use in this species.

2.5. Ear-tag-like device (ETD) deployment

The ETD was tested for 1. Solar recharge, 2. GPS positioning, acceleration data and 3. potential to detect locomotion and lying behavior via raw data streaming to a RD (Table 1).

2.5.1. Solar recharge

Two sets of solar-powered ETD were deployed on the neck of each of the 19 horses between 15.12.2023 and 9.4.2024, during which irradiation was reduced (n= 38 ETD on horses, Table 1). Due to poor data transmission during the first two months of the trial, a second set of ETD was prepared and pre-charged via exposure to a high-intensity greenhouse LED lighting system prior to trial deployment (FTM 150W greenhouse lighting spectrum white 380 - 780 nm, 3000 + 6000K, blue 460 nm, red 660 nm, infrared 730 nm) in February 2024. Thus, we ultimately evaluated device performance with this second set from February to March. This was done to determine the solar recharge of the devices under practical European winter conditions and is of interest, because solar radiation is reduced and additionally horses roll in the mud and tend to cover themselves and potential sensors in mud, reducing the ability to charge them.

2.5.2. GPS positioning and acceleration data

The GPS data from ETD deployed on 19 horses were compared with "control" devices mounted on the neck. ETD data was collected continuously throughout the assessment period (December 2023 to April 2024). In contrast, the GPS control device (Qstarz) was deployed

Table 1
Overview of sensor deployment and periods of valid data collection.

Test phase	Deploy-ment period	Number of animals	Valid data period	Devices considered (ETD, RD)	Data included (incl. control devices)	Device placement
Solar charge+ GPS Positioning and acceleration index	15/12/2023 – 9/4/2024	19	15/12/2023 until 9/4/2024	19 ETD (≤23.02.2024); 38 ETD (>23.02.2024; 2 per horse)	ETD Acceleration and GPS Control GPS Control Acceleration	neck neck leg
		0	ETD at fixed locations: 41 days in February and March 2024	2 ETD at fixed locations	ETD GPS and activity index	roof of a nearby container and behind a shelter
Research Collar Deployment	Two days for 1 hour in March 2024	6	0	6 RD	Not included (acclimatization phase)	neck
	One day for 3 hours in April 2024	6	0	6 RD	Not included (acclimatization phase)	neck
	1 day for 6 hours	6	1 day for 6 hours	6 RD	RD Acceleration	neck
Locomotion and lying behavior	1 hour on 2 days in March 2024	1	1 hour on 2 days	1 ETD, 1 RD	ETD Acceleration RD Acceleration Control Acceleration	leg neck leg

during two consecutive 7-day periods in January and February 2024, monitoring 19 and 17 horses, respectively, as two animals were temporarily off-site for medical treatment during one interval.

GPS positions from the ETD and the control GPS device (Qstarz) were imported and processed in R. For both datasets, timestamps, animal names, and coordinates (latitude and longitude) were extracted and standardized. Animal names were harmonized using string matching (Jaro–Winkler distance) to identify the best correspondence between datasets. Positions were matched based on identical timestamps and corresponding animal IDs. Positional errors between devices were calculated using the Haversine distance. Observations with positional errors exceeding 250 m were removed. These large errors occurred when a device had been detached from a horse (e.g., when an animal was temporarily removed from the research site for medical treatment) and continued transmitting from the office. Agreement between devices was evaluated using descriptive error statistics, Bland–Altman analysis, and Lin's concordance correlation coefficient.

ETD were additionally positioned at fixed locations on the trial site (roof of a nearby container and behind a shelter) for 41 days to assess geolocation accuracy and drift. In a similar preliminary test, one RD unit was left on-site for approximately three hours before deployment on a horse to evaluate baseline accuracy under static conditions (Table 1). Activity indices derived from ETD were analyzed graphically over time only.

2.5.3. *Potential to detect locomotion and lying behavior*

We assessed the potential to detect locomotion and lying behavior in a single horse under controlled conditions comparing visually accelerometry data from ETD, RD and a control device (three axes, Butterworth filtered at native sampling rates: RD and ETD: 50 Hz, MSR: 1 Hz, and RD-derived magnitude). ETD acceleration data was transmitted as raw data streams and recorded via the RD.

For this purpose, the ETD and a reference accelerometer (MSR) were attached to the horse's front leg, while the RD was mounted on the above-described customized halter. All devices and behavioral observations were time-synchronized to a common reference (world clock), enabling direct comparison across data sources (Table 1).

The horse was lunged in both directions and was requested to perform walk, trot, and gallop, as well as lying behavior, during two recording sessions of approximately one hour each. This controlled setup aimed to evaluate the capability of the devices to distinguish between predefined behavioral states. Acceleration data from the MSR logger were processed using the *triact* package and served as the reference for comparative analysis [20].

3. Results

3.1. *Welfare monitoring and suitability of devices for deployment on horses*

While no injuries were observed in connection to the solar-powered devices, the box of the battery-powered control-device (GPS) worn below the neck caused one minor injury on the head of one out of 19 horses. The ETD-bearing collars worn by 19 horses were lightweight and free of sharp edges. In three instances from two different horses, collars detached when entangled in stable infrastructure (e.g., hay racks); no injuries were observed in these events. During the three-hour observation period used to assess device tolerability, one horse wearing an RD showed an abruptly terminated rolling event, indicating interference with natural behavior, particularly rolling.

3.2. *Device and data quality evaluation*

3.2.1. *Energy supply and data yield*

Initially, the solar-powered ETD generated a low data yield, ranging from 0 to 25% of expected data packages across all horses, with substantial variability between individuals. After pre-charging an additional set of ETD under a greenhouse LED lighting system and placing them on the horses alongside the initially deployed devices, a satisfactory data yield was achieved (Fig. 4). Temporary reductions in data transmission occurred when devices were clogged with mud or when animals were temporarily housed indoors for medical reasons. These reductions were transient, and data transmission subsequently recovered.

3.2.2. *Comparison of results obtained with RD and ETD to those from control devices*

The generated data was consistent with the reference data and is described in detail below.

3.2.2.1. Position monitoring. The GPS positions recorded by the ETD appear plausible overall, as they consistently fall within the boundaries of the housing system (Fig. 5).

The relative errors of the two ETD at fixed locations (deviation from the respective centroid of all positions) at the 0.95-percentile were 12.0 and 10.7 m, the median 4.0 and 3.9 m, respectively (n=731 and 262, different due to device performance).

Initially, 19,932 GPS points were received from the ear tag–like devices (ETD) from all 19 horses during the period from December 2023 to April 2024. After filtering for common time coverage with the control devices during two consecutive 7-day periods in January and February 2024, 332 matched GPS observations from 17 horses were included in the analysis. Six observations were excluded due to positional errors exceeding 250 m, which occurred when one device had been removed from a horse but continued transmitting from the office (matching points per animal see Supplementary Table 1).

Across all observations, the median positional error between the ear tag–like device and the control GPS was 18.7 m, with a mean $\pm$ SD of 22.1 $\pm$ 24.3 m, and individual deviations reaching up to ~200 m (Fig. 6). Per-horse distributions indicated similar central tendencies, although some horses exhibited isolated large deviations (Fig. 7).

Bland–Altman analysis indicated minimal systematic bias between devices. For geographic coordinates, the mean biases were 0.0000486° for latitude and 0.000136° for longitude, with limits of agreement ranging from –0.00021° to 0.00031° for latitude and –0.00025° to 0.00052° for longitude. In projected coordinates, the mean differences were 10.4 m for X (east–west) and 5.3 m for Y (north–south), with limits of agreement spanning –111.9 m to 132.7 m for X and –103.9 m to 114.5 m for Y (Fig.s 8 and Supplementary Fig. 1). Concordance between devices was moderate, with concordance correlation coefficients of 0.34 for X and 0.31 for Y.

The RD consistently recorded geolocation data at a frequency of 1 Hz, with GPS positions aligning well with those of the reference devices (Fig. 8). However, the geolocation data obtained from the RD, based on the employed standard, were susceptible to interference from nearby buildings and metallic structures. No static reproducibility analysis of the RD was conducted over comparable durations during the main trials. Nevertheless, a roughly three-hour sample collected from one RD unit before deployment on a horse showed similar accuracy values (95th percentile: 13.5 m; median: 4.3 m; n = 12,060 data points), although performance was visibly degraded due to multipath interference at the preparation site.

3.2.2.2. Accelerometry data and activity measures. Accelerometric output from the ETD was available as hourly summaries of activity indices for transmitted timepoints. Alternatively, raw tri-axial acceleration data could be recorded at 50 Hz via Bluetooth to the SD card of a RD. Validation of activity alarms was not part of the present study. In general, high-activity alerts demonstrated high sensitivity but low specificity: no clear intrinsic or extrinsic triggers, such as e.g. colic or environmental disturbances, were consistently observed during the trial

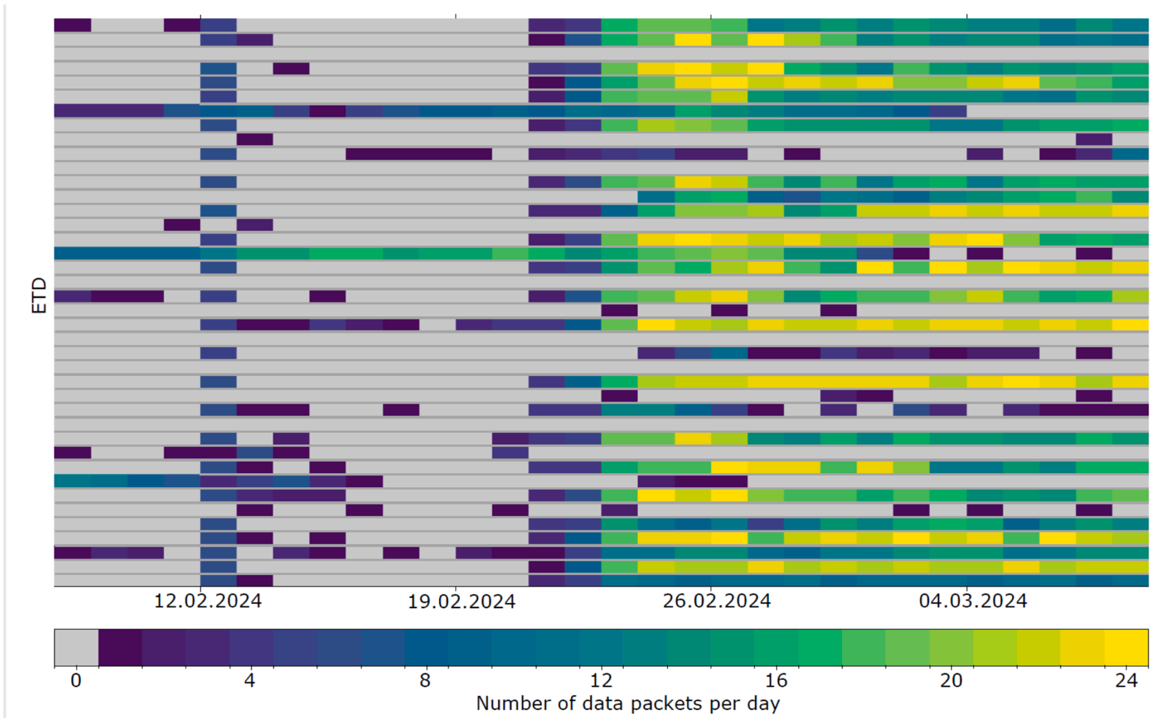

Fig. 4. Data output from 40 ear tag-like devices (each line represents one ETD), categorized as not pre-charged (≤ 23.02.2024) and pre-charged (> 23.02.2024). The figure shows a selected excerpt of the dataset highlighting transition in transmission patterns, rather than the full recording period (December 2023 to April 2024). The number of data packets transmitted per study horse per day is displayed for time periods before and after pre-charging. Nineteen horses were initially equipped with one device each; subsequently, an additional pre-charged set was deployed on the same animals, resulting in two devices per horse during the later phase. Two further devices (bottom two lines) were placed stationary within the housing system as controls. The number of transmitted data packets per device per day is shown. The selected time frame represents winter conditions in Central Europe, where device performance depends on energy availability and satellite connectivity.

to explain the increased activity. The rule, defined as nine times the standard deviation relative to the individual's activity over the previous six days, captures deviations from typical behavior rather than specific causes. It should be emphasized that this Technical Note focused on hardware performance, and the data is insufficient to draw conclusions on the reliability of the implemented algorithms.

A median representation of reported activity from the ETD for the different groups shows synchronicity between all groups and the consistent occurrence of most high-activity alerts (Fig. 9). Furthermore, establishing data transfer between RD and ETD often failed and remained limited to pre-set pairings, but once established, raw accelerometry data from the ETD were accessible for storage on the RD.

3.2.3. Potential to detect locomotion and lying behavior

The leg-mounted ETD provided accelerometry data comparable to those obtained from the MSR logger and allowed for a reasonably accurate classification of locomotion and lying behavior based on the corresponding video footage. The RD aided in distinguishing between sternal and lateral recumbency, as the neck turns to the side in lateral recumbency, thereby altering the orientation of the sensor axes. However, fixation of the device to the leg appears to be advisable, as the neck position in sternal recumbency closely resembles that in a standing posture, which may limit the effectiveness of axis-based orientation analysis when using a neck-mounted sensor alone (Fig. 10).

A further symptom, sudden atonic collapses, was captured during the deployment. These were non-targeted but observed and recorded events. The data of these instances suggest a characteristic and sufficiently simple two-axis signature of progressive head steepening and sudden re-positioning (Fig. 11).

4. Discussion

4.1. Device suitability and welfare considerations

The research device (RD)–ear-tag-like device (ETD) ecosystem was tested under conditions representative of real-world equine group housing in Switzerland (Central Europe), where group sizes are typically small. Within this context, the RD, although successfully attached via a custom-made leather halter, interfered with natural behaviors such as rolling or lateral recumbency, limiting its suitability for prolonged unsupervised deployment. Consequently, the RD is recommended only for short-term use under controlled conditions. A lighter version under development for small ruminants may offer a more horse-compatible alternative in the future.

In contrast, ear-tag-like devices (ETD) mounted on lightweight collars proved suitable for long-term use. Horses tolerated continuous wear for several months without observable welfare impairment. The ETD-bearing collars were lightweight, free of sharp edges, and the safety break function of the collar reliably prevented injuries when collars became entangled with stable infrastructure (e.g., hay racks). ETD detachments posed a very minor risk of temporary data loss, occurring only three times over four months in two out of 19 horses. The counterweight system of 0.5kg maintained stable, sun-exposed positioning without behavioral interference.

However, several practical limitations were observed. In environments where horses frequently roll in mud or soil, which is a natural behavior in horses, solar panels may become soiled, reducing charging efficiency and requiring cleaning. Artificial light was also needed to maintain charge under low sunlight, indicating that solar power alone is insufficient in temperate regions like Switzerland. While performance supposedly improves during spring and summer, year-round monitoring remains challenging. Since the present study, newer ETD generations

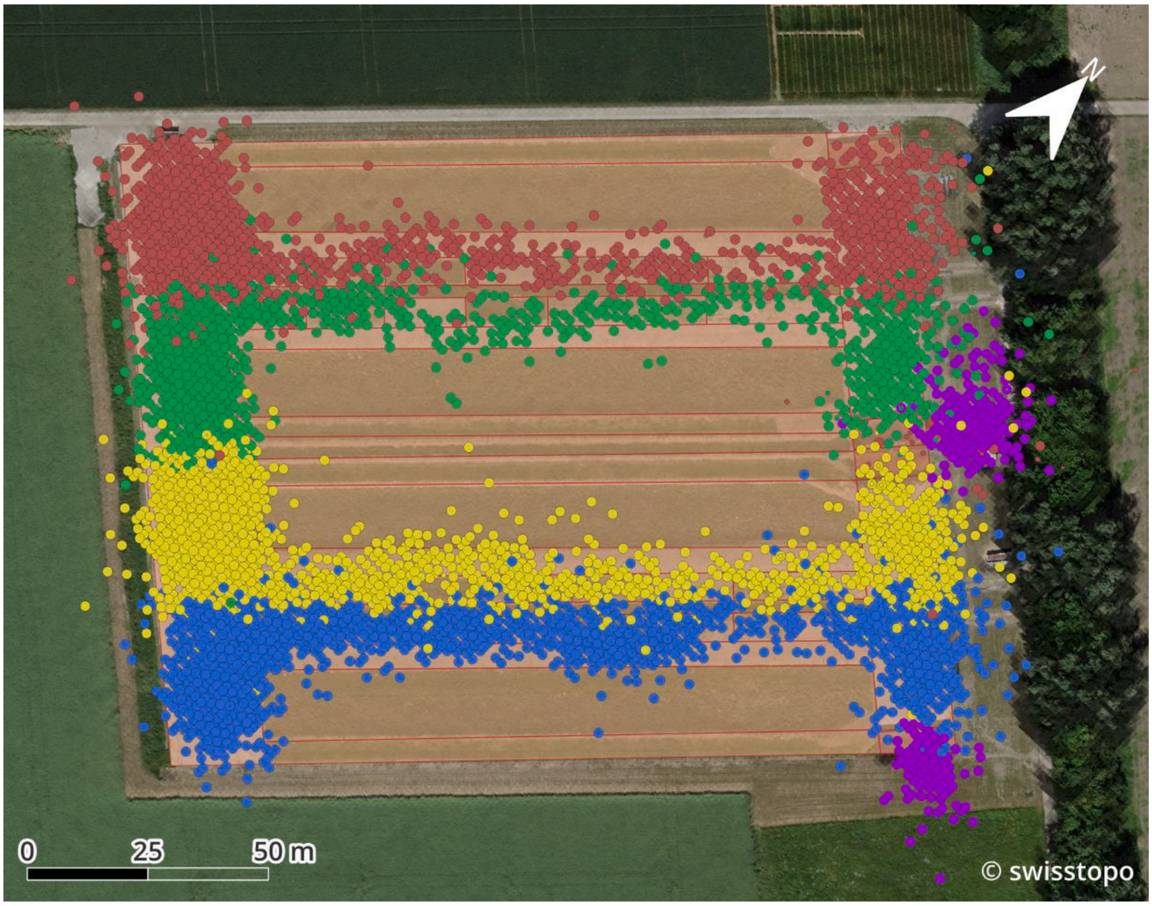

Fig. 5. Overview of all GPS positions reported by ear tag-like devices (ETD) over a period of four months (December 2023 until April 2024). The four colors represent the four distinct horse study groups. The reported accuracy estimate is represented by circle size (inverse). Two ETD were placed at fixed locations to assess positional reproducibility for only 41 days (purple color). The polygon (red line with dotted filling) indicates the boundaries of the housing areas.

with higher battery capacity, improved energy management, enhanced solar panels, updated firmware, and gateway access have been developed, potentially enhancing usability and data yield under European conditions.

4.2. Data quality and monitoring capabilities

The ETD provides valuable insights into equine behavior, but its utility is constrained by energy-dependent data transmission. Ideally, positional data are transmitted at regular intervals of up to one hour. Under limited energy conditions, low battery states reduce the number of transmitted packets, producing partial behavioral records and occasional data loss rather than complete time series. Similar patterns have been observed across equine and wildlife systems: in a kinetic-harvesting wildlife tracker (Kinefox), messages could only be sent sporadically (every 4–24 days) when harvested energy dropped below a voltage threshold, leading to large temporal gaps [21]. Design solutions therefore focus on harvesting more energy and, critically, transmitting less but smarter data. In equine systems, satellite-enabled devices such as the Smart One C offer improved performance, combining high positional accuracy with extended battery life of up to six months [22].

In general, ETD data are limited by low sampling frequency, which constrains detailed individual behavior detection. However, it should be emphasized that ETD data are primarily intended for routine monitoring rather than detailed analytical purposes, for which the RD system is designed. Nevertheless, median positional accuracy of ETD was 4.0 m (95th percentile 12.0 m), with deviations largely random rather than systematic. The control device, QStarz, is marketed for higher accuracy (1–3 m), consistent with Homburger et al. [23], who reported a median of 1.5 m and a 0.95-percentile of 2.4 m. Stewart et al. [24] similarly found out that solar-powered GPS ear tags exhibit greater horizontal error and occasional data loss compared to GPS collars. In that study, GPS collars achieved approximately 2 m error and successfully recorded a position every time they attempted (“100% fix rate”), whereas ear tags showed 41–59 m error and recorded positions only 31–99% of the time, indicating intermittent data loss. High deviations in our study also occasionally occurred possibly due to environmental obstacles such as shelters or hay racks. In addition, QStarz data were downsampled to 0.1 Hz, which may have reduced positional scatter. Overall, the inherent variability of GPS measurements limits meter-scale precision, constraining robust distance-based analyses of social herd structures and interactions.

Despite these limitations, ETD captures spatial patterns suitable for paddock- and pasture-scale monitoring and provides informative herd-level summaries. In the future, group-level activity indices can reveal behavioral disturbances due to external factors (e.g., weather, human presence) or indicate synchronization patterns within and across horse groups [25], supporting its practical value for cost-effective herd-level monitoring. Individual daily activity patterns could further support the early detection of health issues such as lameness or colic.

Moreover, alarm functions operate independently of routine transmissions. Abnormal activity or inactivity triggers alerts within minutes when predefined algorithm thresholds are exceeded. For geofencing, alarms are generated only when multiple animals appear outside a defined polygon within a specified time window, reducing false positives from single erroneous positions. While not an inherent ETD feature,

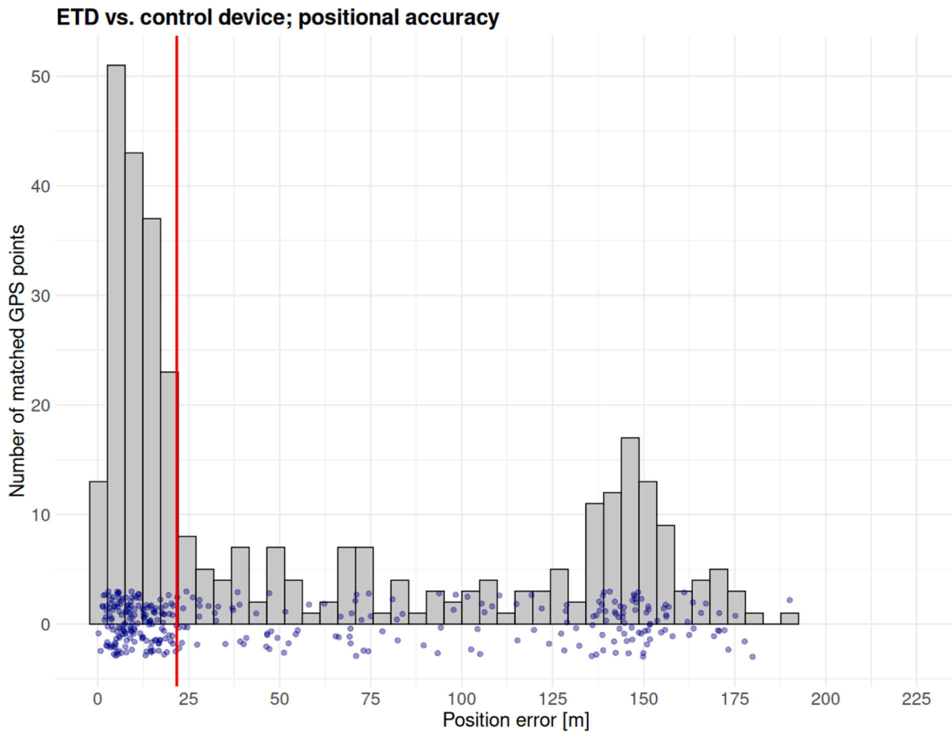

Fig. 6. Distribution of positional error between the ear tag–like device (ETD) and the control GPS across all matched observations (n = 332; grey bars). The red line indicates the median positional error. The blue points indicate the positional error of the individual matched observations.

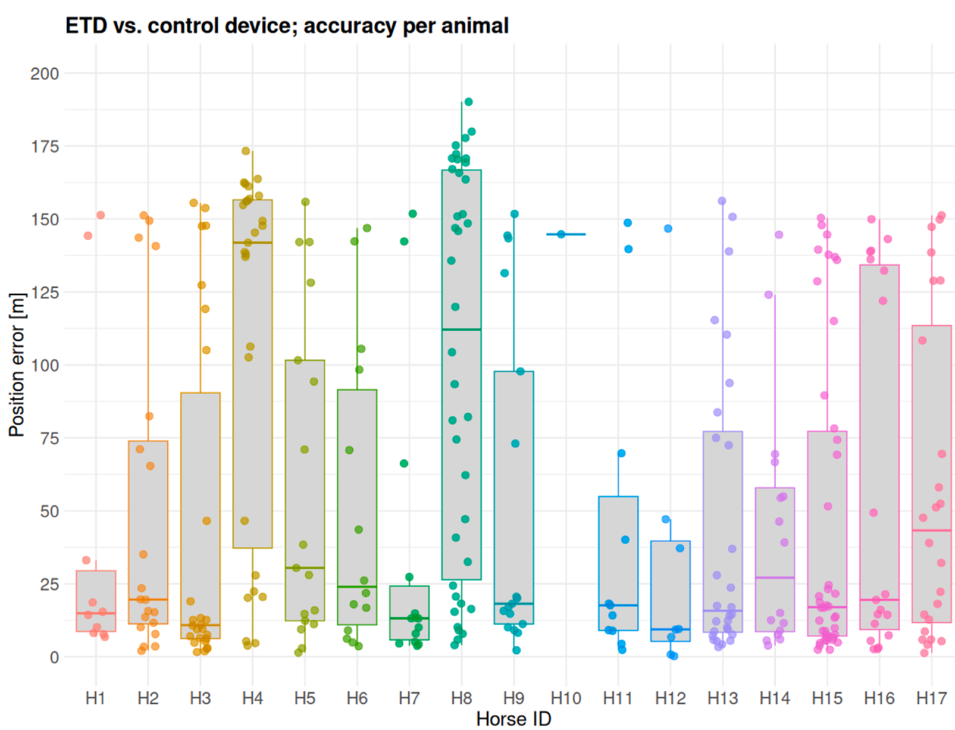

Fig. 7. Positional error between the ear tag–like device (ETD) and the control GPS for individual horses (n = 17). Boxes represent the interquartile range and points indicate individual observations.

this approach was developed based on empirical patterns observed in the study and demonstrates how adaptive rules can improve practical monitoring under real-world conditions.

High-activity alerts are individualized, triggered whenever deviations exceed nine times the standard deviation relative to a six-day baseline profile (internal communication with the provider, 2023). Multiple stimuli—play, thunderstorms, caretakers, or nearby machinery—may trigger alerts. Single alerts should not automatically prompt intervention; however, the flexibility of the alerting system allows aggregation across multiple animals or time windows to reduce

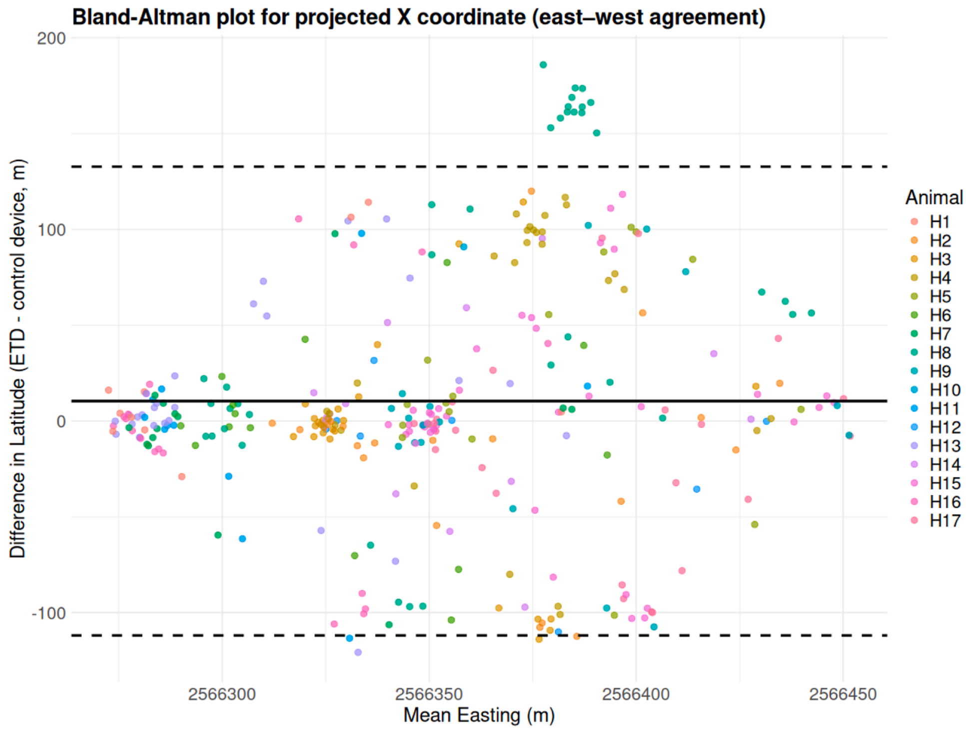

Fig. 8. Bland–Altman plot illustrating agreement between the ear tag-like device and the control device using projected x coordinates. Differences between devices (in meters) are plotted against the mean coordinate (x-axis, in meters) for each horse (H1–H17). Solid lines indicate mean bias; dashed lines represent 95% limits of agreement (±1.96 SD).

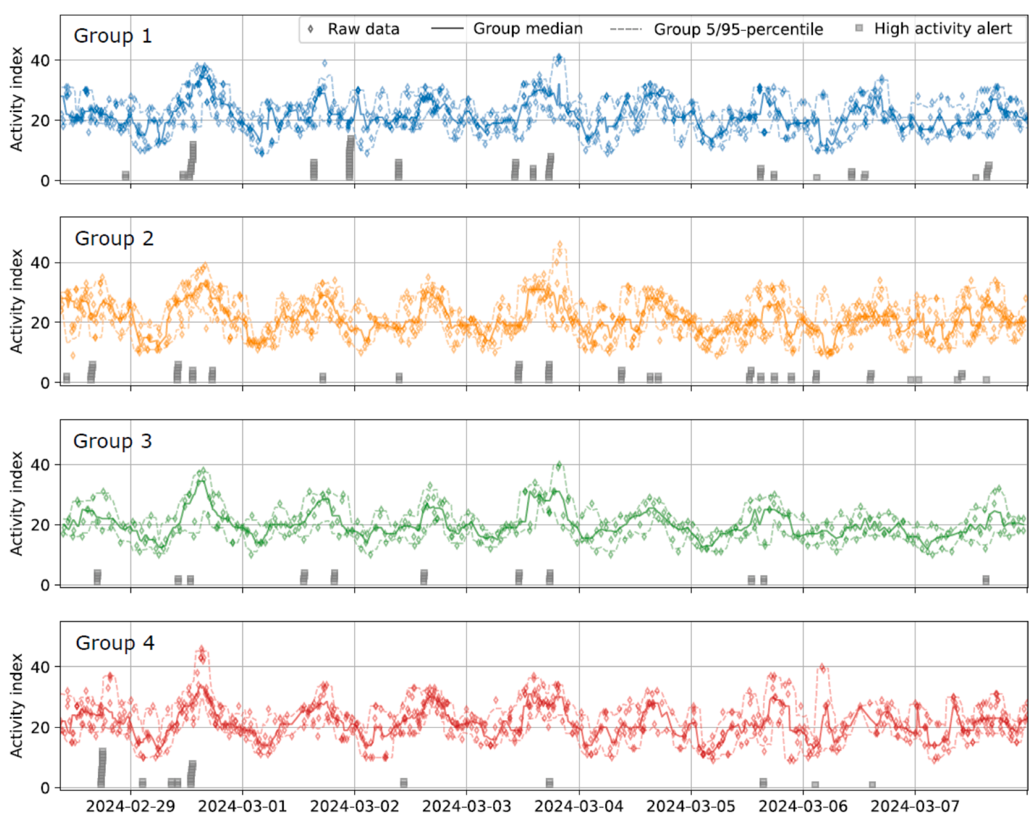

Fig. 9. Moving median of the activity index recorded by ear tag–like devices (ETD) for four groups (4–5 horses per group) housed under identical conditions. Activity is expressed on a scale from 0 to 63.

false positives. Integrating raw sensor data with labeled observations could further improve detection specificity and efficiency, although the

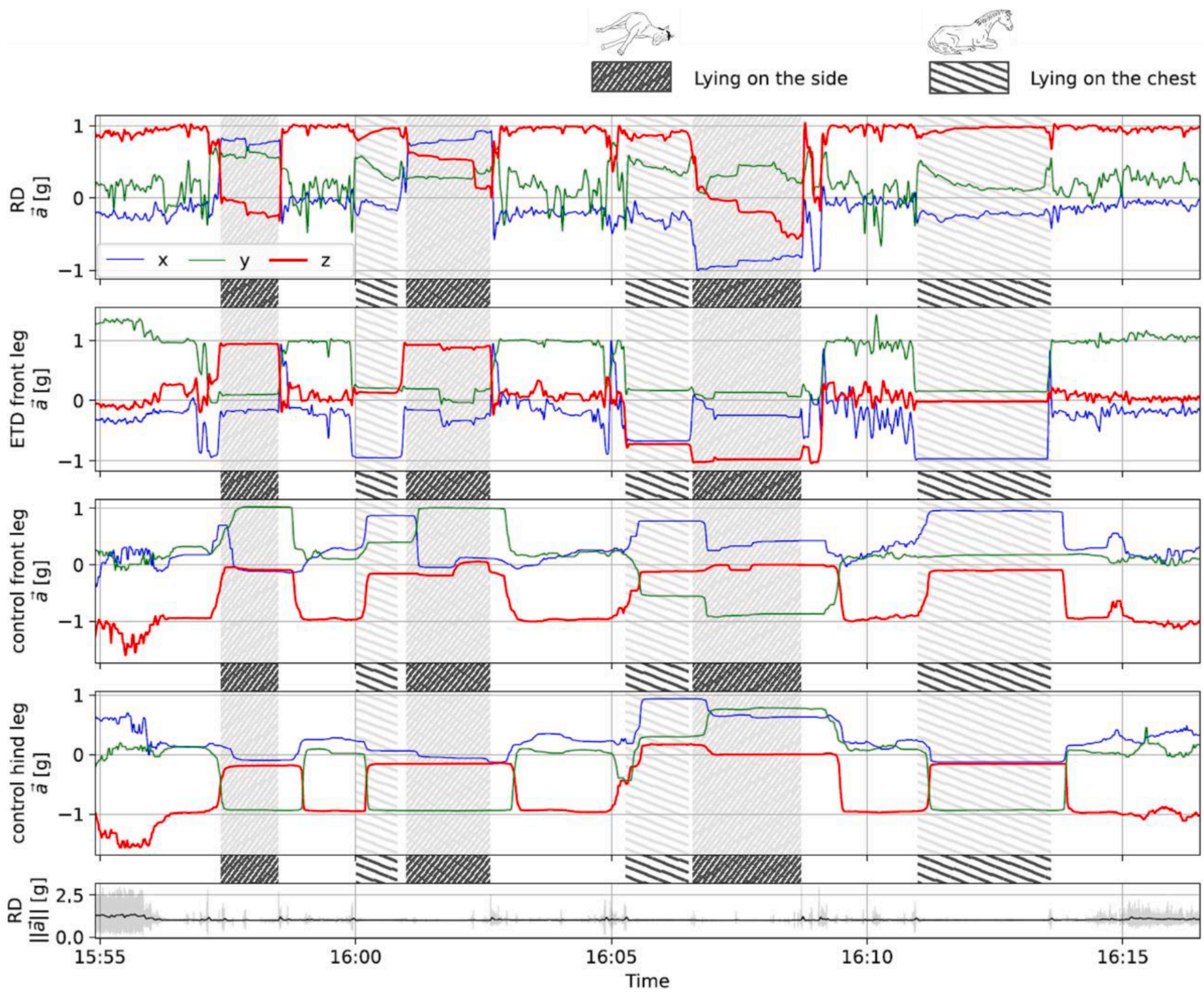

Fig. 10. Comparison of data from different sensors recorded simultaneously during the same induced lying behavior. Top four panels: accelerometer components for devices in different positions. Bottom panel: accelerometry magnitude for RD filtered at different frequencies, indicating general activity and resting. Note slight time-shift between ETD and RD versus control devices, which has not been corrected for the purpose of illustration.

deployment of such algorithms entails scientific and economic challenges [26–28].

Like in cattle, individualized baseline activity derived from triaxial accelerometers helps account for inter-animal differences and improves detection of abnormal behavior [15]. Building on this, the RD complements the ETD by providing continuous high-frequency raw data, enabling more detailed behavioral resolution. In our study, raw data and direct observations indicate that the RD, alone or in combination with ETD, can distinguish locomotion behaviors such as walking, trot, and gallop, and may even detect sudden atonic collapses. If systematically confirmed, this capability could provide substantial welfare value by supporting the identification of undiagnosed conditions and the monitoring of at-risk animals. In contrast to previous work on equine sleep and rest patterns, which relies largely on manual annotation of resting postures [29], such sensor-based approaches offer the potential to automate the detection of resting states.

However, differentiation of low-activity behaviors remains challenging. While accelerometer rotation enables detection of posture changes and elongated body positions, consistent with findings from limb-mounted devices [18,30], distinguishing between sternal and lateral recumbency using neck-mounted sensors is still limited. Lateral lying can be identified, whereas sternal lying remains difficult due to minimal changes in neck orientation. Addressing these limitations will require large, labeled datasets and dedicated equine-specific algorithm development [31–33].

In terms of practical application, the system supports complementary roles depending on device type and deployment. The ETD is suited for long-term, herd-level monitoring of activity patterns, spatial use (e.g. paddock or pasture), and deviations over time, forming the basis for alert systems. While current configurations do not reliably support continuous high-resolution monitoring or detailed behavior classification in horses, algorithms developed from high-resolution datasets on the RD could be deployed on the ETD to enable targeted detection of specific behaviors and trigger alerts when relevant patterns occur (e.g., atonic collapses). In contrast, the RD provides continuous, high-resolution data and is therefore primarily suited for research applications, such as algorithm development, validation, and detailed behavioral analysis, rather than routine on-farm deployment.

Device performance and suitability are strongly influenced by sensor placement and orientation. Neck-mounted ETD offers a favorable compromise between stable solar exposure and minimal interference with natural behavior, making it suitable for low-impact, long-term monitoring under field conditions. In contrast, leg-mounted sensors, although more accurate for locomotion and lying behavior classification, are less suitable for prolonged deployment in group housing systems and are not well adapted for solar-powered devices, due to lower solar exposure. Both RD and ETD rely on solar panels, which are less effectively oriented on the limb compared to the neck, and the RD is

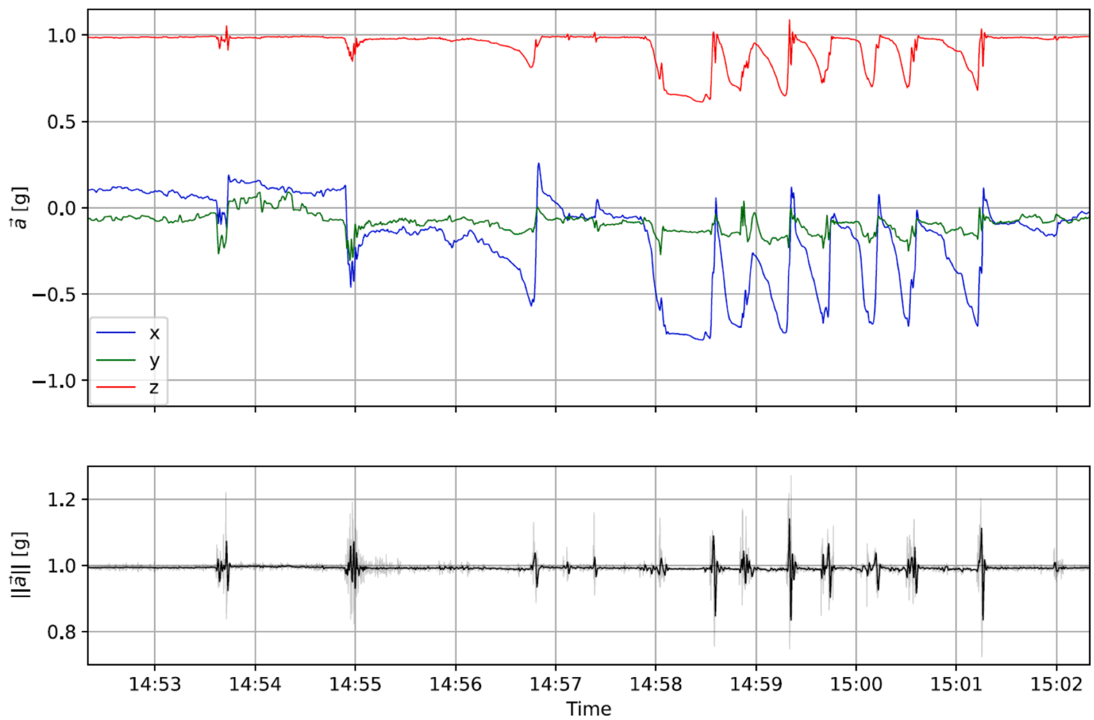

Fig. 11. RD data representation for observed instances of sudden atonic collapses in a horse. Black curves: magnitude indicate relative calmness, which is usually the context in which atonic collapses occur. Top right panel: accelerometer components for RD in a neck position. Bottom right panel: accelerometry magnitude for RD filtered at different frequencies, indicating general activity and resting around the collapse movements. The typical head and neck movement are both reflected in the x- and z-axes, i.e. the xz-plane through which the head moves.

currently too large for practical leg-mounted use.

In horses, frequent rolling behavior represents a further constraint, as it can lead to dirt accumulation on solar panels, particularly under muddy conditions, reducing charging efficiency. This limitation is less relevant in cattle and small ruminants, which do not exhibit rolling behavior to the same extent. Furthermore, under winter conditions in temperate regions, the ETD system is currently not fully energy-autonomous and may require management interventions (e.g., pre-charging) or seasonal use. Consequently, its present application is best suited for long-term herd-level monitoring of activity patterns and spatial use, rather than continuous, high-resolution individual behavior tracking. While intermittent transmission limits complete time series, relative changes in activity and group-level dynamics remain robust indicators. Ongoing hardware and firmware improvements are expected to further enhance energy autonomy and data reliability. Central to this progress is improved energy management, driven by highly efficient solar cells, optimized battery systems, and firmware that actively regulates device operation. In parallel, adaptations in housing systems, such as integrating UV light sources into hayracks or shelters, could enable in situ solar recharging while devices remain attached to the horse and should be explored in future research. Overall, the RD serves short-term, high-resolution data collection for algorithm development, while the ETD is designed for robust, low-maintenance long-term monitoring.

4.3. Transferability and algorithm development

Previously developed cattle algorithms are position-dependent and not directly transferable to horses, particularly due to differences in sensor placement (ear vs. collar) [16,34,35]. Simple activity metrics are comparatively robust across attachment sites and remain informative for general monitoring [10,11,36].

For practical deployment in equine husbandry, acceleration-based algorithms must be calibrated and validated on horse-specific datasets to ensure reliable behavior recognition and welfare monitoring [33]. Integration of high-frequency raw multi-modal sensor data (e.g., RD) with labeled observations could further enhance algorithm performance and efficiency, enabling smaller devices as ETD to generate actionable alerts from raw data while remaining practical for real-world herd management [8,32]. Key anatomical, behavioral, and environmental differences between cattle and horses affecting system transferability are summarized in Table 2.

5. Conclusion

The RD–ETD ecosystem proved feasible for herd monitoring and individual behavior surveillance in real-world equine husbandry conditions. The ETD captures group-level activity and spatial patterns, with potential to detect events such as breakouts, while the RD provides continuous high-frequency data for locomotion analysis, daily distance quantification, and detection of sudden events like atonic collapses. Integrating RD data with labeled observations supports development of event- or state-specific algorithms, enabling the ETD to report only relevant behaviors.

Although some 2023–2024 limitations, such as low winter solar recharge, may have been addressed in newer hardware and firmware, consistent year-round deployment still requires reliable energy supply under low-light conditions and validated equine-specific acceleration algorithms. Future work should use equivalent sensor positioning across devices, combined with video or direct observations. This will enable robust validation and calibration of behavior classification while maintaining the low-impact, practical monitoring approach demonstrated here.

Ethical statement

This study was conducted in compliance with Swiss animal welfare legislation and the principles of responsible animal research. Experimental procedures were approved by the Cantonal Authority of Fribourg

Table 2
Key anatomical, behavioral, and environmental differences affecting transferability of cattle-derived sensor systems to horses.

Domain	Cattle (original system)	Horses (this study)	Implication for ETD / RD deployment in horses vs. cattle
Sensor attachment	ETD as ear tags (fixed position) / neck collar-mounted RD with counterweight	Neck collar-mounted ETD/ halter-mounted RD	Increased movement variability and reduced stability for behavior classification in horses
Anatomy & movement	Limited head/neck mobility	Long, highly flexible neck	ETD: Counterweight enables stable positioning at neck level RD: head-collar fixation more suitable in horses than heavy neck counterweights
Behavior	Rumination, minimal rolling	No rumination, frequent rolling (natural behavior)	ETD: No horse-specific algorithms or validated alerts yet; however, group-level activity, spatial patterns as well as inactivity alerts remain transferable RD: device size may interfere with rolling behavior
Housing system	Large extensive grazing systems	Structured group housing, paddocks	Higher interaction with infrastructure (e.g., hay racks, stable fittings), leading to reduced device stability, increased detachment risk, and greater susceptibility to mud coverage
Solar exposure	Relatively consistent exposure throughout grazing period	Highly variable due to multifactorial issues: mud, shelters, hayracks.	ETD: Soiling during rolling reduces solar charging efficiency and energy autonomy. Required artificial solar recharge with the type of device we had at disposal at the time of the study.
Data requirements	Herd-level production monitoring	Individual welfare-oriented monitoring	Demand for higher temporal resolution and continuity (e.g., detection of changes in resting behavior)

(authorization number 2022-20-FR). Horses were housed in established group facilities that met or exceeded Swiss legal requirements for animal welfare. Care was taken to minimize disturbance and avoid discomfort during device fitting and monitoring. The safety and welfare of the animals remained the primary consideration throughout the study.

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CRediT authorship contribution statement

Miriam Baumgartner: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. **Kosuke Ueda:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Marianne Cockburn:** Conceptualization, Methodology, Validation, Visualization, Writing – review & editing. **Iris Bachmann:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **Stefan Rieder:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

Two authors (SR, KU) collaborated with the manufacturer of the solar-powered ear tag-like device (ETD) during the adaptation and testing of the technology for use in horses. This collaboration was limited to technical support and did not involve financial compensation, consultancy agreements, or ownership of intellectual property. The manufacturer had no role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript. All other authors declare no conflicts of interest.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.atech.2026.102390.

Data availability

The datasets supporting the results of this study are openly available and freely accessible via Zenodo.

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