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Suitability of a commercial low-cost biologging system for monitoring movement, behaviour and heart rate of grazing dairy cows

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ABSTRACT

This study explored the suitability of a commercial biologging system incorporating GPS and heart rate (HR) sensors to monitor grazing cattle's movement, behaviour and heart rate. We preliminarily tested the GPS accuracy with stationary tests and then monitored six dairy cows grazing in an alpine summer pasture for 20 days and nights. We trained a random forest model on direct observations to infer cows' behaviours (resting, grazing, walking) from GPS movement data. We associated each GPS position with the HR (beats per minute - bpm) mean and maximum-minimum difference in the 120–second interval preceding its acquisition. The GPS sensor showed high accuracy (positioning error lower than 2 m in open sky-view and 3 m under tree canopy cover) and efficiency of position acquisition of 95% after excluding outlier positions. The efficiency of HR data acquisition was lower, peaking at 77% during daytime activity and dropping to 50% during night-time resting. The HR mean and the maximum-minimum difference were lower during resting and at night and higher during grazing, walking, and daytime. They also increased with slope and Temperature Humidity Index (THI). This study indicates that this commercial biologging system is suitable for short-term monitoring of animals' movement, behaviour and physiological responses to varying pasture and climatic conditions, offering insights for livestock management in alpine summer pastures.

HIGHLIGHTS

- A commercial biologging system showed high accuracy and efficiency of GPS positions acquisition and allowed us to infer main behaviours (resting, grazing, walking).
- Efficiency of acquisition of HR data was lower but allowed associating HR to movement data and identify its variation in response to behaviour, slope and climate.
- The system can be used in short-term studies to monitor movement and behaviour and index the welfare of grazing cattle.

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GPS tracking; heart rate; grazing; dairy cows; behaviour

Introduction

Mountain pastures produce essential feed for livestock mountain systems (Zendri et al. 2013; Herzog and Seidl 2018), ensure biodiversity-rich habitats and carbon soil sequestration (Bunce et al. 2004; Schils et al. 2022), and contribute to mountain cultural landscape and heritage (Schirpke et al. 2016; Bele et al. 2021). These multiple benefits depend on complex interactions between the land morphology, soil, vegetation and livestock components of pasture systems. In particular, the livestock component may, on the one hand, impact the pasture ecosystem functions through vegetation removal, movement and trampling, and excreta deposition (Ronchi and Ramanzin 2024). On the other hand, it may be affected by the pasture environmental conditions because slope, forage productivity, vegetation composition may impose significant limitations to livestock movement, grazing patterns, welfare and productivity (Rivero et al. 2021). Therefore, knowledge of livestock movement, behavioural patterns, and welfare is needed to understand better how livestock impact pasture conditions and, in turn, how pasture conditions affect them. For the purpose of describing the movement and behavioural patterns, the application of GPS technologies has recently opened new perspectives (Bailey et al. 2018; Rivero et al. 2021), because the GPS sensors coupled with accelerometers allow the remote and continuous

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monitoring of movement, activity patterns and behaviours of free-ranging animals with a spatial accuracy of a few metres (Parraga Aguado et al. 2017; Werner et al. 2019; Acácio et al. 2022). Examples of applications of this technology for fine temporal and spatial scale analysis of livestock movement, pasture use intensity, selection of vegetation and morphological features, and animal behaviour in Alpine pastures are in Homburger et al. 2015; Pittarello et al. 2019; Pittarello et al. 2021; Raniolo et al. 2022. On the other hand, while the welfare of livestock at pasture is a critical issue, it has been less explored, also due to the need for specific protocols differing from those used in indoor conditions (Spigarelli et al. 2020; Aubé et al. 2022), especially with the use of remote technologies (Rivero et al. 2021; Aquilani et al. 2022). For the purpose of addressing animal welfare, the heart rate (HR), varying with physiological and psychological conditions, can index animal stress (von Borell et al. 2007; Kovács et al. 2014; Erdmann et al. 2018). For example, HR has been used to estimate or index energy expenditure (Green 2011), assess different sleeping phases (Hunter et al. 2021), indicate animal stress in various contexts (Hagen et al. 2005: cows during milking; Erdmann et al. 2018: early detection of metabolic stress in dairy cows; Kitajima et al. 2021: heat stress in free-ranging sheep and goat;). Heart rate can be monitored through different systems (Kovács et al. 2014), but the most frequently used in farm or field conditions are wearable electrode belts (Hagen et al. 2005; Essner et al. 2013; Kitajima et al. 2021) or implantable devices (Fuchs et al. 2019; Palacios et al. 2021) which however require surgical intervention. However, the application of devices to monitor heart rate in mountain pastures is, at the best of our knowledge, still unexplored. Therefore, the integration of GPS and heart rate monitoring provides an opportunity to enhance the understanding of livestock behaviour in these ecosystems, improving pasture management and animal welfare.

In the present study, we wanted to test the applicability of a commercial biologging system, composed of a sports watch with a GPS unit connected to an HR sensor attached to a wearable belt, to simultaneously monitor the movement, behaviour and HR patterns of grazing dairy cows in an alpine summer pasture. Our specific aims were a) to assess the positioning accuracy and efficiency of the acquisition of the GPS sensor and the possibility of using movement metrics for the remote detection of the main behaviour categories (resting, grazing, and walking); b) to assess the efficiency of data acquisition of the HR sensor and their association with GPS positions; c) to relate HR with movement, behaviour and environmental variations. We hypothesised that the HR would increase when the cows were grazing and especially walking with respect to when they were resting, when they experienced above-optimal thermal conditions and when they moved on steeper slopes. We conversely hypothesised that the HR would decrease during the night due to decreasing of the circadian rates of a reduction of metabolism. We also wanted to verify whether the HR differed between day and night, which could reflect a circadian rhythm (Kovács et al. 2016).

Material and methods

Sensors tested

We tested three 'Polar Pacer GPS sport watches' (hereafter: 'Polar Pacer') combined with three Polar H10 heart rate sensors (hereafter: H10) produced by Polar Electro, 90440 Kempele, Finland. Each Polar Pacer (weight = 40 g) contained a GPS unit and was used for the collection and storage of position data and the of HR data received *via* Bluetooth from the H10 (weight = 20 g). The H10 was attached to the Polar elastic belt (weight = 100 g), which incorporated two specific electrodes sensitive to the heart's electrical signals. The Polar Pacer can be set to collect positions at 1 s, 1 min or 2 min intervals, while the H10 records the HR as beats per minute (bpm) every 1 s. According to the manufacturer, the positioning error of the Polar Pacer is within 5 m.

Polar Pacer accuracy

We tested the positioning accuracy of the three Polar Pacers with stationary tests (Parraga Aguado et al. 2017) in open sky view or below tree canopy cover (> 70% of sky view obstructed) because, in most grazing conditions, these are the factors that may obstacle GPS signal transmission (DeCesare et al. 2005). We recorded the true position of 3 sites in open and 3 sites in canopy sky view as the centroid of 10 positions recorded by a portable GPS receiver (Garmin eTrex 10 with high-sensitivity, WAAS-enabled and HotFix satellite prediction, Garmin, Schaffausen, Switzerland). We positioned the three Polar Pacers in each site at approximately 1 m from ground level and recorded positions for two hours at 1 s, 1 min and 2 min intervals, between 10 am and 5 pm in variable weather conditions comprising cloudy and sunny periods. Therefore, our results include the possible variability associated with this factor which however is much lower than due to canopy cover (Sando et al. 2005; Zheng et al. 2005). We calculated the distance of each collected position from the true one both as a continuous variable ('position error') and as a binary variable ('error threshold') by classifying as 'below' all positions within 5 m (the error declared by the manufacturer) and as 'above' all positions above this threshold. We analysed the log-transformed 'position error' with a linear mixed model based on a normal distribution using the 'lmer' function of the 'lme4' library (Bates et al. 2015) and the 'error threshold' with a generalised mixed model based on a binomial distribution using the 'glmer' function of the 'lme4' library in R (Core Team Citation 2016). Both models implemented the 2–way interaction between sky-view (canopy and open) and position acquisition schedule (1 s, 1 min, 2 min), and the random effect of the Polar Pacer unit.

Study area, animals, GPS and HR data collection

The study was conducted in the 'Juribello' summer farm in the Trento province, eastern Italian Alps (46°18′45″N 11°46′31″E). Summer farms are temporary units traditionally used in the Alps during the summer transhumance of livestock from lowland permanent farms to alpine pastures (Sturaro et al. 2013; Zendri et al. 2016). The 'Juribello' summer farm is located at 1950 m a.s.l., where the climate is Alpine (Tattoni et al. 2010) with rainy and fresh summers (mean June-September 2000–2021: precipitation 147.5 mm ± 48.05 mm; temperature $10.9\,°C \pm 3.9$ °C). During the study period, it hosted a dairy cattle herd of 151 livestock units (LU) in a pasture area of 180 hectares, with an average stocking rate of 0.84 LU/ha. The cows were kept outside day and night and inside the barn only during milking.

We monitored three multiparous Brown Swiss and three multiparous Simmental lactating cows between August 2 and August 31, 2023. We alternated the two groups each week. We fastened the Polar Pacers on top of the collars worn by the cows to hold the traditional bell to ensure maximum sky visibility. We plugged in the H10 following the manufacturer's instructions and the procedure reported by Wierig et al. 2018. After wetting the coat, we fastened the elastic band to the cow's thorax, positioning the H10 and the electrodes on the left flank near the front leg. We set the GPS unit of the Polar Pacers to collect a position every two minutes and the H10 to collect the HR every second. Each day, during the evening milking, we downloaded the GPS and HR data from the Polar Pacers and cleaned and relocated the H10 bands. At the evening milking every four days, we removed the Polar Pacers and H10 to recharge their batteries and re-positioned them during the following morning milking. Therefore, the cows were monitored during both day (between the morning and evening milkings) and night (between the evening and morning milkings) for 11 days (for 20 h/d, excluding the milking periods), while for the other 18 days, they were monitored either during the day or the night (9 nights and 9 days for 10 h). During each milking, we noted the time spent by the cows in the barn, which we excluded from the analysis.

GPS data editing and efficiency of position acquisition

We stored the collected GPS positions in a geodatabase in PostGres SQL (version 14.5) with the PostGIS extension (version 3.2.3). We conducted data editing and all statistical analyses in R 4.3.1 (R Core Team 2016). For each pair of consecutive positions (i.e. each step of the movement trajectory), we first calculated the following movement metrics (Urbano and Cagnacci 2014; see Figure S1 and Table S1 for details): 'step length', as the distance in m, corrected for altitude differences between positions using the correction of spheroid WGS 84 with the PostGIS function ST_DistanceSpheroid (Urbano and Cagnacci 2014), 'step speed', calculated as time interval/'step length' (expressed in Km/h), and 'turning angle' (expressed in cosine of radiants) that indicates the deviation in direction of each step as respect to the previous one, calculated as in Urbano and Cagnacci (2014). We associated with each acquired position the 'step length' and 'step speed' of the preceding and following steps (i.e. the step ending and the one starting at the position, respectively, see Figure S1) and the 'turning angle' of these two steps. We then identified and excluded unreliable positions as those characterised by 'step speed' faster than 15 km/h and impossible combinations of 'step speed' and 'turning angle' ('step speed' $>$2.4 km/h and 'turning angle' < -0.97), according to Raniolo et al. (2022). We calculated the acquisition efficiency of GPS positions as a 'validated GPS position rate' that considered the ratios between the sums of GPS positions acquired and validated (i.e. after excluding outlier positions) and the sums of positions expected during each day and night and in total. To test the significance of differences in acquisition rates, we compared the corresponding the numbers of acquired/retained and expected positions with a Chi square test.

We then associated with each validated position 15 other movement metrics (see Table S1 for a detailed description) that, briefly, described the means and variability of movement metrics over 2, 3 and 4 steps and the distances between the centroids of pairs of consecutive groups of 2, 3 or 4 positions. As for the single positions, we calculated these metrics for the groups of steps preceding and following each position. Finally, we categorised each position for the individual cow, Julian date, hour, 'day-period' (day and night), slope expressed in degrees and obtained from a Digital Terrain model with a resolution of 25 m provided by the Natural Park 'Parco Naturale Paneveggio Pale di San Martino' (https://siat.provincia.tn.it/stem/), and the hourly Temperature Humidity Index (THI; Hahn et al. 2009; Rashamol et al. 2019), calculated from data of the weather station of Passo Rolle (46°17′52.5″ N, 11°47′13.6″ E) according to the equation of Kibler (1964).

Modelling behaviours from movement data

To model behavioural states from movement data, we used a procedure based on the association of the movement metrics obtained from the GPS of the Polar Pacer with the concomitant animal behaviours recorded from visual observation (Homburger et al. 2014). We observed the cows equipped with the Polar Pacers for 78 h (13 ± 4 h per individual). With the aid of a digital clock with a 1–second resolution, synchronised on the Polar Pacers time, we recorded the time spent into behavioural bouts of at least 10 s according to the following states: grazing (i.e. biting, chewing and swallowing, also if interrupted by relocation movements between clusters of plants; Owen-Smith et al. 2010); walking (with a clear directionality, without interruptions for grazing); and resting (i.e. standing without leg movements or lying). We then classified the GPS positions ($N = 2338$) collected during the observation time as grazing, walking, or resting when these behaviours were observed for 60% or more ($\geq$ 72 s) of the 120 s of each step preceding the position. To integrate this dataset, we added 3761 positions (equivalent to 125 h) which, based on the movement features, could be unequivocally assigned to grazing (the position is part of a sequence with slow 'step speed' at short 'step lengths' along irregular directions), walking (the position is part of a sequence with fast 'step speed' at longer 'step lengths' with clear directionality) and resting (the position is part of a sequence with short 'step lengths' at random directions around a centre, due to the random error of location), according to Raniolo et al. (2023). We obtained a final database of 6099 behaviour-associated positions (equivalent to 203 h) that we used to develop two sequential random forest classifiers (Valletta et al. 2017) with the function 'random forest' of the library 'random forest' (Liaw and Wiener 2002). First, we developed a model to classify the positions corresponding to active (grazing and walking) and inactive (resting) behaviours using 2000 active and 2000 inactive randomly selected positions. These numbers are equivalent to 133 h of observations, which are similar or higher than in other studies (Homburger et al. 2014 – 44 h; Balasso et al. 2021 – 27.3 h). In this way we wanted to balance the trade-off between the increased accuracy and the require computational effort (Bergen et al. 2023). Then, we randomly extracted 1200 active positions to develop the second model for separating grazing from walking positions. Both models implemented the movement metrics associated with each position (see Table S1 for details). We randomly split each dataset into a training (80% of positions) sub-dataset to develop the model and a testing (20% of positions) sub-dataset to test it. We estimated the relative importance of each variable for the classification with the Gini index (Nicodemus 2011 – see Figure S2). After testing the models, we applied them to assign behaviours to all the validated GPS positions.

HR data acquisition efficiency

First, we edited the HR (bpm) values following the suggestions of Wierig et al. (2018), excluding values below 40 bpm and above 190 bpm due to their physiological incompatibility with cows (Kovács et al. 2015). We also considered the RR interval (i.e. the time between two heartbeats, measured in milliseconds as the ratio between 60,000 ms and the bpm number; Malik et al. 1996; von Borell et al. 2007), excluding the intervals that differed by more than 100 ms from the previous one, as indicated by Marchant-Forde et al. (2004) and Wierig et al. (2018). Then, we calculated an 'HR acquisition rate' that considered the ratios between the sums of the acquired and validated heart rates (at 1–second intervals) and of those expected in each day and night and in total. In addition, since we were interested in associating the HR with GPS positions and behaviours, we calculated a 'HR-GPS acquisition rate' that considered only the HR values that could be associated with acquired and validated positions. For this purpose, since we had collected positions at 2–minutes intervals and HR at 1–second intervals, we associated with each validated position the mean of the HR values acquired in the 120 s interval preceding its acquisition ('HR-GPS mean'). In this process, we excluded the positions associated with less than 60 HR measurements (i.e. less than 50% of acquired over expected HR values in the 120 s interval). We then calculated 'validated GPS-HR acquisition rates' as the ratios between the sums of retained 'HR-GPS means' and the sums of validated GPS positions in total, in each 'day-period', and for each 'day-period' and behaviour, respectively. To test the significance of differences in acquisition rates, we compared the corresponding numbers of acquired/retained and expected positions with a Chi square test.

Factors of variation of HR

To complement the 'HR-GPS means' with a measure of heart rate variability, we calculated the difference between the maximum and minimum HR values ('Max-min HR') within each 120–second interval associated with GPS positions. (Shaffer and Ginsberg 2017). This heart rate variability metric is related to respiratory sinus arrhythmia in humans and gives information about the respiration-driven speeding and slowing of heartbeat through the vague nerve (Shaffer and Ginsberg 2017). We chose this metric because it is more related to physical effort than psychological stress, and the 2–minute GPS position acquisition schedule was shorter than the intervals recommended for other HRV metrics, such as RMSSD (Shaffer and Ginsberg 2017).

We analysed the 'HR-GPS means' and the 'Max-Min HR' with a generalised linear mixed model based on a normal distribution after a log transformation of dependent variables using the function 'glmmTMB' from the 'glmmTMB' library (Brooks et al. 2023). The model included the random effect of the individual cow and the fixed effects of the class of THI (≤ 50; $>50 \leq 60$; > 60), the class of slope (degrees: ≤ 5; $>5 \leq 10$; $>10 \leq 15$; $>15 \leq 20$, >20) and the 2–way interaction between behaviour (three levels: resting, grazing, and walking) and day-period (two levels: day and night). We verified the assumption of normality of residuals with the function 'simulateResiduals' from the 'DHARMa' library (Hartig and Hartig 2017) and the collinearity with the function 'check_collinearity' from the 'performance' library (Lüdecke et al. 2021).

Results

Polar Pacer GPS accuracy and position acquisition rates

With the position acquisition schedule increasing from 1 s to 1 min and 2 min, the 'position error' (Figure 1, panel A) varied between 0.8 m to approximately 2.0 m in open sky view and from 2.2 to approximately 3.6 m under canopy cover (interaction sky view x position acquisition schedule: $p < 0.001$; see Table S2 for the coefficients of the model). At the same position acquisition schedules, the probability of the error being within the threshold of 5 m (Figure 1, panel B) varied from almost 1 to around 0.9 in open sky view and from 0.95 to 0.77 under canopy (interaction sky view x position acquisition schedule: $p < 0.001$; see Table S2 for the coefficients of the model). Although the interaction was statistically highly significant, the effects of sky view and position acquisition schedule followed nearly parallel patterns, with the effect of sky view being more important.

In the *in vivo* study, we acquired 34889 GPS positions out of the 34944 expected (99.8%). We excluded 1737 positions (5.0%) as outliers and validated and retained 33152 positions. Therefore, the average 'validated GPS acquisition rate' was 94.9%. It was significantly affected (Chi square: 11.15; df: 1; $p < 0.001$ – Table S4) by 'day-period', being lower during the night than during the day, but the difference was very small (93.9% *vs* 97.4%; Figure 1, panel C).

Inference of behaviours from movement data

The Random Forest model classifying active and inactive positions had a lower performance than the model classifying the active positions into grazing and walking positions, but both showed highly significant predictive ability (see Table S3 for the coefficients of the models). The model classifying active and inactive positions had an error rate of 10.9% in predicting those active and of 16.8 in predicting those inactive. The model classifying the active positions into grazing and walking positions an error rate of 5.6% in predicting the grazing ones and an error rate of 3.0% when predicting the walking ones (Figure 2). The relative contributes of movement metrics to the classifications differed between the two models (Figure S1). The classification of active and inactive positions depended more on metrics calculated over 2 and 3 steps and that of grazing and walking positions depended more on metrics calculated over 1 and 2 steps.

HR acquisition rates

We acquired 2936466 1–second HR values out of the 4186680 expected, with an average 'HR acquisition rate' of 70.5%). The 'HR acquisition rate' was markedly lower during the night than during the day (56.1% *vs* 80%; Chi square: 82770; df: 1; $p < 0.001$- Table S4;

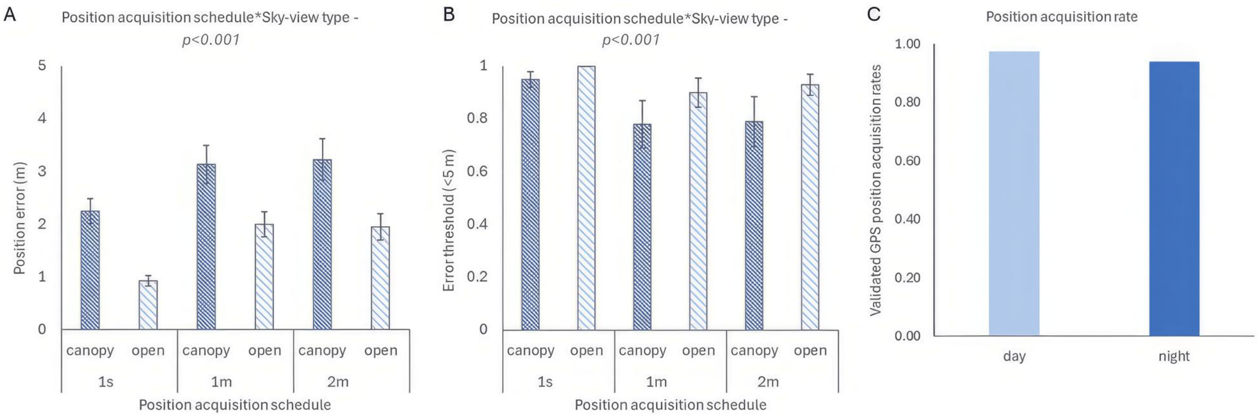

Figure 1. Effects of the two-way interactions between position acquisition schedule (1s: 1 s; 1 m: 1 min; 2 m: 2 min) and sky view on the Polar Pacer 'position error' (distance in m from the true position, panel A) and 'error threshold' (probability of the position error to be lower than 5 metres, panel B). Whiskers indicate 95% confidence intervals. For details of the coefficients of the statistical models, see Table S2. Panel C shows the effect of the 'day-period' on the 'validated GPS acquisition rates' (validated GPS positions/expected GPS positions).

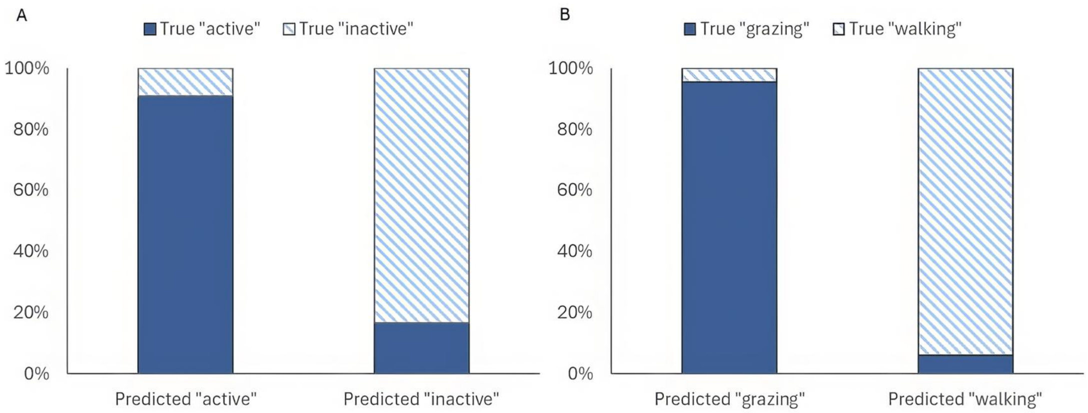

Figure 2. Error rates of the random Forest models differentiating between active and inactive positions (panel A) and between grazing and walking within active positions (panel B). For details of the statistical models see Table S3.

Figure 3, panel A). In editing the data, we excluded from the analysis 47837 acquired HR values (1.65%) which were below 40 bpm or above 190 bpm and 1665 HR values (0.05%) that differed by more than 100 ms from the previous ones. In the process of associating the HR values with the validated GPS positions ($N = 33152$), we excluded 10640 'HR-GPS means' (32.1%) calculated on less than 60–seconds intervals. Therefore, the final validates GPS positions associated with 'HR means' were 22512 with an average 'validated GPS-HR acquisition rate' of 67.9%. This value was the result of acquisition rates being remarkably higher during the day when they differed little between behaviours (range: 75.2–78.7%; Chi square: 3.12; df: 2; $p = 0.21$ -Table S5) than during the night, when they were lower for resting than for the other behaviours (grazing: 73.9%; walking: 72.9%; resting: 58.9%; Chi square: 96.58; df: 2; $p < 0.001$ -Table S5; Figure 3, panel B).

Factors affecting the variation of HR

The 'HR-GPS mean' showed high variability among individuals (see Figure S2 for a visual comparison), as indicated by the conditional R^2 of the model being 2.5 times higher than the marginal R^2 (see Table S6 for the coefficients of the model). It increased significantly from the lowest to the highest classes of THI (from 72.1 ± 0.5 bpm to 76.7 ± 0.6 bpm, Figure 4, panel A; $p < 0.001$), and slope (from 71.6 ± 0.4 bpm to 75.8 ± 0.6 bpm, Figure 4, panel B; $p < 0.001$). The 'HR-GPS means' were lower for resting than grazing and walking, and at night than during the day, but only when cows were grazing (resting-day: 64.4 ± 0.4 bpm; resting-night: 63.8 ± 0.5 bpm; grazing-day: 73.8 ± 0.4 bpm; grazing-night: 69.8 ± 0.5 bpm; walking-day: 73 ± 0.5 bpm; walking-night: 73.8 ± 1.5 bpm; Figure 4, panel C; $p < 0.001$).

The individual random effect on the 'Max–min HR' was less marked than that observed on the 'HR-GPS

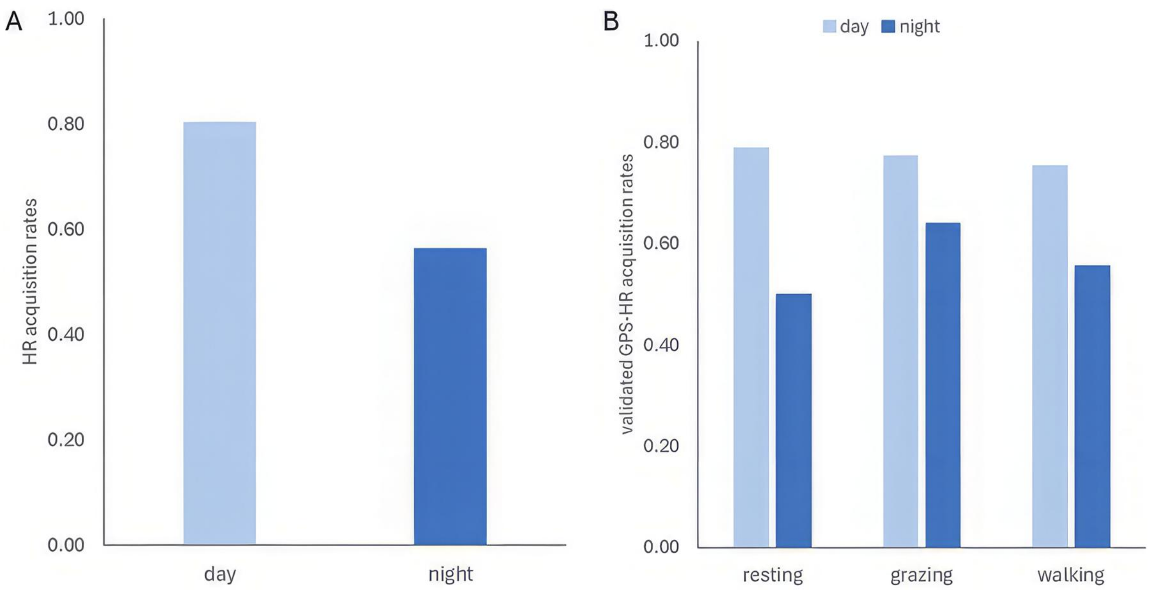

Figure 3. 'heart rate (HR) acquisition rates' (acquired HR values/expected HR values, panel A) during night and day, and 'validated GPS-HR acquisition rates' (validated HR and associated GPS positions/validated GPS positions; panel B) when cows were resting, grazing and walking. See text for a description of variables and Table S5.

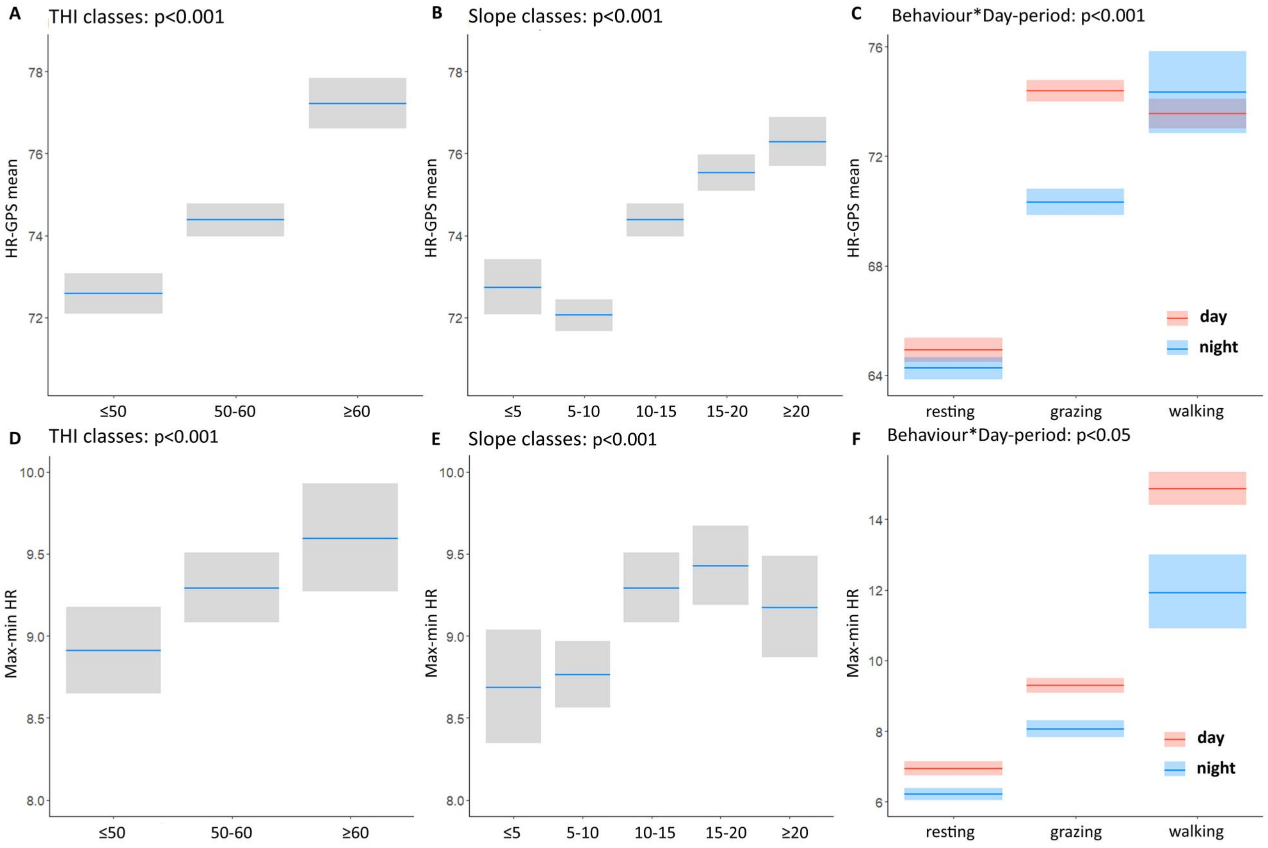

Figure 4. Predicted effect after exponential back-transformation of the class of THI (three levels: ≤50; >50 ≤ 60; > 60), class of slope (degrees, five levels: ≤5; >5 ≤ 10; >10 ≤ 15; >15 ≤ 20, >20) and the 2–way interaction between behaviour (three levels: resting, grazing, and walking) and 'day-period' (two levels: day and night) on the 'HR-GPS mean' (mean of the HR values associated with each validated GPS position) and 'Max–min HR' (difference between the maximum and minimum HR values in associated with each validated GPS position). Shaded areas indicate the 95% confidence intervals. For details about the models' coefficients, see Table S6.

mean' (Table S6). The 'Max–min HR' increased significantly from the lowest to the highest THI classes (from 8.9 ± 0.3 bpm to 9.6 ± 0.3 bpm; Figure 4, panel D, $p < 0.05$) and with slope classes steeper than 10 degrees (from 8.7 ± 0.3 bpm to 9.4 ± 0.2 bpm and then to 9.2 ± 0.3 bpm; Figure 4, panel E, $p < 0.001$), but with a much less marked trend that of the HR-GPS mean'. The 'Max-min HR' increased from resting to grazing and to walking, consistently showing higher values at daytime than night-time (resting-day: 6.9 ± 0.2 bpm; resting-night: 6.2 ± 0.2 bpm; grazing-day: 9.3 ± 0.2 bpm; grazing-night: 8.1 ± 0.2 bpm; walking-day; 14.8 ± 0.5 bpm; walking-night; 11.9 ± 1 bpm; Figure 4, panel F, $p < 0.05$).

Discussion

We will discuss our results by first considering the Polar pacer's suitability for monitoring animal movement (positioning accuracy and acquisition rate) and modelling behaviours from movement metrics. Then, we will address the efficiency of HR data acquisition and its association with movement steps. Finally, we will discuss how the HR patterns varied in response to day-period, behaviour, THI, and slope.

Polar Pacer suitability for monitoring movement and behaviours

The analysis of the GPS error confirmed the manufacturer's indications of the positioning error mainly being well below 5 metres under both canopy and open sky view, with median errors ranging between 2.39 m and 1.00 m according to positioning schedule and sky view. Other systems designed specifically for tracking free-ranging mammals, had similar errors (Forin-Wiart et al. 2015; Parraga Aguado et al. 2017). The decrease of accuracy with a less frequent positioning schedule was expected (Acácio et al. 2022), but it was of a minor magnitude. This small effect is most probably related to the range of location intervals being very frequent (between 1 s and 2 min), which allowed a continuous contact with the visible satellites. Considering the accuracy range of the positions and the speed of movement of the cows (median 'step speed': 0.15 km/h), the 1–second schedule does not seem able to discriminate between true movement and positioning error. Since the accuracy does not vary between the 1–minute and the 2–minutes position schedules it is possible to choose the more extended schedule to reduce battery use and increase monitoring time if needed. Accuracy was lower under canopy cover than open sky view, and also this result was expected because the tree canopy partially obstructs the transmission of the satellites signal (Hansen and Riggs 2008; Parraga Aguado et al. 2017). This decrease, however, although being proportionally important (the error increased by approximately one third) does not seem to affect the possibility of estimating movement patterns markedly, because the median error remained low (1.2 m) and the proportion of locations within 5 m remained remarkably high (range: 0.77 – 1).

The suitability of the Polar Pacers for the high-frequency monitoring of movement patterns of the cows is confirmed by the very good position acquisition rate and low outlier proportions that were in the range of those observed for grazing cows in Alpine pastures with other dedicated systems (Raniolo et al. 2023). In wild herbivore species, behaviour may affect position acquisition rate and accuracy (Moen et al. 2001; Bourgoin et al. 2009, Parraga Aguado et al. 2017), probably because different behaviours, and especially resting, are associated with the choice of habitats with a reduced sky-view and/or body mass obstructs the satellites signals. In our study, the small differences in the Polar Pacers' performance observed between daytime, when cows were mostly grazing and walking, and during night-time, when they were mostly resting, indirectly suggest this was not the case. The GPS positions can be very useful for the assessment of the selection of land cover and other environmental features exerted by grazing livestock (Homburger et al. 2015; Raniolo et al. 2022; 2023). Since missed locations do not occur randomly but happen more frequently when animals use habitats with lower sky views, estimates of the use of these habitats might be biased. In this respect, average position acquisition rates above 90% are recommended to ensure unbiased estimates (Frair et al. 2010; Dupke et al. 2017). In our study, this requirement was satisfied.

Remote inference of free-ranging animals' behaviours in GPS positioning studies can be obtained with good accuracy by using the signals of accelerometers embedded in the devices, alone (Semenzato et al. 2021; Riaboff et al. 2022) or in combination with movement metrics (Guo et al. 2009; Brennan et al. 2021; Raniolo et al. 2023). In the absence of accelerometers, provided that high-frequency positioning schedules and detailed trajectories are available, movement metrics describing the specific patterns of movement associated with different behaviours can be used (Homburger et al. 2014; de Weerd et al.

2015). Although our GPS positioning schedule had longer time intervals than those used in these studies, by using a two-step consequential random forest modelling, we were able to achieve accuracy values comparable to those obtained with the use of accelerometers (Semenzato et al. 2021; Raniolo et al. 2023; Versluijs et al. 2023). The use of variables considering metrics calculated over multiple consecutive steps was essential to this result, especially for separating the active positions (when considering multiple steps allowed to capture the progressive shift of animals' positions) from the inactive ones (when animals were not shifting their positions and the steps were due only due to the positioning error, which resulted in lower distances and random angles between consecutive steps). In the case of assessment of behaviours being the main purpose of a study and/or more specific and rarer behaviours than the ones we used here being addressed (de Weerd et al. 2015), we suggest that tighter positioning schedules than the 2 min used here could be used. However, very tight schedules might introduce a bias because the positioning error might be larger than the distance possibly covered in the time intervals between locations. Finally, the results that we obtained on the HR variation in response to behaviour (see below for this discussion) suggest that HR could be used to complement movement metrics in differentiating active from inactive positions. In this study, however, since we wanted to assess the variation of HR during different behaviours, we did not use HR for behaviour assessment to avoid introducing circularity.

Efficiency of HR data acquisition

The extensive monitoring period, which covered all hours of the day, highlighted significant variations in the efficiency of the HR recording system. This efficiency was significantly higher during the day than at night, likely due to the prevalence of the resting behaviour at night. During resting, especially when animals lay down for prolonged periods, as during the night (Raniolo et al. 2023), the elastic band is more susceptible to accidental movements and possibly detachments from the skin, which would lead to a loss of the heart rate signal (Hopster and Blokhuis 1994; von Borell et al. 2007; Wierig et al. 2018). The mispositioning of the elastic band probably persisted when the cows resumed active behaviours, which would explain why signal losses were higher for grazing and walking during the night than during the day. On the contrary, during the day, when resting periods are much shorter and often with the cows standing, accidental mispositioning of the elastic band is much less frequent, and signal losses are lower and are little influenced by behaviour.

One limitation due to the HR signal losses is that they reduce the number of available positions when these positions must be associated with HR values. On the other hand, most of the physically challenging behaviours occur during the day, when the efficiency of acquisition of the HR signal, although lower than that of GPS positions, allowed to use 75–80% of the available positions and examine variation of HR in relation with movement and other factors (see below). To the best of our knowledge, there are no studies considering the efficiency of HR acquisition with this system in free-ranging livestock, which prevents us from comparing it with other studies. On the other hand, if monitoring of movement and HR are addressed in short-term studies, for instance, during transportation to summer farms, interactions between individual animals or with personnel and other humans as tourists, interactions with dogs, etc., the impact of signal losses is expected to be much lower.

Factors of variation of heart rate

The 'HR mean' values differed highly among individuals, as has been observed by others (Minero et al. 2001; Hagen et al. 2005; Kovács et al. 2015; Frei et al. 2022). Interestingly, the individual effect on the 'Max-min HR' used to index HR variability was less marked than that on the 'HR mean', suggesting that individual cows differed more in their HR intensity than relative variability. In this preliminary study, we did not have the sample size to test the effects of breed, body weight (Hagen et al. 2005), productivity and possibly other individual factors (Frei et al. 2022) that might partially explain individual variability and should be investigated further in future studies.

In general, the HR range of the dairy cows at pasture was within the values reported in the literature in different contexts (Frondelius et al. 2015; Kovács et al. 2015; Frei et al. 2022), and HR very rarely exceeded 100 bpm (see Figure S3). This suggests the absence of prolonged or important stressing conditions during the study period (Comin et al. 2011). However, the HR responded clearly to environmental and movement variables, suggesting, if not yet, conditions of stress, processes of adaptation to external influences, and an increase in the energy costs for the animals. Below, we will briefly address the specific responses to each variable.

Thermal stress risk is increasing in the European context (Hempel et al. 2019), and the observed increase of HR variables with THI was expected, because high temperature and humidity can induce a higher heat dissipation through the peripheral circulatory system of the animal and a faster respiration rate (McCafferty et al. 2017, de Andrade Ferrazza et al. 2017; Galán et al. 2018; Pinto et al. 2019) that require an increase in HR. The cut-off values of heat stress in dairy cows are indicated at 68 – 75 for THI (Armstrong 1994; Dikmen and Hansen 2009; De Rensis et al. 2015). These values were never reached during the study (min: 40, max: 68, mean: 53). Still, our results indicated a linear increase of both 'GPS-HR mean' and 'Max-min HR' in response to enhanced THI that, although being moderate, suggests a response by the animals. Cut-off values of thermal stress indexes may be context-specific, and in conditions varying from indoor housing, and grazing thresholds between 60 and 75 were indicated (Brügemann et al. 2012; Hammami et al. 2013; Gorniak et al. 2014; Lambertz et al. 2014; Pinto et al. 2020; Hut et al. 2022). In addition, thermal stress can both influence and be influenced by behaviours (Hut et al. 2022) and it tend to be lower in outdoor condition under sunlight's that increases the effect of temperature (Gaughan et al. 2012).

In addition to THI, slope positively affected 'GPS-HR mean' and 'Max-min HR'. Moving in steeper areas requires a greater effort. Thus, this effect of the slope was expected. As for the case of THI, the increases in HR mean values and variability were moderate, but it suggests an increase in the energy costs of movement. Dairy cows prefer flat areas and avoid slopes steeper than 30 degrees (Raniolo et al. 2022, 2023), and they might limit energy costs by reducing speed and/or moving horizontally when walking on steeper areas, but these adaptions were insufficient to counterbalance the increased effort fully. Therefore, using marginal areas, which are usually steeper and farther from the barns (Sturaro et al. 2009), implies a higher energy cost for the animals, especially during the hottest daily hours. A reasonable management implication is that cattle should be conducted to marginal/steeper areas in the cooler days or hours, although shepherds might prefer the opposite (Raniolo et al. 2022).

The HR varied in response to behaviours and time of the day. In general, and as we expected because of increased cardiovascular activity (Kézér et al. 2017), both HR metrics increased from inactive to active behaviours. However, the 'HR-GPS mean' did not differ between grazing and walking during the day. We do not have a clear explanation for this result. We may hypothesise that during the day, when most of the grazing and walking occur (Raniolo et al. 2023), cows frequently shifted between the two behaviours and, hence, maintained a higher HR. In addition, we found that the HR variables had lower values during the night, which might reflect a circadian rhythm (Piccione et al. 2005), except for the 'HR-GPS mean' that did not differ between times of the day when cows were resting and walking. Again, we have no clear explanation for this discrepancy. When resting, cows had the lowest HR values, which might limit the effect of a night-time reduction of cardiovascular activity. On the other hand, walking during the night was very limited, as indicated by the high confidence intervals (see Figure 4, panel C), and this might have influenced the lack of difference with grazing. In any case, it is interesting that the 'Max-min HR' we used as an index of heart rate variability responded much more clearly to behaviours and time of the day than the mean HR values. Further studies are needed to address the possible effects of circadian activity rhythms and their interaction with behaviours in HR frequency.

Finally, the clear differences in HR mean and variability between behaviours suggest that these metrics could be used to complement movement metrics in modelling behaviours to increase the accuracy of predictions. However, this integration would limit the databases since acquired HR values are less than acquired positions, and it is not advisable when HR has to be compared between behaviours.

Conclusion

In this study, we found that a low-cost commercial biologging system provides reliable and frequent positioning of cattle grazing in mountain pastures and can be used to predict their main behaviours. Heart rate data acquisition was less efficient than GPS tracking, likely due to sensor mispositioning during extended monitoring. Overcoming this limitation might be difficult and will require dedicated system improvements. Also, considering the short battery life that requires frequent recharges, this system appears most practical for short-term, intensive studies that might involve in this study, we found that a low-cost commercial biologging system provides reliable and frequent positioning of cattle grazing in mountain pastures and can be used to predict their main behaviours. Heart rate data acquisition was less efficient than GPS tracking, likely due to sensor mispositioning during extended monitoring. Overcoming this limitation might be difficult and will require dedicated improvements to the system developed for short-term monitoring. Therefore, considering the short battery life that requires frequent recharges, this system appears most practical for short-term, intensive studies that might involve even large numbers of animals if they can be easily grouped and handled. Despite these limitations, the combined GPS-heart rate data acquisition over our extended monitoring was sufficient to detect how heart rate frequency and variability increased with active behaviours, steeper slopes, and higher temperature-humidity index (THI), indicating physiological responses to environmental factors. These results suggest that the system tested can also help study how livestock impact pastures by varying their spatiotemporal intensity of use and how pastures and environmental conditions may impact their welfare. This information would be beneficial for improving grazing management to combine animal welfare and productivity and pastures' ecosystem services. Future research should also investigate animal-specific factors that might contribute to heart rate variability, such as age, breed, body weight, and productivity, that we could not address here. We recommend also expanding the studies to conditions that, because of management practices (e.g. the transport from the permanent farms to the summer pastures and the subsequent adaptation, the grouping and moving of livestock between plots) or environmental conditions (e.g. slope, distances between plots, environmental temperature), are more challenging than those experienced by the cows in this study.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Ethical approval

The study was approved by the ethical committee of the University of Padova with prot. number 49172.

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Data availability statement

The data of this study are freely available from the corresponding author upon request. The data are not publicly available due to the involvement of private partners (farmers).

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