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Review

Autonomous on-animal sensors in sheep research: A systematic review

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ABSTRACT

This systematic review explores the use of on-animal sensor technology in sheep research. A total of 71 peer-reviewed articles reporting on 82 independent experiments were reviewed, ranging in publication date from 1983 to 2017 and distributed across all populated continents. The findings demonstrate increasing numbers of published studies that validate the application of sensor technology to categorise and quantify sheep behaviour. The studies also used sheep sensors for environmental management, validation of data analysis methods and for health and welfare research. Whilst historically many applications of sensors in sheep research have been conducted over a short period with small numbers of experimental animals, this trend appears to be changing as technology develops and access improves. The literature suggests that many applications of sensors have already or are currently moving through a proof-of-concept stage, allowing future applications to focus on commercialisation of technology and potential integration with other technologies already in use (e.g. weather data).

1. Introduction

Location technology was first used to study animal movement in the 1960s, when very-high frequency (VHF) transmitters revolutionised our ability to monitor complex animal behaviour (Kochanny et al., 2009). Two decades later, the satellite-based system ARGOS was employed for wildlife observation (Swain et al., 2011), followed by Global Positioning System (GPS), which was first applied to monitor moose (*Alces alces*) in 1994 (Rempel et al., 1995). Whilst these location technologies were being established, concurrent development of body movement monitoring technology was also occurring, including pressure sensors to monitor standing and lying in cattle (Canaway et al., 1955), pedometers to measure walking behaviour in sheep (Powell, 1968) and mercury tilt switches to indicate cattle and sheep body posture (Champion et al., 1997; Rutter et al., 1997a). More recently, accelerometers have been used to measure linear acceleration along one or multiple reference axes (Yang and Hsu, 2010). Inertial Monitoring Units (IMUs) extend this and include gyroscopes and/or magnetometers for additional measurements of angular motion and gravitational force (Andriamandroso et al., 2017). Other sensor developments include: contact loggers for the study of pair interactions in sheep (Broster et al., 2010; Broster et al., 2012; Freire et al., 2012); and heart rate monitors (Goddard et al., 2000; Simitzis et al., 2009; Destrez et al., 2012; Simitzis et al., 2012; Coulon et al., 2015) and oxygen sensors (Barkai et al., 2002) to help understand physiological change.

According to the FAO, overall food production needs to increase by 70% to meet growth projections of the world population by 2050 (FAO, 2009). This will require technologies that improve current efficiency standards. Whilst the use of sensors in livestock research has shown promise, their application in existing farming systems is still in its infancy (King, 2017). The exception to this is the dairy industry, where commercial sensors such as the GEA CowView System (GEA Farm Technologies, Bönen, Germany) and Afimilk Silent Herdsman (Afimilk, Kibbutz Afikim, Israel) are among several commercial offerings used to monitor health and oestrous behaviour (Tullo, 2016; King, 2017). In contrast, the use of digital technologies to measure extensive livestock performance and behaviour is lacking. This is considered an untapped area for development, particularly in countries such as Australia and New Zealand where nearly half of all agricultural businesses (including cropping) indicate a main agricultural activity of beef and/or sheep farming (Australian Bureau of Statistics, 2012; Statistics New Zealand, 2012).

Small ruminants, particularly sheep, are hugely important in many regions of the world, providing both food and fibre. According to the FAO, Asia is the largest global producer of sheep products contributing 52.6% of sheep meat and 45.6% of sheep milk production in 2016 (FAO, 2017). In addition, they are the world's leading producer of greasy wool, providing over 900,000 tonnes in 2013 (FAO, 2017). Whilst Asia remains dominant across the three major industries, the regions providing the next largest production value differs between commodities, with Africa the second largest sheep meat producer (18.8%), Europe the second largest sheep milk producer (29%) and

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Oceania the second largest greasy wool producer (24.2%) (FAO, 2017). This global contribution to sheep production highlights the importance of the industry and indicates how collective improvements in production efficiency could significantly improve the outlook for future food security.

The aim of this review was to use a quantitative systematic methodology to review how sensors have been applied in sheep research and trends for their application. The focus was on commercially relevant technologies. To the best of the authors' knowledge, this current review is the first for on-animal sensors used in sheep research.

2. Materials and methods

2.1. Search strategy

The method for this review was based on that used in Higgins and Green (2011) and Williams et al. (2016). A search of electronic databases was conducted in February 2017 and May 2017 for literature concerning the use sensors in sheep production systems. Searches were performed in the following databases: Scopus, ScienceDirect, CAB Abstracts and ProQuest. Search terms used were 'sheep', 'ovine', '*Ovis aries*', 'ewe*', 'ram' and 'lamb' in conjunction with 'gps', 'global positioning system*', 'gnss', 'global navigation satellite system*', 'accelerometer*', 'proximity log*', 'contact log*', 'rumen sensor', 'rumen bolus', 'body temperature monitor', 'body temperature AND sensor', 'blood pressure monitor' 'blood pressure AND sensor', 'heart rate monitor' and 'heart rate AND sensor'. Search terms were not case-sensitive. Initial searches including 'ram*' and 'lamb*' returned many irrelevant results and thus the truncation option was not used. Searches were restricted to titles, abstracts and keywords. The Boolean search term 'AND' was used in each search to join the sheep-related and sensor-related terms, respectively (e.g. sheep AND GPS, ewe* AND accelerometer). When searching Scopus, if irrelevant results were still found (e.g. RAM computer memory), the search was limited to the 'agricultural and biological sciences' subject area. However, this option was not available when searching the other databases.

Articles were required to meet the following criteria for inclusion: (i) written in English; (ii) included domestic sheep (*Ovis aries*) as subjects (some studies involved additional species and were also included); and (iii) included at least one type of on-animal autonomous sensor attached to at least one sheep subject. Books and book chapters were not included. If a paper was not peer-reviewed or missing data (e.g. conference papers), a comprehensive search for peer-reviewed articles presenting the data was made. If no peer-reviewed article could be found, the paper was excluded. If an article was unavailable online, a comprehensive search through affiliated networks and interlibrary loan services was conducted before the article was discarded. Articles that involved invasive animal procedures such as implantation of sensors into the abdominal cavity (Faurie et al., 2004) or skull (Bishai et al., 2003) of an unborn foetus or measuring brain wave activity at slaughter (Rodríguez et al., 2012), were excluded as these were considered to have minimal commercial relevance. Similarly, articles involving monitoring of animals in oxygen chambers (Aharoni et al., 2003) or metabolism cages (López and Fernández, 2013) were excluded as irrelevant as were those monitoring the stress response during transport (Fisher et al., 2010; Hall et al., 2010; de la Fuente et al., 2012; Santurtun et al., 2014; Santurtun et al., 2015). Other studies that were excluded included those that involved manual measurements e.g. heart rate measured once daily (Piccione et al., 2007) and studies that employed radio-frequency identification (RFID) as a data management tool (Ait-Saidi et al., 2014). For all articles that met the above criteria, a comprehensive bibliographic search was conducted to identify other relevant literature. A search for literature that had cited the original paper was also conducted using Google Scholar.

2.2. Data collection and extraction

Once a complete list of articles meeting the criteria was established, the bibliographic details including author, title and year of publication were listed. If multiple experiments were presented in one article, they were treated as a single study unless explicitly separated with results independently analysed and reported. Details of each experiment were then recorded, including the location of each experiment site by country and then more broadly by continent: Africa, Antarctica, Asia, Europe, Oceania, North America and South America. If no details on experiment site were documented, the location of the First Author's institution was used. Climate details (e.g. tropical, arid, temperate, cold, polar) were based on the Köppen-Geiger system detailed in Peel et al. (2007). Further details including the year of experiment initiation and conclusion and the season in which the experiment was conducted was also recorded. Seasons were based on standard quarterly grouping of months for the northern and southern hemispheres i.e. December to February, March to May, June to August and September to November corresponding to winter, spring, summer and autumn for the northern hemisphere and summer, autumn, winter, spring for the southern hemisphere. Experiments were then classified as 'grazing' or 'intensive'. A 'grazing' experiment was one in which animals were managed in outdoor paddocks and grazed forage for either all or part of the day (Williams et al. 2016). In comparison, an 'intensive' experiment was one where animals were housed in small pens or barns for the duration of the study. Experiments in which animals were grazed during the day and kept indoors at night were still considered 'grazing' if sensors were removed overnight. If however the sensors remained on the animals whilst indoors, this was recorded as a 'combination'. Duration of experiments was then determined using three criteria: (i) the period of time between first sensor attachment and last sensor removal; (ii) the maximum period of sensor deployment used throughout the experiment; and (iii) the total length of time sensors were deployed, even if this was done over multiple deployments. Durations were 'clustered' based on defined periods of time (i.e. 1–2 weeks, 2–4 weeks) and clusters were always classified to the smaller cluster group (i.e. a 14-day study was classified as 1–2 weeks, not 2–4 weeks). When determining experiment duration, a month was considered to be four weeks. The number of repeat deployments per experiment was also recorded.

Animal details were recorded for each experiment, including sheep breed, class (ewe, ram, wether, hogget, lamb) and number used. Details of additional species co-monitored with the sheep were also recorded. Sensor information was then extracted, including the sensor type (GPS, accelerometer etc.), attachment method and programmed data collection interval. Finally, the broad focus of the study based on the objectives of each experiment, was determined to be up to two of the following: (i) behaviour; (ii) health; (iii) methods validation; (iv) environment management; (v) sensor validation; (vi) welfare; and (vii) other (Table 1).

3. Results

3.1. Database and bibliographic search results

Database searches identified 2294 unique documents containing the relevant search terms. Approximately 11.6% (n = 266) and 6.5% (n = 149) of articles were excluded as they related to sheep but not sensors, or sensors but not sheep, respectively. A further 11.3% (n = 260) were not relevant to either subject area. Due to the large number of results returned, a large proportion of documents (51.9%; n = 1191) were excluded as soon as their non-relevance to sheep was determined without examining their relevance to sensors. Approximately 8.4% (n = 192) of articles were excluded based on the document type (e.g. book, book chapter, review, conference paper) and 1.2% (n = 27) as non-English language. Of the remaining 209 articles, a further 42 were excluded as they involved invasive medical procedures,