Towards sensor-based calving detection in the rangelands: a systematic review of credible behavioral and physiological indicators

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ABSTRACT: Calving is a critical point in both a cow and calf's life, when both become more susceptible to disease and risk of death. Ideally, this period is carefully monitored. In extensive grazing systems, however, it is often not economically or physically possible for producers to continuously monitor animals, and thus, calving frequently goes undetected. The development of sensor systems, particularly in these environments, could provide significant benefits to the industry by increasing the quantity and quality of individual animal monitoring. In the time surrounding calving, cows undergo a series of behavioral and physiological changes, which can potentially be detected using sensing technologies. Before developing a sensor-based approach, it is worthwhile considering these behavioral and physiological changes, such that the appropriate technologies can be designed and developed. A systematic literature review was conducted to identify changes in the dam's behavioral and physiological states in response to a calving event. Articles (n = 104) consisting of 111 independent experiments were assessed following an intensive search of electronic databases. Commonly reported indicators of parturition (n = 38) were identified, and temporal trend graphs were generated for 13 of these changes. The results compare trends in behavioral and physiological changes across a variety of animal-related factors and identifies several reliable indicators of parturition for detection with sensors, namely calf grooming behavior, changes in rumination duration, and lying bouts. This synthesis of literature suggests that variability exists between individuals and thus, combining several calving indicators may result in a more broadly applicable and accurate detection of parturition.

Key words: behavior, cattle, parturition, precision livestock management

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INTRODUCTION

Reproductive efficiency is an important driver of economic profitability in commercial cattle production. In dairy production systems, pregnancy and consequently calving are essential processes for the production of milk. Similarly, in beef cow–calf operations, the profitability of the enterprise is reliant upon the successful production and growth of calves to weaning. Calving is a period of increased biological challenge and risk, marked by a series of behavioral and physiological changes. Complications during the calving period can result in cow and calf morbidity or death, leading to reduced economic and animal welfare outcomes. The most common complication is

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dystocia, which refers to an abnormal, prolonged, and/or difficult calving, the period of time which commences with the onset of uterine contractions (Meijering, 1984; Mee, 2008). Dystocia increases the likelihood of stillborn calves and decreases calf vigor during the neonatal period (Riley et al., 2004; Barrier et al., 2012). Close monitoring of cattle around the time of calving can assist in the early detection and adequate management of complications. Traditionally, monitoring the behavioral and physiological changes associated with calving has been undertaken by experienced managers through careful observation in the field. The extensive nature of some production systems prevents close human observation of animals in the herds, and in some situations, the lack of available skilled labor further limits the capacity to conduct these observations.

To overcome these limitations, the livestock industry has been exploring the potential for technologies to remotely detect the behavioral and physiological changes associated with parturition. There are several examples of sensor systems, which have been developed or modified to detect parturition, however, most remain relevant in a research context or, at best, in more intensive production systems (Trotter, 2010; Trotter et al., 2010). To optimize a parturition detection system for extensive grazing systems, an enhanced understanding of the anticipated behavioral and physiological factors likely to be expressed is needed.

A systematic literature review was conducted to examine the results of scientific studies pertaining to behavioral and physiological changes expressed by a cow before, during, and after calving. The following questions were explored: 1) How does cow behavior and physiology change around a calving event? 2) How does methodology, breed, and production style vary in existing literature? 3) How could the behavioral and physiological indicators of calving best be detected using sensor technology?

MATERIALS AND METHODS

Search Strategy

A systematic literature review methodology based on that described in Williams et al. (2016) and Fogarty et al. (2018) was used for searching for articles for inclusion in this review. This methodology involved searching online databases to find articles that met a number of strict criteria (Grant and Booth, 2009). Further evaluation was conducted to determine whether the results of the articles were quantitative and sufficiently comparable to undertake a meta-analysis (Grant and Booth, 2009). In this review, however, the variation between data were too substantial and a true meta-analysis could not be conducted.

Electronic databases were searched in March 2018 for literature investigating changes in the behavior and physiology of cows around a calving event. The databases utilized for the search were BioOne, ProQuest, ScienceDirect, and Web of Science. Articles that met the set criteria underwent a further bibliographic search for relevant articles. The terms used in the database search included combinations of the following terms: "behavior*," "birth*," "calf," "calving*," "cow*," and "parturition*."

Articles had to meet the following criteria to be included: 1) be written in English; 2) identified cattle as the primary subjects; 3) had to occur within 1 mo prior to and/or following parturition; and 4) had to be focused on dam behavior and/or physiological changes. Books and book chapters that were unavailable electronically were excluded. Literature review articles were excluded, but any literature reviews of a relevant topic underwent an extensive bibliographic search, with appropriate references subsequently included. Dissertations and theses were automatically filtered out on ProQuest; however, if a dissertation or thesis was identified during a bibliographic search, the thesis was included. No other dissertations or theses were found using any of the other database search engines. Similarly, conference papers were also excluded unless these were published or referenced in a subsequent peer-reviewed article. In experiments where human intervention occurred, such as the administration of pharmacological substances, the induction of parturition, or caesarean sections, these articles were excluded. The exception to this was an article where cow–calf separation occurred (Lidfors, 1996). Because the intervention did not directly affect the process of parturition, all prepartum and calving changes were included, but all results were omitted following the dam–calf separation.

Data Collection and Extraction

For each study that met the required search criteria, the author, year of publication, and title were recorded. Articles with multiple experiments using different animals that were studied independently of one another, were considered separate experiments. In the event where each independent experiment examined a different calving indicator and for which there were inconsistent results, the experiment in which the change was observed was recorded. For example, in Lidfors et al. (1994), which was made of three independent studies, isolation was only observed in experiment two and three, and would be labeled as so, whereas location changes were shown in all three experiments and thus the experimental number was not disclosed. The experimental location was recorded by country then by geographic region (Africa, Asia, Europe, North America, South America, and Oceania). If no experimental location was provided, the location was considered to be the address of the first author of the article. The experimental animals were classified based on a combination of breed and experimental site—dairy cattle, extensive beef cattle, and intensive beef cattle. Dual purpose animals were classified based on the descriptor in the article and if none was provided, the experimental animals were considered to be beef cattle. For the purposes of the present literature review, extensive beef cattle were those that had access to pasture for the entirety of the trial, although intensive beef cattle were any species that did not have constant access to pasture or where the experimental conditions were not specified. Number of experimental animals was recorded, as well as birth type (dystocia, eutocia, both), cattle breed, and parity (multiparous, primiparous, both). If the birth type was not specified, it was assumed that a normal birthing process had occurred. For each independent experiment, the duration and intensity of observations were recorded relative to the point of calving (the point at which the calf is fully expelled). Experimental intensity was more broadly categorized as being high intensity (50% or more of the time monitored) or low intensity (less than 50% of the time monitored) For experiments that commenced based on a behavioral change, such as the first stage of labor (Selman et al., 1970; Wehrend et al., 2006), behavioral signs of parturition (Owens and Edey, 1985), the visibility of the amniotic sac (Schuenemann et al., 2011), and the appearance of the calf's hooves (Lidfors et al., 1994), start and end points were calculated based on the time intervals identified in any of the articles that met the search criteria. Methodology and technology usage was first recorded as methodology or technology type (accelerometer [leg-deployed], accelerometer [other, e.g., collar or ear tag], blood sample, feed intake monitor, global positioning system [GPS], heart monitor, liver biopsy, real time forage weighing, visual observation, ruminal bolus, ruminal fluid sample, rumination monitor, spectrophotometer, tail movement detector, temperature data logger, thermometer, video, and water intake monitor), then categorized more broadly by methodology or technology type (sensor technology and traditional methodology). Technologies were classified as sensor, where the devices had the capacity to store or transmit data, although traditional methodologies required manual data collection with further analysis. Rumination monitors were considered to be rumination detection systems that were microphone based. Accelerometers that were used for the purposes of rumination detection were categorized as being accelerometers. Rumination halters were halters that utilized a pressure sensor to determine when a cow was ruminating.

Data Analysis

The results of each independent experiment were analyzed to identify any behaviors or physiological changes that were associated with parturition. Behaviors that were identified in three or more articles were categorized as "commonly reported" indicators of parturition. Indicators that were observed instantaneously as being present or absent, were scored on a discrete scale, or had discrete characteristics were excluded from temporal analysis. These were considered "categorical" indicators. For example, dam isolation from the herd was observed as being present or absent at the end of the calving period, udder changes were observed on a scale corresponding to the state of the udder, and location consisted of discrete, non-measurable characteristics, such as calving on the sand or calving in a forest. A present or absent status was allocated based on the behavior or physiology displayed by the majority of the animals. For example, in Lidfors and Jensen (1988), 2 of 20 cows were observed isolating themselves prior to calving, therefore, the study was recorded to have an "absent" status for isolation, as the majority of animals did not isolate themselves.

A simple vote counting method was used to compare the number of experiments that reported positive, negative, or no change trends for each indicator with temporal data pre- and post-parturition, where each observation was delineated a "point" or "vote" for the corresponding category (Williams et al. (2016). These indicators were considered "continuous" The trend of change was determined based on the magnitude of change between the values at the start of the observation to the end; therefore, if a spike was detected midway through the observation period, it was ignored. If there were multiple categories of animals with different trends, another "vote" was allocated. Articles where the continuous variable was observed instantaneously, or its presence was simply noted, were omitted from the vote counting, but were still included in the corresponding reference list.

Articles reporting trends over time were common in the literature, and so a method of broadly visualizing the trends in these results was developed. Time series graphs were generated for behaviors and physiological changes where quantifiable data was made available in five or more independent studies. Two temporal graphs were generated for each of the described changes—a short-term graph depicting the 24 h prior to and following parturition, and a long-term graph spanning the 30 d prior to and following parturition. This approach ensured that there was sufficient data generated for a baseline trend (control) to be established for comparison to parturition behaviors or physiology. The latest timeframe any study used as a control period was 1 d prior to parturition (Miedema et al., 2011a, 2011b). Data collected over a time period were plotted as occurring at the end of the observation period. For example, if lying behavior was observed from −10 to −2 h, the data would be plotted for the −2 h time point. In many studies, observations ceased at common time points, such as −2h, but commenced over a variety of periods, for example, −10h and −5h. By allocating the data value to the end point of the observation period, the number of datapoints at commonly reported time points, such as −2h, is maximized. As such, the trendline generated for the time series graphs experiences less bias as there are fewer single datapoints to skew the line. A new series was generated for each experimental unit, for different parities, and/or for different birth types. If figures were made available, but no data were presented or discussed in the text, the data were estimated from the figures.

On a subday scale, all sources that did not have a data point within the 24 h time period were excluded from the graph to increase clarity. When constructing the long-term graphs, measurements were only included if these were recorded at a minimum interval of 24 h. For example, if dry matter intake was measured from −4 to −1 d, this data point would be excluded from the long-term graph, as the interval was for more than 24 h. In the event where two units were used for a physiological change, for example, µg/mL and ng/mL, and a direct conversion was not possible, a secondary axis was used to plot the second measurement.

To enable a basic visualization of the changes in physiological or behavioral characteristics, all data were plotted using a time series point plot. A simple means of visualizing the overall trend in physiological or behavioral characteristics was developed. The values generated for each timeframe were averaged, and a rolling mean was created from the data, incorporating the value for the time prior to and following any one interval. This reduced the incidence of skewed and biased data, due to the lack of data present for some timeframes. The visualization technique developed is not intended to represent the true or absolute likely changes expressed in the data but is designed to provide an overall indicator of likely variation over time. There are obvious limitations to this technique, where large variation in the range of data exists. This will be highlighted in the results and discussed later.

RESULTS

Search Statistics

The database search returned 594 articles for analysis. Approximately 15.8% (*n* = 94) involved other species that were not cattle, such as deer, moose, and ungulates. There were 13.8% (*n* = 82) in which the topic was not within the designated time frame (1 mo prior to and/or following birth). Another 24.1% (*n* = 143) did not focus on the dam's behavior and/or physiological state, although a further 1.52% (*n* = 9) of articles were eliminated as they involved some form of human intervention to the normal calving process. The majority of articles (27.6%, *n* = 164) were eliminated based on the document type and a further 0.5% (*n* = 3) were excluded as these were not written in English. A further 7.2% (*n* = 43) were not retrievable. There were 9.4% (*n* = 56) of articles that were consistent with all of the selection criteria and were included in the initial count of eligible articles for review. The bibliographies of these initial eligible articles were examined for additional eligible articles.

The bibliographic search resulted in 135 unique articles that were considering as being potentially relevant. Upon further investigation, only 35.6% (*n* = 48) were considered eligible as per the criteria applied to select the first cohort of articles. There were 7.4% (*n* = 10) of articles that did not investigate dam behavior around calving, 4.4% (*n* = 6) that did not fall within the designated time period, and 3.0% (*n* = 4) were considered irrelevant because there was administration of pharmacological substances or the induction of parturition. A large proportion of articles (41.5%, *n* = 56) were irretrievable, although one article (0.7%) was not written in

English, and a further 6.7% (n = 9) were excluded based on the type of article.

A total of 104 articles in which there were reports on 111 independent experiments, were determined to meet the selection criteria pertaining to relevant dam behavior and physiology information around the time of calving (Supplementary Table S1).

Animals and Study Environment

The independent experiments spanned across 6 continents and 25 countries: Africa (n = 1), Asia (n = 6), Europe (n = 47), North America (n = 45), South America (n = 1), and Oceania (n = 6) (Supplementary Table S1).

The majority of experiments were conducted using cattle of the *Bos taurus* genotype (98.2%, n = 109), with only two experiments utilizing *Bos indicus* cattle (Supplementary Table S1). A combination of primiparous and multiparous cows were researched in 43.2% of the studies (n = 48). In an additional 39 experiments, only multiparous cows (35.1%) were studied and in 9 experiments only nulliparous cows were studied (8.1%). For 15 individual experiments, there was no specification of cow parity. In the majority of the studies, cows experienced a normal birthing process (76.6%, n = 85), but in 26 experiments, there were cows included that also experienced dystocia (23.4%, n = 26). No studies exclusively reported the use of cows with dystocia.

Dairy cattle were the most common category (81.1%, n = 91), with a comparatively small number of studies reporting on extensive beef cattle (9.9%, n = 11) and intensively managed cows (8.1%, n = 10) (Figure 1).

A total of 23 different cattle breeds were used to conduct the research in 111 independent experiments, the most common being Holstein/Friesian varieties (n = 78), followed by crossbreed animals (n = 13). The breed was not recorded for eight experiments (Supplementary Table S1).

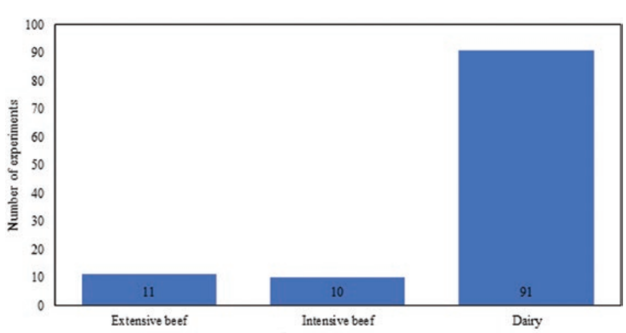

Figure 1. Distribution of articles that were accessed in which there were independent experiments conducted with extensive beef cattle, intensive beef cattle, and dairy cattle. The experimental animals were dairy cattle in the vast majority of the retrieved articles.

Monitoring Techniques and Technologies

Traditional monitoring techniques, such as observation and body fluid sampling, occurred in 64.2% (n = 122) of the studies, compared to sensor-based monitoring, which occurred in 35.8% (n = 68) of the studies. Blood sampling was the most commonly used methodology (28.7%, n = 35), followed by visual observation (27.9%, n = 34). The most commonly reported technologies used were the feed intake monitor and the leg-based accelerometer (23.9%, n = 16). The least commonly reported technologies used were the GPS, rumination halter, and tail movement detector, which were only used in one experiment each (Figure 2).

Sensor technologies were used at both a high and low observational intensity in almost equal measures (51.5%, n = 34 and 48.6%, n = 32 respectively), although traditional sampling was predominantly low intensity (less than 50% of the experiment monitored; 70.3%, n = 85). Sensor technologies made up 48.6% of high intensity methodology (more than 50% of the experiment monitored), although traditional sampling comprised of 72.7% of all low intensity trials.

Of particular interest in this study was the use of sensors in the articles reporting on extensive grazing environments. Only one article was identified that described the use of a sensor (GPS) in an extensive grazing environment (Flörcke and Grandin, 2014).

Duration and Observation Intensity

Experiments started on average 28.2 d prior to calving and concluded 20.8 d following calving, for a total average duration of 48.5 d. The longest study was conducted by Laporta et al. (2014), commencing 165 d prior to parturition and finishing 190 d following parturition, for a total length of 355 d (Supplementary Figure S1). More than half of the studies were considered long-term (longer than 1 wk prior to and following calving; 61.3%, n = 68).

More than half of the independent experiments were considered low intensity (64.22%, n = 70). Most of the long-term studies were done at a low intensity (72.06%, n = 49), although the short-term studies were more commonly done at a high

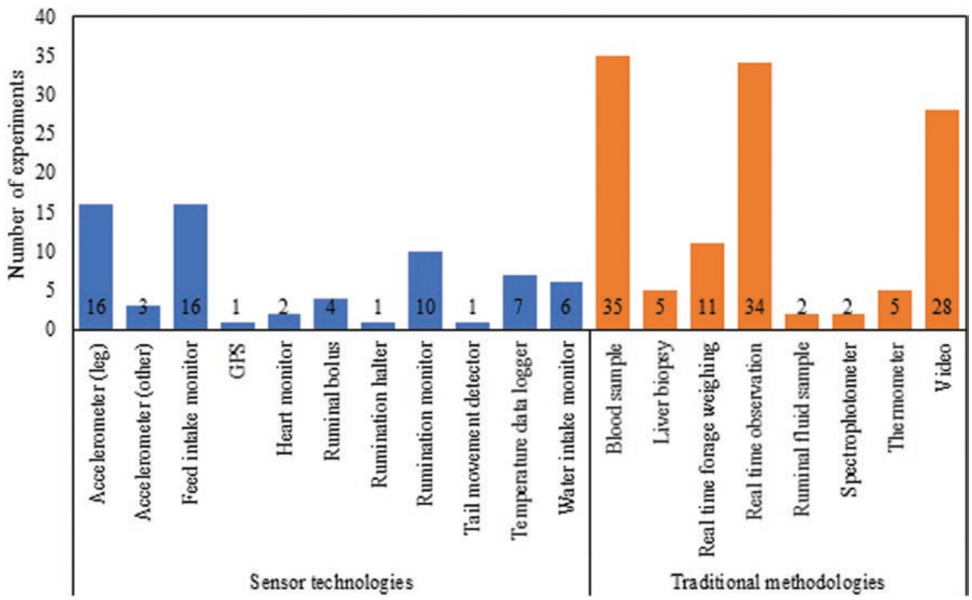

Figure 2. Methodology and technology utilization in all studies. Sensor technologies utilized included devices capable of storing or transmitting data to the observer, although traditional methodologies required manual data collection. Although a wider range of sensor technologies were used in the various experiments, there was an overall preference for use of traditional methodologies.

intensity (53.49%, n = 23). One study did not specify the measurement intervals within their experiments and thus, could not be allocated an intensity category.

Trend and Magnitude of Change in Calving Indicators

Indicators reported in three or more studies were more closely examined to identify patterns of change relative to parturition. Some of the behavioral indicators were classified as being "categorical" and could only be summarized at the level of being present or absent. Of these, the most commonly recorded changes were changes in udder appearance (n = 15), followed by changes in vulva appearance (n = 10), changes in location (n = 9), and the appearance of the amniotic sac (n = 9). Only two of these categorical behaviors were observed following parturition (arched back, placentophagia; Supplementary Table S2).

Change in cow location was of particular interest, given [c] the intent of this article to explore indicators in extensive grazing systems and was subsequently explored in more detail. Location at calving varied between studies, but there was a preference for sheltered areas, such as buildings or covered yards, and open areas, such as fields, observed. In two studies, there were also indications that cattle had a preference for calving in areas where other cattle had previously calved (Rørvang et al., 2017, 2018) (Supplementary Table S3).

Most of the indicators were classified as being "continuous" and could initially be summarized as either increasing or decreasing (Supplementary Table S4). The most commonly recorded indicator of calving was proportion of time spent lying, which was examined in 30 independent experiments. Of these, 25 were conducted with dairy cattle, 4 with beef cattle in extensive settings, and 1 study with beef cattle in an intensive setting. The majority of studies reported time spent lying to decrease before parturition (12/16), but others reported an increase (3/16) or no change (1/16). Other commonly identified calving changes included dry matter intake (n = 24), feeding (n = 21), lying bouts (n = 19), and rumination (n = 19) (Supplementary Table S4). Other commonly identified calving indicators included changes in dry matter intake (n = 24), feeding (n = 21), lying bouts (n = 19), and rumination (n = 19) (Supplementary Table S4). Of all of these, the most consistent indicators prior to parturition were a decrease in rumination (100% of studies) and an increase in lying bouts (92.9% of studies). Calf licking behavior only commenced following parturition and was reported to decrease over time in all eight studies.

Changes in behavior and physiological state were most commonly observed in the prepartum period (n = 24) as compared with the postpartum period (n = 8). For the majority of the reported indicators of calving, consistent results were reported between all the references. The exceptions to this were BHBA concentration postpartum, insulin concentration postpartum, lying duration postpartum, rectal temperature postpartum, respiration rate both pre- and postpartum, and stepping behavior postpartum (Supplementary Table S4).

Of particular interest from a sensor-based perspective is heart rate and body temperature. The number of studies reporting on heart rate were low (n = 4), however, the majority reported an increase in heart rate prior to parturition (75%; Supplementary Table S4). Likewise, the number of studies reporting on body temperature were low (n = 3), however, all studies found that body temperature decreased prior to and increased following calving (Supplementary Table S4).

Temporal Changes

Temporal graphs were generated for all eligible indicators to enable a broad, visual understanding of which changes might provide the most reliable indication of a parturition event.

Physiological indicators. For the long-term assessment, most studies reported that BHBA increased during the pre-partum period, with a peak occurring 5 d post-partum (Figure 3a). In some studies, a decrease in glucose concentration was observed prior to calving, although in others, an increase was observed, resulting in no discernible overall trend across studies (Figure 3b). There was a slight decrease in insulin concentration across articles as measured in ng/mL during the calving period, although insulin concentration in studies measured using uIU/mg reported a positive quadratic curve, with the minimum concentration occurring during parturition (Figure 3c). One study was excluded (Grum et al., 1996), because there was a magnitude inconsistency in concentrations compared with those in the other studies. The units of measure for NEFA concentrations were µEq/L and mmol/L. For both units of measurement, there was a significant increase immediately prior to calving with concentrations returning to basal in the first few days following calving in all studies (Figure 3d). The short-term graph indicated that in the majority of studies, there was an increase in progesterone in the hours leading pre- and postpartum (Figure 3e). In two studies, there was a significant decrease in progesterone concentrations approximately 10 d before parturition (Figure 3f). Two other studies showed similar rapid declines around 5 d prior (Figure 3f). All studies reported that minimum concentrations occurred at the time of calving and basal concentrations sustained during the early postpartum period (Figure 3f).

Behavioral indicators. Only two studies contained graphable dry matter intake data for the short-term, subday graph. One study reported both pre- and post-calving, although the other study only reported on dry matter intake prior to parturition. In both studies, a decrease in dry matter intake was observed prior to calving (Figure 3g). One article reported an increase in dry matter intake following calving (Figure 3g). Several studies reported changes in dry matter intake over the long-term. Most studies reported a slight decrease in intake prior to calving, with an increase following calving (Figure 3h).

Three studies reported on time spent drinking in the short-term—one in the pre-calving period, one in the post-calving period, and one across the pre- and post-calving period. The study reporting on drinking time in both the pre- and post-calving periods indicated a decrease prior to calving, before increasing thereafter (Figure 3i). This post-calving trend was also observed in the study reporting on drinking time following parturition (Figure 3i). Duration of drinking increased over time in the days before and after calving (Figure 3j).

Feeding duration decreased in all but one study in the prepartum period before increasing in all studies after calving (Figure 3k). Over the long-term, feeding duration remained relatively consisted in all but one study (Figure 3l).

In all studies, licking of the calf decreased at an exponential rate following calving, with the most rapid decrease observed in the first 6 h after birth (Figure 3m). Cows began licking their calves on average 12 min following birth, with the longest latency to lick being 258 min following birth by a dairy heifer as reported by Selman et al. (1970) following a long and difficult labor (Figure 3m). Only two studies reported on calf licking duration over the long-term, however, the decreasing trend was only observed in one of the studies, although the other study did not show a marked change over time (Figure 3n).

The number of lying bouts increased leading up to calving in all studies, with a peak occurring during parturition and a decrease in the number of lying bouts in the initial period after calving (Figure 3o). For the long-term, lying bouts were quite consistent across most studies (Figure 3p). In one study, a peak was observed at the time of calving (Figure 3p).

There was no distinguishable pattern identified in duration of lying in the period prior to and following parturition in the majority of studies (Figure 3q). In two studies, an increase was observed

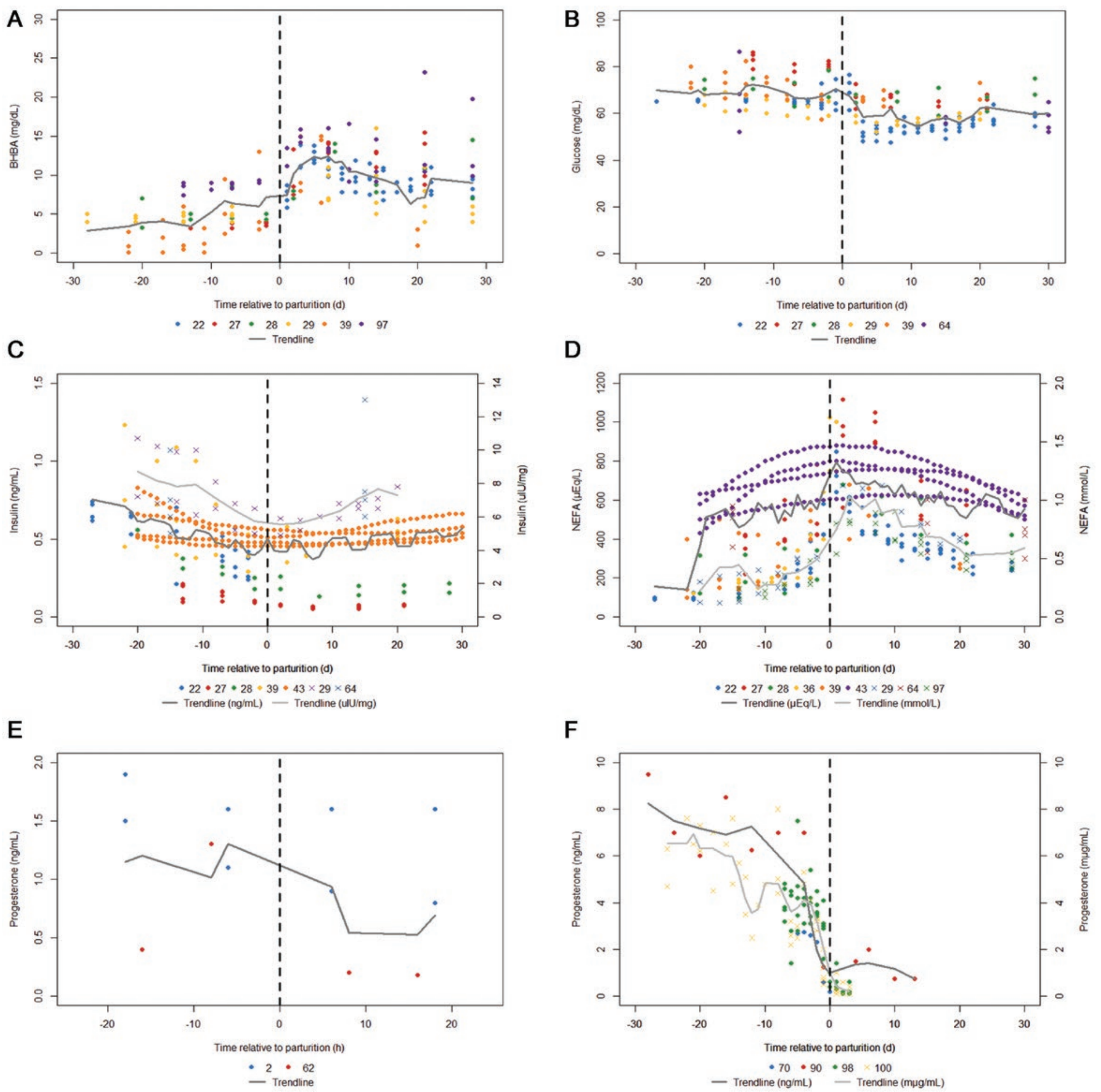

Figure 3. Long- and short-term temporal graphs generated for (a) β-hydroxybutyric acid (BHBA) (long-term), (b) glucose (long-term), (c) insulin (long-term), (d) non-esterified fatty acids (NEFA) (long-term), (e) progesterone (short-term), (f) progesterone (long-term), (g) dry matter intake (short-term), (h) dry matter intake (long-term), (i) drinking duration (short-term), (j) drinking duration (long-term), (k) feeding duration (short-term), (l) feeding duration (long-term), (m) calf licking (short-term), (n) calf licking (long-term), (o) lying bouts (short-term), (p) lying bouts (long-term), (q) lying duration (short-term), (r) lying duration (long-term), (s) rumination duration (short-term), (t) rumination duration (long-term), (u) standing duration (short-term), and (v) standing duration (long-term). Graphs for short-term assessments had time ranges from the day prior to and following parturition, although long-term graphs include a 30 d period from before and after calving. A secondary axis was generated where there was more than one unit of measurement used. Data associated with the secondary axis are depicted with a cross marker, as opposed to the circle marker for data corresponding to the primary axis. Thick grey lines depict the rolling average trendline, and darker grey thick lines correspond to the secondary axis. Crosses used for graphing the short-term calf licking pattern refer to the time taken for the cow to initiate licking after birth. These data were excluded from the trendline analysis. Numbers in the legend coincide with a reference, as listed in Supplementary Table S1.

around calving (Figure 3q). In the long-term, the majority of studies reported on lying time prior to calving (Figure 3r). In these, there was a slight decrease in lying duration leading up to calving (Figure 3r).

Studies reporting on rumination time in both the short- and long-term reported a decrease in the lead up to parturition, before increasing thereafter (Figure 3s and t).

Only three studies reported on standing time in the short-term (Figure 3u). In the majority of studies reporting on time spent standing, no discernible change was observed on a subday or long-term level (Figure 3u and v).

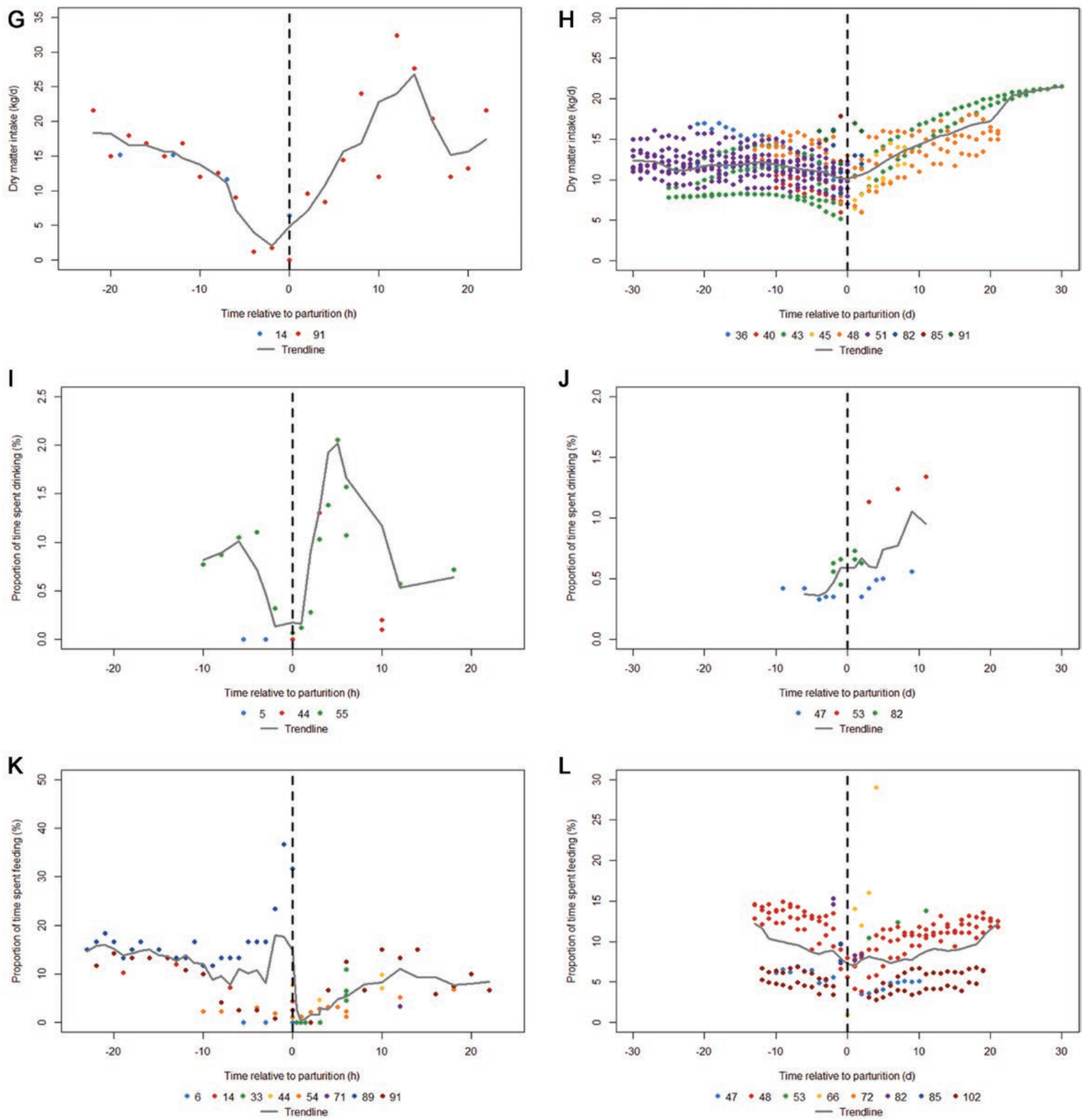

Figure 3. Continued

DISCUSSION

The overarching objective of this article was to develop an understanding of the potential for a sensor-based approach for detecting parturition in extensive beef grazing systems. An essential component of this is the evaluation of changes in animal physiology or behavior that might be measured using sensors. The initial analysis revealed that only 11 studies focused on monitoring parturition in extensively grazed cattle and only one study applied a sensor (GPS). Comparing this to the 91 studies in dairy cattle suggests that there is a significant opportunity for further research in this area.

To focus the development of a sensor-based approach, this article has sought to identify the behavioral and physiological changes associated with a parturition event and to synthesize the existing literature reporting on these changes. Analysis of 104 articles identified 38 commonly reported indicators that demonstrate variation around the time of parturition, 23 of which were behavioral. Several key indicators of parturition that will be discussed have also been summarized in Supplementary Table S5, and have been assigned a low, medium, or high status depending on the likelihood of commercial adoption for calving detection at this time. This

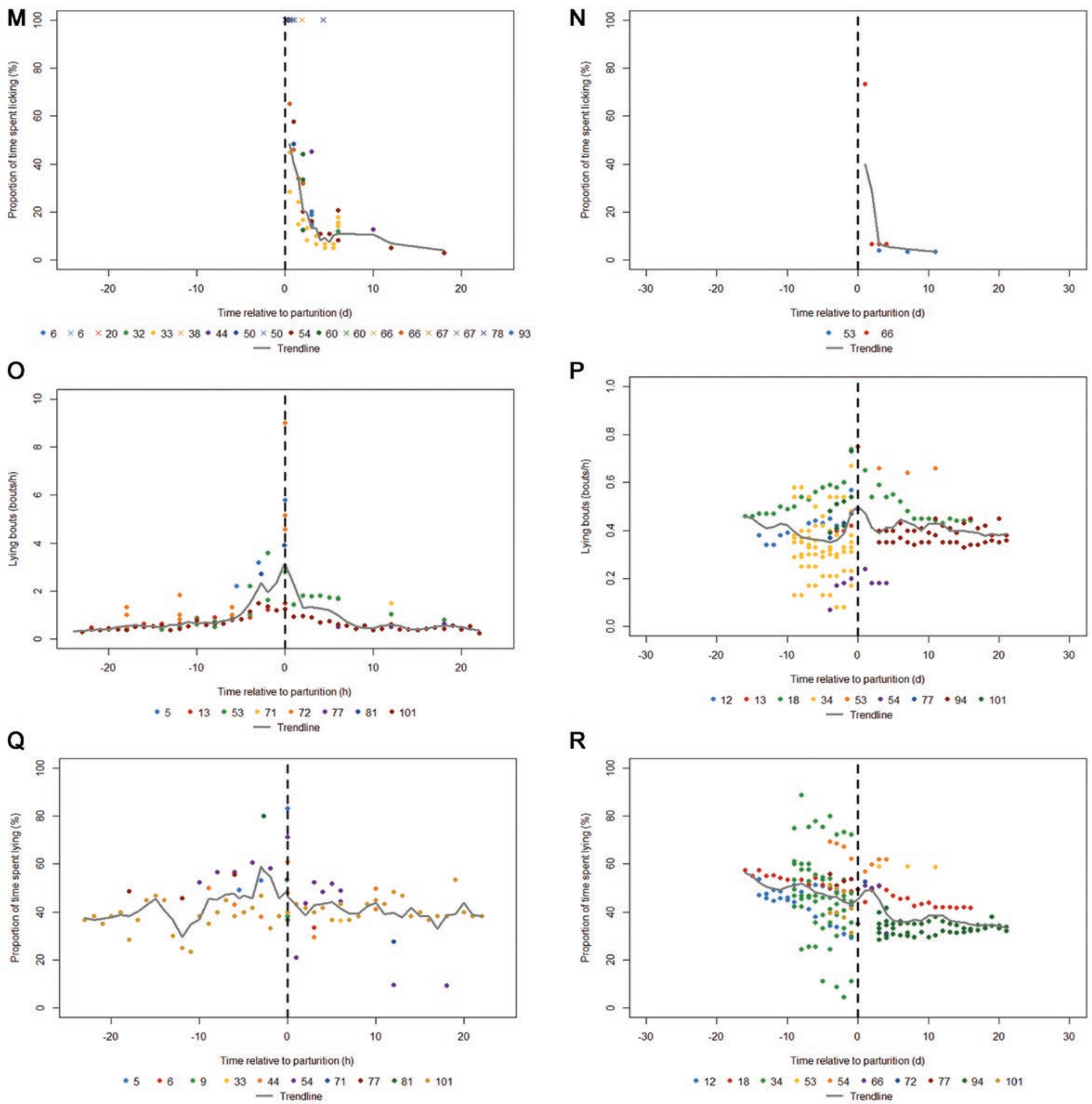

Figure 3. Continued

took into consideration the potential for practical development in an extensive grazing context, the availability of a commercial device, the ease of deployment, and the consistency of reporting on the indicator.

The following discussion will focus on how these indicators might be useful in the context of sensor-based systems aimed at detecting the parturition event. In the context of investigating how indicators might be detected in a sensor-based approach, we have deliberately sought to focus on those behavioral or physiological characteristics, which are more consistently reported in the literature and those for which the change is clearer and more apparent. As such, other valuable calving indicators may exist, however, given the lack of literature available, they were not discussed in detail. The more consistent and apparent changes in behavior or physiology are more likely to lend themselves to being detected by a sensor system and consequently, are the focal point of this discussion.

Sensor technologies for monitoring livestock are many and varied. Trotter et al. (2018) provides a comprehensive list of the types of on-animal sensors being developed and applied in the livestock sector and is worth reviewing to gain a broad understanding of the current state of the art in this field. This discussion, however, will refer to

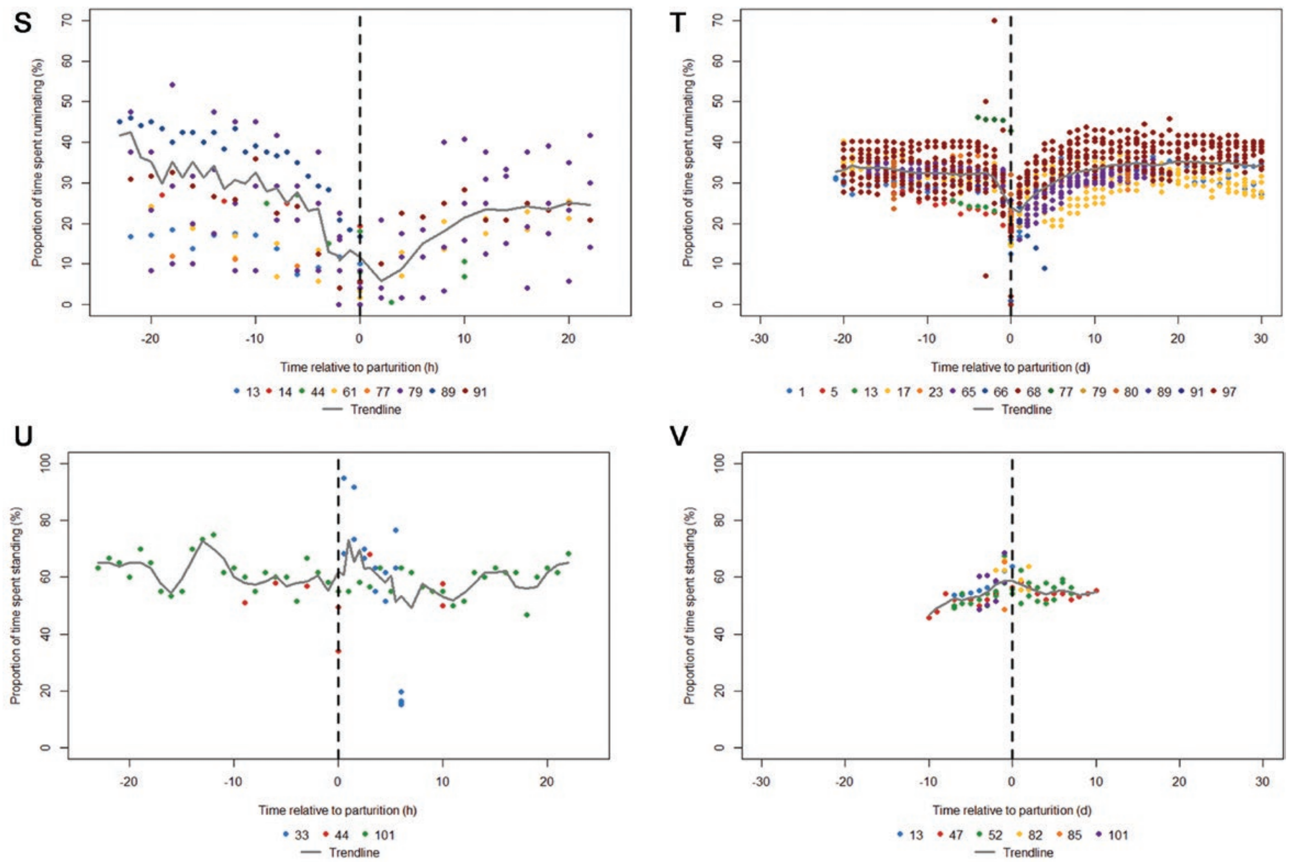

Figure 3. Continued

specific sensor development and validation as they relate to each indicator reported. One key issue that will be discussed is the practicality of sensor systems in extensive grazing environments as commercially viable solutions. Although some sensors lend themselves to deployment in these environments at reasonable costs, for example, accelerometer ear tag sensors, others, such as image analysis, cannot be easily deployed in large areas and others remain too expensive or impractical for whole herd deployment in a commercial context. New sensor systems, however, are constantly evolving and potential future developments enabling new deployment strategies and refinements in cost will also be explored where relevant.

Behavioral Indicators

Of the behavioral indicators identified, a small proportion were non-continuous and were exclusively present or absent. Most of these features provided very clear and well-defined signals of impending or occurring parturition. This is not surprising, given that many represent the very obvious physical conditions experienced during calving, such as the emergence of calf feet. The high level of consistency across the varying references indicate that these changes could be highly valuable in identifying a calving event. A number of challenges exist, however, that impede the detection of these changes, particularly in extensive grazing systems.

The appearance of the amniotic sac of calf marks the initiation of the second stage of parturition and is an obvious key component of the calving process (Saint-Dizier and Chastant-Maillard, 2015). A number of commercially available devices have been produced that utilize magnetic, mechanical, or light sensors to identify the separation of the vulval lips or are expelled prior to the calf, as described by Saint-Dizier and Chastant-Maillard (2015). These devices are generally expensive and deploying them across a whole herd would be prohibitive in a commercial context. Some of these devices will also require surgical or specialist deployment for accurate detection and adequate retention and as such, this is unlikely to be easily adopted by industry (Saint-Dizier and Chastant-Maillard, 2015; Grodkowski et al., 2018).

Although udder and vulva changes have been consistently observed across numerous studies, the ability to detect these indicators will be difficult to identify with a sensor. One potential candidate would be using automated image analysis (Ozkaya, 2015). Although only one system would be required, achieving reliable collection of imagery in extensive systems will be challenging. Cattle must be presented in a consistent manner that allows for clear analysis, and visualization systems would need to be deployed in areas that cattle frequently visit. One potential location for deployment could be on a walk-over-weigh system enclosing a water trough or supplementation.

Cow isolation was commonly reported as being a potential indicator of impending parturition. Two sensor systems exist that could be used to identify isolation behavior—proximity loggers and GPS devices. Although proximity loggers measure the duration and frequency of interaction between two devices (Boyland et al., 2013), GPS systems provide the animal's finite position. Both of these sensors are being pursued as potential commercial solutions, as they can be integrated within collars and ear tags (Trotter et al., 2018).

Calving location showed a great deal of variation between the studies. The choice of calving location is dictated primarily by the production style, where dairy and intensive beef enterprises often have more limited calving location options compared to extensively grazed beef cattle. The majority of the studies investigating location at calving were conducted in a dairy environment and consequently, the results reflect location preference when presented with limited options. More research into calving location as an indicator in extensive environments needs to be undertaken to confirm the potential value of this indicator.

Numerous behavioral indicators expressed a pattern of change over time. In order to capture these indicators, frequent monitoring is required. Traditional methods of calving detection require experience to recognize the behavioral changes associated with parturition and is a labor and time intensive task.

Rumination is a key indicator of cow health and productivity, and as such, has been extensively explored by the dairy industry (Stangaferro et al., 2016; Beauchemin, 2018). Rumination monitoring has primarily been detected using an accelerometer deployed in a collar or ear tag (Bikker et al., 2014; Pahl et al., 2014; Ouellet et al., 2016; Rutten et al., 2017) or an acoustic detection sensor, which detects the distinctive sounds of rumination (Adin et al., 2009; Kovács et al., 2017). Several commercially available tools have been developed to detect rumination in the dairy industry (Reith et al., 2014; Eslamizad et al., 2018; Reynolds et al., 2019). The gradual decrease in rumination prior to parturition and then its increase thereafter at both the multiday and subday scale suggest that it may be a key indicator for inclusion in algorithms aimed at calving detection.

Calf licking behavior is a commonly reported event that is initiated soon after birth and declines exponentially in the hours following calving. Grooming behavior is an essential part of the maternal bonding process, and assists with drying the calf of amniotic fluid and preventing heat loss (Hudson and Mullord, 1977; Edwards and Broom, 1982; von Keyserlingk and Weary, 2007). At this current time, no formal studies have been conducted that investigate the use of accelerometers to identify calf grooming behavior. Despite this, it is theoretically possible to detect grooming behavior using ear- or neck-based accelerometers. Accelerometers detect variations in linear acceleration along the x-, y-, and z-axes to determine distinct behaviors (Barwick, 2016). It is, therefore, plausible to conclude that ear- or neck-based accelerometers could be used to the detect the distinctive drawn out down-up head movement associated with licking a calf. One potential issue, however, is the distinction between grazing and grooming. Similarly, grooming could also theoretically be detected using an audio sensor. Combining an audio and accelerometer device could also potentially provide a method to distinguish between grazing and grooming. If grooming could be detected using sensors, it might be possible to explore other features of parturition, such as maternal investment, which is known to impact later calf health, and potentially survival (Stěhulová et al., 2013).

The studies examined showed that the rate of lying to standing transition peaked at the time of calving (both at the multiday and subday scales). This behavior has been frequently measured in the literature, often using leg-based accelerometers (Blackie et al., 2006; Chapinal et al., 2010; Calderon and Cook, 2011; Jensen, 2012; Felton et al., 2013; Sepúlveda-Varas et al., 2014; Borchers et al., 2015; Titler et al., 2015; Black and Krawczel, 2016; Ouellet et al., 2016; Borchers et al., 2017; Neave et al., 2017). It is more difficult, however, to distinguish between a lying and standing position with an ear- or neck-based accelerometer as the two behaviors show similar accelerometer readings. Leg-based accelerometers, however, show a distinct crossover of two axes and can easily be utilized to determine a standing or lying position, and consequently, the number of lying bouts performed. More recently, Busch et al. (2017), described the use of a neck accelerometer in distinguishing between the lying and standing position via the detection of the transitional movement, that is, a lying bout. This behavior is a strong candidate for integration into algorithms for detection of parturition.

Dry matter intake, drinking time, and feeding time decreased in the period prior to calving, before increasing again. These changes are frequently reported in the literature as being measured, but exclusively using off-animal technologies, such as feed and water intake monitors (Huzzey et al., 2007; Proudfoot et al., 2009; Chapinal et al., 2010; Jawor et al., 2012; Neave et al., 2017). Existing systems utilize an electronic identification tag attached to the cow's ear to provide an individual with access to food or water. The system automatically measures the initial and final weight of the contents of the bin to deduce how much water or food was consumed. To convert the amount of consumed food into dry matter intake, the forage must be manually analyzed. These off-animal technologies can only feasibly be utilized in intensive settings, where feed and water are available exclusively from these troughs. In more extensive settings, it is difficult to control food and water consumption from other sources. Alternatively, drinking and feeding could potentially be measured using ear- or neck-based accelerometers. A number of studies exist that identify grazing behavior from both ear- and neck-based accelerometers (Pereira et al., 2018; Rahman et al., 2018). Another study by Greenwood et al. (2014) posits the use of an on-animal sensor to quantify actual measures of feed intake, however, this concept remains in development. Drinking behavior has been measured using a neck-based accelerometer, however, has not been compared with grazing behavior (Williams et al., 2017). While potentially difficult to objectively measure, these indicators could be valuable components in a sensor-based system and warrant further investigation.

Physiological Indicators

The vast majority of physiological indicators were hormonal, which is unsurprising given the role that the endocrine system plays in parturition (Shenavai et al., 2012). Although numerous technologies exist that have the capacity to measure non-hormonal physiological traits, such as heart rate and temperature, on-animal biosensor development for commercial deployment is non-existent at this time. Despite this, it is worth discussing these indicators as future sensors may be developed to measure them and at the very least, these physiological changes are often the key drivers of the behavioral indicators previously explored.

The studies reporting on NEFA and progesterone concentration changes show a high degree of repeatability and indicate similar patterns of distinctive changes relative to parturition in different experimental conditions, with varying breeds, and nutritional regimes. Likewise, the reported results for estrogen show high levels of consistency between sources. At this current time, biosensors in animals do not exist at a commercial level to allow for the detection of these hormones. Biosensors in human medicine have been more extensively researched compared with in livestock and could be adapted for use in animals. One successful and commercially available biosensor in humans is the continuous glucose monitoring pump for patients with diabetes. These devices are commonly inserted into the abdomen and arm and have the capacity to provide alerts when blood glucose falls below the recommended level (Cappon et al., 2019). Future development into biosensing technologies capable of monitoring blood chemistry and providing alerts in this manner would be a highly valuable asset in detecting impending calving.

Temperature detection systems are a well-established technology with numerous commercially available options predominantly focused on the intensive livestock industries. An extensive list detailing the company and sensor deployment location is available at Sellier et al. (2014). As indicated by Sellier et al. (2014), sensor deployment location is a key factor influencing the ease and invasiveness of deployment. Temperature sensors that require surgical deployment will require specialist training and incur additional time and medical costs. Rumen or reticulum boluses, on the other hand, are less invasive and more easily deployed, but are influenced by the ingestion of feed and water, resulting in temperature fluctuations (Sellier et al., 2014). Similarly, intravaginal deployment is often less invasive, but require specialist deployment to ensure adequate retention up until the time of calving (Menzies et al., 2016). A potential noninvasive method of detecting body temperature is via an infrared camera targeting the eye (Scoley et al., 2019). These systems are only available in an off-animal form, which may be difficult to install and achieve reliable results in an extensive environment.

Heart rate detection is common in the equestrian sporting industry, where animal stress response, recovery, and training intensity are of high importance (von Lewinski et al., 2013). As such, heart rate monitoring devices are more commonly designed for horses. Studies measuring heart rate in this literature review utilized these equine-designed devices, such as electrode belts (Kovács et al., 2015). This technology, however, is commonly positioned around the chest of the animal and would be unsuitable for deployment in systems where animals are unaccustomed to being handled and for long-term use. Additionally, animals must be prepared by shaving excess hair and applying electrode gel for accurate generation (Lefcourt et al., 1999; Kovács et al., 2015). Another potential method of heart rate detection is an optical heart rate sensor. In these systems, light emitting diodes (LED) are used to detect changes in blood flow to determine heart rate (Schubert et al., 2018). The ear could provide a viable location for these sensors.

Although many physiological sensors could provide very good indicators of parturition these are generally more difficult to achieve in a sensor-based approach targeted at commercial deployment in extensive grazing systems.

Limitations and Future Directions

The majority of studies examined in this literature review were conducted with dairy cattle, and almost all experiments utilized *B. taurus* cattle. Dairy cattle and beef cattle, and *B. taurus* and *B. indicus* cattle, have been bred and used for different purposes and exhibit different physiology and behaviors. The overrepresentation of dairy cattle could influence the perceived intensity of behavioral changes in relation to calving compared with beef cattle, leading to over- or underexaggerated calving parturition indicators. For example, dairy cattle have been bred for high milk production and therefore water consumption in these animals is far greater compared with beef cattle (Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, 2000). Although acknowledging this key limitation, there are clearly valuable insights to be gained from the current analysis in guiding future sensor-based developments.

The majority of studies did not include data that could be used for further analysis. For reliable time series graphs to be generated, and a true meta-analyses to be conducted, more data was required. The data that was available was unevenly distributed across varying time periods, resulting in multiple data points at one period and only one data point at other times. As a result, the trend lines developed for each indicator became skewed to a greater or lesser extent. An attempt was made to minimize this effect by using a rolling average, but despite the transformation, bias still exists and needs to be considered when interpreting the results. For example, in the temporal graph for feeding duration, there appears to be a peak 1 h prior to calving, however, this apparent peak could instead be due to the lack of data at that time point. Only one source was available for that time period, influencing the trendline upwards. The reliability of this change is unknown, given the lack of available data.

The methodology used in this study allocated a "vote" for each experiment that reported a positive, negative, or null trend (Williams et al., 2016). For a "vote" to be assigned to a trend, a majority of animals had to display the behavior or physiological indicator. A minor proportion of experimental animals, however, may not have displayed the calving indicator in the same manner as the remainder of the herd. For example, in Flörcke and Grandin (2014), 95.2% of the cows isolated themselves more than 50 m from the main herd at the time of calving, although the remaining 4.8% did not participate in this behavior. Therefore, although the majority of animals displayed the behavior described, others did not. This individual variability is a key factor in producing accurate algorithms for sensor-based detection of parturition. In the majority of the studies included in this article, however, this variability has not been described. Instead, particularly where quantifiable data was made available, the average value or behavior is provided. Future research with more in-depth analysis describing individual variability would be of great benefit in the development of sensing systems for precision livestock management. Consequently, the described changes in detecting parturition must be interpreted with caution, however, using multiple indicators of calving may increase the accuracy of parturition detection.

As discussed, individual variability exists when performing calving behaviors. Some animals may display more subtle behaviors as they approach calving, although other animals may not display a described behavior at all. The integration and detection of multiple calving indicators, however, could provide a viable solution to this issue. Two approaches can be used when integrating indicators: one multifunctional sensor might be used, such as an accelerometer; or multiple sensors, requiring coordination and/or data integration, can be utilized. There are two possible ways of obtaining data suitable for this integrated approach. Firstly, a single sensor, for example, an accelerometer, might be used to derive multiple behavioral indicators. Secondly, a number of different sensors might be applied, such as accelerometer or GPS, from which the required data is derived.

Potential behavioral indicator candidates for calving detection using a single accelerometer include lying bouts, rumination time, and calf grooming behavior. Both lying bouts and rumination time have the capacity to be detected by ear- or neck-based accelerometer. Calf grooming behavior could then be used to verify the conclusion of a calving event. These behaviors could also be detected in conjunction with isolation behavior, using a GPS device.

When integrating indicators to monitor parturition, the number of behavioral thresholds that must be met before it is positively identified as a calving event must be considered. When too few behaviors are included, the threshold for calving identification might become too low and oversensitive. Many calving indicators might be mistaken for diseased states, and as such, it is possible that a model with too few indicators will not detect actual parturition events (Proudfoot et al., 2014; Stangaferro et al., 2016). For example, an isolated cow with decreased rumination activity could be sick, instead of calving. Conversely, if too many calving indicators are integrated, animals that have more subtle or do not express the calving behaviors may be overlooked.

All of the described considerations need to be taken into account in future research investigating the development of sensors for parturition and dystocia detection on-farm. There is considerable scope for future research in this area, particularly in the context of optimizing systems across the great diversity of grazing animal production systems.

CONCLUSION

As a cow approaches calving, she undergoes a number of behavioral and physiological changes. Measuring and detecting these changes could help in informing an impending or ongoing calving event and could improve production and welfare outcomes. The results of the systematic literature review suggest that the automated monitoring and detection of calving, as well as of dystocia incidents, is possible. The results, however, also indicate that although there are many important behavioral changes that are associated with calving, many of these vary between individual animals. Thus, combining several key indicators would result in a more accurate detection of time of parturition. Future research into automated biosensing technologies to detect hormone concentrations would further increase the accuracy of calving detection, given the consistency of results between different breeds, nutritional planes, and environmental settings. At the current point in time, however, on-animal sensor technology could be used to automatically detect calving to enhance managerial decisions and maximize on-farm efficiency, productivity, and animal welfare.

SUPPLEMENTARY DATA

Supplementary data are available at *Translational Animal Science* online.

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