sustainability

MDPI

Review

Information Technologies for Welfare Monitoring in Pigs and Their Relation to Welfare Quality®

Mona L. V. Larsen *, Meiqing Wang and Tomas Norton

Group M3-BIORES: Measure, Model and Manage Bioresponses, Division Animal and Human Health Engineering, Department of Biosystems, KU Leuven, Kasteelpark Arenberg 30, 3001 Heverlee, Belgium; meiqing.wang@kuleuven.be (M.W.); tomas.norton@kuleuven.be (T.N.)

* Correspondence: monalilianvestbjerg.larsen@kuleuven.be

Abstract: The assessment of animal welfare on-farm is important to ensure that current welfare standards are followed. The current manual assessment proposed by Welfare Quality® (WQ), although being an essential tool, is only a point-estimate in time, is very time consuming to perform, only evaluates a subset of the animals, and is performed by the subjective human. Automation of the assessment through information technologies (ITs) could provide a continuous objective assessment in real-time on all animals. The aim of the current systematic review was to identify ITs developed for welfare monitoring within the pig production chain, evaluate the ITs developmental stage and evaluate how these ITs can be related to the WQ assessment protocol. The systematic literature search identified 101 publications investigating the development of ITs for welfare monitoring within the pig production chain. The systematic literature analysis revealed that the research field is still young with 97% being published within the last 20 years, and still growing with 63% being published between 2016 and mid-2020. In addition, most focus is still on the development of ITs (sensors) for the extraction and analysis of variables related to pig welfare; this being the first step in the development of a precision livestock farming system for welfare monitoring. The majority of the studies have used sensor technologies detached from the animals such as cameras and microphones, and most investigated animal biomarkers over environmental biomarkers with a clear focus on behavioural biomarkers over physiological biomarkers. ITs intended for many different welfare issues have been studied, although a high number of publications did not specify a welfare issue and instead studied a general biomarker such as activity, feeding behaviour and drinking behaviour. The 'good feeding' principle of the WQ assessment protocol was the best represented with ITs for real-time on-farm welfare assessment, while for the other principles only few of the included WQ measures are so far covered. No ITs have yet been developed for the 'Comfort around resting' and the 'Good human-animal relationship' criteria. Thus, the potential to develop ITs for welfare assessment within the pig production is high and much work is still needed to end up with a remote solution for welfare assessment on-farm and in real-time.

Keywords: sus scrofa; sow; precision livestock farming; behaviour; remote; automation; sensor

Citation: Larsen, M.L.V.; Wang, M.; Norton, T. Information Technologies for Welfare Monitoring in Pigs and Their Relation to Welfare Quality®. *Sustainability* **2021**, *13*, 692. https://doi.org/10.3390/su13020692

Received: 28 October 2020
Accepted: 5 January 2021
Published: 12 January 2021

1. Introduction

The demand for animal products including pig meat has increased the last decade; a trend expected to continue for the next decade, with an expected 11% expansion in the global human population as the main driver [1]. This increase has been sustained by intensification of the production through large-scale systems increasing productivity. Already in the 1960s by the publishing of the book 'Animal Machines' by Ruth Harrison [2], it was recognised that such intensification of production heavily challenges the welfare of the animals. To increase productivity, animals may have less space and less enriched environments, among other living conditions, and have been genetically selected for production levels higher than their physical abilities. Although animal welfare is not explicitly mentioned in the UN sustainable development goals, working to achieve these goals is compatible with animal welfare improvement [3]. When considering the three pillars of sustainability (social, environmental, economic), an increase in animal welfare will most likely be associated with an increase in productivity, better meat quality and an increased social acceptability of the production form and thus, both an increase in economic and social sustainability; whereas the relationship between animal welfare and environmental sustainability is more complicated [4]. Within intensive piggeries, several animal welfare challenges have been identified as a result of intensification including, but not excluded to, excessive sow prolificacy, heat stress, early weaning practices, pressure wounds/body lesion susceptibility, and tail biting behaviour [5]. Further, intensification results in more animals per hired stockperson and thus, more limited capacity to individually monitor animals. Despite several years of research, development and improvement efforts, several welfare challenges are still present within pig production.

Besides improving animal welfare, another important aspect is to ensure that current welfare standards are followed. In 2004, the European Commission launched the Welfare Quality® (WQ) project resulting in the development of species-specific WQ assessment protocols including one for pig production covering sows, piglets, and growing pigs [6]. The goal of the protocols are to provide piggeries with objective and validated measures to evaluate animal welfare at on-farm herd level based mainly on animal-based measures. The WQ assessment is divided into four principles (Good feeding, Good housing, Good health and Appropriate behaviour) and in total into 12 criteria (2–4 for each principle) where each criterion has one or more measures. The assessment is conducted by an assigned assessor visiting the herd. Based on scores for each measure, the herd is rated as unacceptable, acceptable, enhanced or excellent when considering the welfare of the animals. Although being an essential tool to ensure appropriate animal welfare, the WQ assessment method includes disadvantages such as being a point estimate in time, being very time consuming to perform, only evaluating a subset of the animals on the herd and, although considered as objective measures, the human assessor will undoubtedly still be subjective and possibly biased. Automating the WQ assessment measures will lower the workload [7], as well as provide a continuous and more objective measurement across farms in real-time and of all animals.

Precision livestock farming (PLF) applies the development of information technologies (ITs) for livestock management to increase and ensure livestock productivity, health and welfare. Such ITs are intended to monitor animal or environmentally based parameters automatically and continuously in real-time, on-farm and idealistically for the individual animal [8]. Building ‘digital representations’ of animals is intended to improve animal monitoring by providing the farmer with important information on individual animals [9]. Thus, ITs developed within the PLF research field could be the solution to automating the WQ assessment measures. Although, it may seem unlikely that farms across regions and countries will have similar enough PLF systems installed to be able to use a remote WQ assessment for certification purposes, the WQ assessment protocol do provide a relevant framework to identify measures of animal welfare and potential knowledge gaps that could benefit from remote assessment.

PLF demands a high level of collaboration between research fields and specialists including biosystem engineers, data scientists, animal scientists and ethologists [9]. Thus, an understanding of the general terminology within the field is important. General terms include target variable, gold standard, feature variable, field data and labelling [9,10]. The relationship between these terms are simplistically illustrated in Figure 1. For welfare monitoring, the target variable is directly related to the welfare issue studied e.g., lesions on the body of the pig and can be measured by the validated gold standard. However, the gold standard is limited as it cannot be measured continuously and in real-time. Thus, a feature variable is needed to indirectly measure the target variable, e.g., the performance of aggressive behaviour. The feature variable is extracted from the field data collected through sensors such as cameras, microphones or sensors attached to the animal. Two algorithms are developed; one to extract the feature variable from the field data, which demands detailed labelling of the field data, and one to associate the feature variable to the target variable, which demands the measurement of the gold standard. Thus, the development of a PLF system for a specific welfare issue can be at different stages of development depending on whether the feature variable or target variable (or both) are studied, and whether the system is being developed, validated or implemented.

The current systematic review aims to summarise the available literature on ITs developed to ensure or evaluate animal welfare within the pig production chain by (1) evaluating the development stage for the ITs, (2) relating the identified publications and ITs to the WQ principals and criteria, and (3) identifying potential knowledge gaps in automating the WQ assessment.

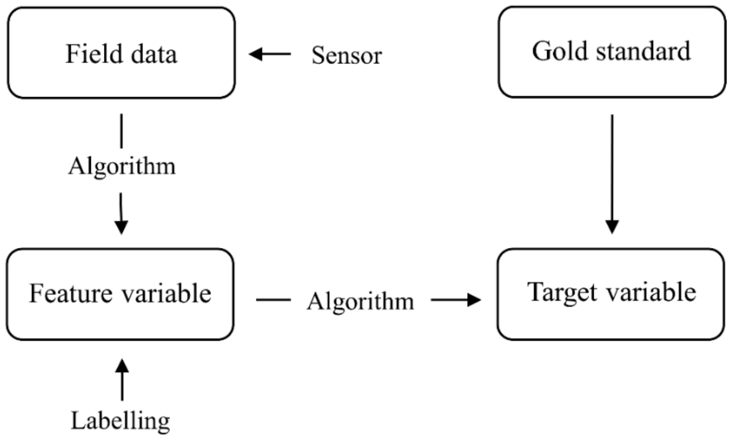

Figure 1. Flow-chart illustrating the relationship between general terms within the Precision Livestock Farming research field.

2. Materials and Methods

2.1. Systematic Literature Search

Prior to the systematic literature search, an initial non-systematic literature search was performed by two researchers independently. This initial search was inspired by the concept map used by Rios et al. investigating ITs for welfare assessment in broilers [11]. After the initial search, the two researchers created in collaboration the concept map used for the systematic literature search as presented in Table 1. The concept map is divided in three columns representing the animal studied, the method used and the subject investigated by the searched literature. In the systematic search, rows within each column of the concept map were separated by the Boolean operator OR whereas the columns were separated by the Boolean operator AND. The systematic search was conducted in the database "Web of Science" using the field "Topic" and in the database "Scopus" using the field "Article title, abstract, and key words". No limitation was set for publication year. The systematic search was conducted by a single researcher on 12 July 2020.

Table 1. Concept map terms used for the systematic literature search.

Animal	Information Technology	Animal Welfare
Pig	Technolog *	Welfare
Pigs	"Precision Livestock Farm *"	Wellbeing
Swine	Computer *	Well-being
Piglet	Digital *	"Early warning *"
Piglets	Remote *	
Sow	Automat *	
Sows	Camera *	
Boar	Microphone *	
Boars	Sensor *	
	Radio *	
	Video *	
	Image *	
	Sound *	
	Algorithm *	
	Prediction *	

Rows within each column are combined with the Boolean operator OR and columns are combined with the Boolean operator AND. Asterix (*) is used to indicate an optional end to the word. Phrases enclosed in quotation marks ("") are searched as one word.

Publications obtained from the systematic literature search were imported to the StArt tool (State-of-the-Art through Systematic Review, version 3.3 Beta 03, LaPES, Brazil) to systematically perform the selection of relevant publications. First, duplications were identified and excluded. Second, each remaining publication were evaluated according to the following exclusion criteria in the prioritised order: (1) Not concerning animal welfare within the pig production chain; (2) Not involving the development, validation or implementation of an IT; (3) Is a review; (4) Is a conference abstract/paper; (5) Is not a peer-review publication; (6) Full-text is not in English; (7) Full-text is not available. Third, the remaining publications were extracted and included in the systematic literature analysis described in Section 2.2. The selection and extraction of relevant publications for the systematic literature analysis were performed by a single researcher.

2.2. Systematic Literature Analysis

Each publication considered relevant for the systematic literature analysis was analysed by two researchers independently. First, the following general information were noted for each publication: (1) Title; (2) Year of publication; (3) Journal; (4) Country where the experiment was conducted; (5) Country of the first author. Second, a checklist of queries presented in Table 2 were answered for each publication. Terms used in the analysis are defined in Appendix A. Afterwards, the two independent analyses were compared and if differences were identified, the publication were again checked for the specific queries. The raw analysis data can be found in the Supplementary Excel sheet S1.

Table 2. Checklist of queries for each publication during the systematic literature analysis.

Analysis Question	Categories	Mutually Exclusive [1]
What IT was investigated?	-	-
What sensor technology was used?	-	-
What type of variable was captured?	Feature, Target, Both	Yes
What was the level of the variable?	Individual, Pen, Batch, Laboratory	No
What biomarker type was used?	Animal, Environmental	No
What biomarker name?	-	-

What biomarker property?	Behavioural, Physiological	No
What stage of IT development?	Development, Validation, Development and Validation, Implementation	Yes
What pig production stage?	Piglet, Weaner, Finisher, Gilt, Insemination sow, Gestation sow, Lactating sow, Individual sow, Group-housed sow, Boar, Transport, Abattoir, Artificial	No
What animal welfare issue was studied?	-	-
What animal welfare evaluation method was used	Real-Time, Retrospectively, Both	Yes
Which Welfare Quality principle does the study relate to?	Good feeding, Good housing, Good health, Appropriate behaviour	No
Which Welfare Quality criteria does the study relate to?	Absence of prolonged hunger, Absence of prolonged thirst, Comfort around resting, Thermal comfort, Ease of movement, Absence of injuries, Absence of diseases, Absence of pain induced by management procedures, Expression of social behaviour, Expression of other behaviour, Human-animal relationship, Positive emotional state	No

[1] If the possible categories of an analysis question is considered mutually exclusive, the frequency across categories should sum to the number of analysed publications; otherwise, this may not be the case.

3. Results

3.1. Systematic Literature Search

Figure 2 illustrates a flowchart of the methodology used in the systematic literature search and presents the results of the search. The search resulted in 2000 publications with 1046 publications from the database "Scopus" and 954 publications from the database "Web of Science". Out of these, 624 were duplicates. Of the rest (n = 1376), 405 did not concern animal welfare within the pig production chain which can partly be explained by the use of pigs as a model in human health research and the involvement of the word "pig" in e.g., research in guinea pigs. Of the rest (n = 971), 731 did not involve the development, validation or implementation of an IT which can partly be explained by the use of e.g., cameras for behaviour recording in animal welfare research. Out of the publications concerning pig welfare and involving an IT (n = 240), 28 were reviews, 78 were conference abstracts/papers and 8 were other types of publications except for international peer-review publications. Further, 21 publications did not have a full-text in English, mainly due to these publications being written in Chinese, and for four publications the full-text was not available. In the end, 101 publications were selected for the systematic literature analysis.

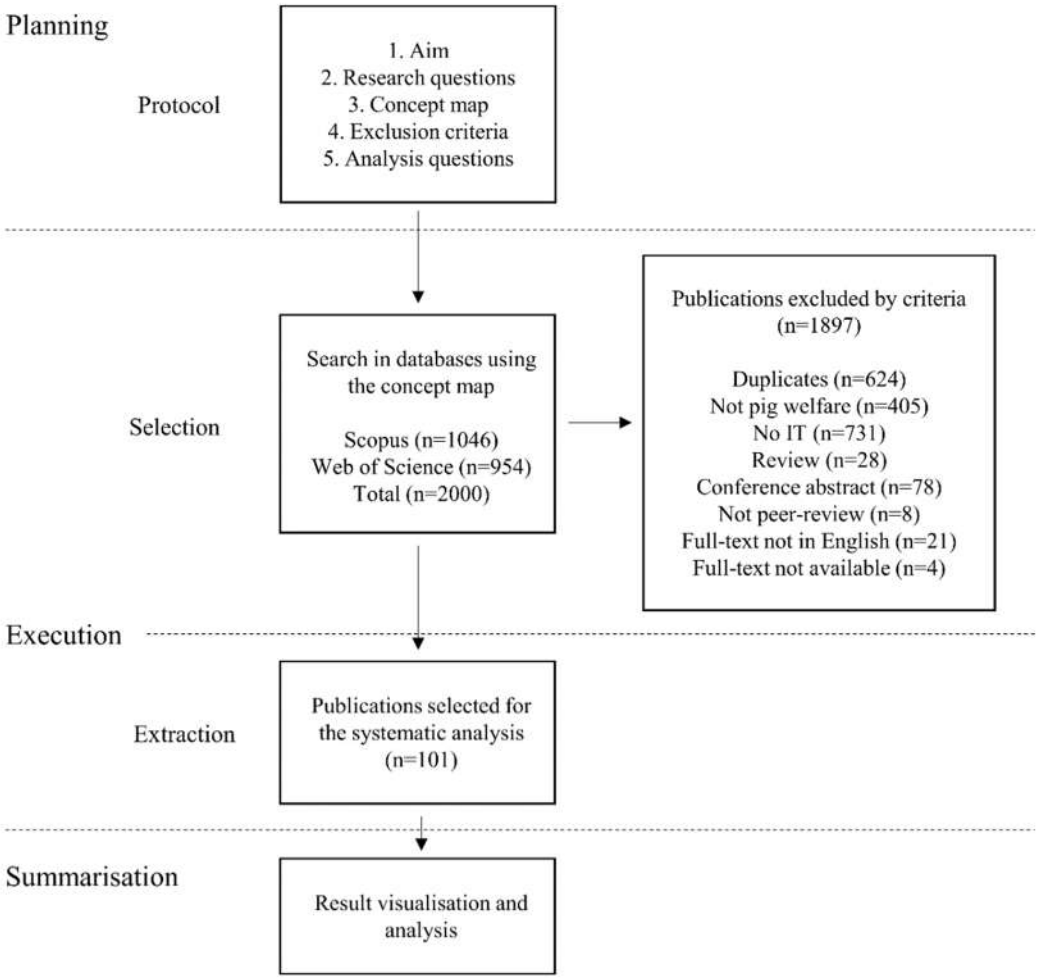

Figure 2. Flow-chart summarising the methodology used in the systematic literature search and literature search tally.

3.2. Systematic Literature Analysis

3.2.1. General Characteristics of the Publications

The general characteristics of the 101 included publications including year of publication, journal and country of experiment/first author origin is presented in Figure 3. The earliest publication was published in 1989, whereas 81% of the publications were published within the last decade and 63% were published between 2016 and mid-2020. The journal representing the highest percentage of publications was "Computers and Electronics in Agriculture" (37%) followed by "Biosystems Engineering" (14%). The countries of experiment/first author origin most often represented included Belgium, Brazil, China, Denmark, Germany, UK, and USA.

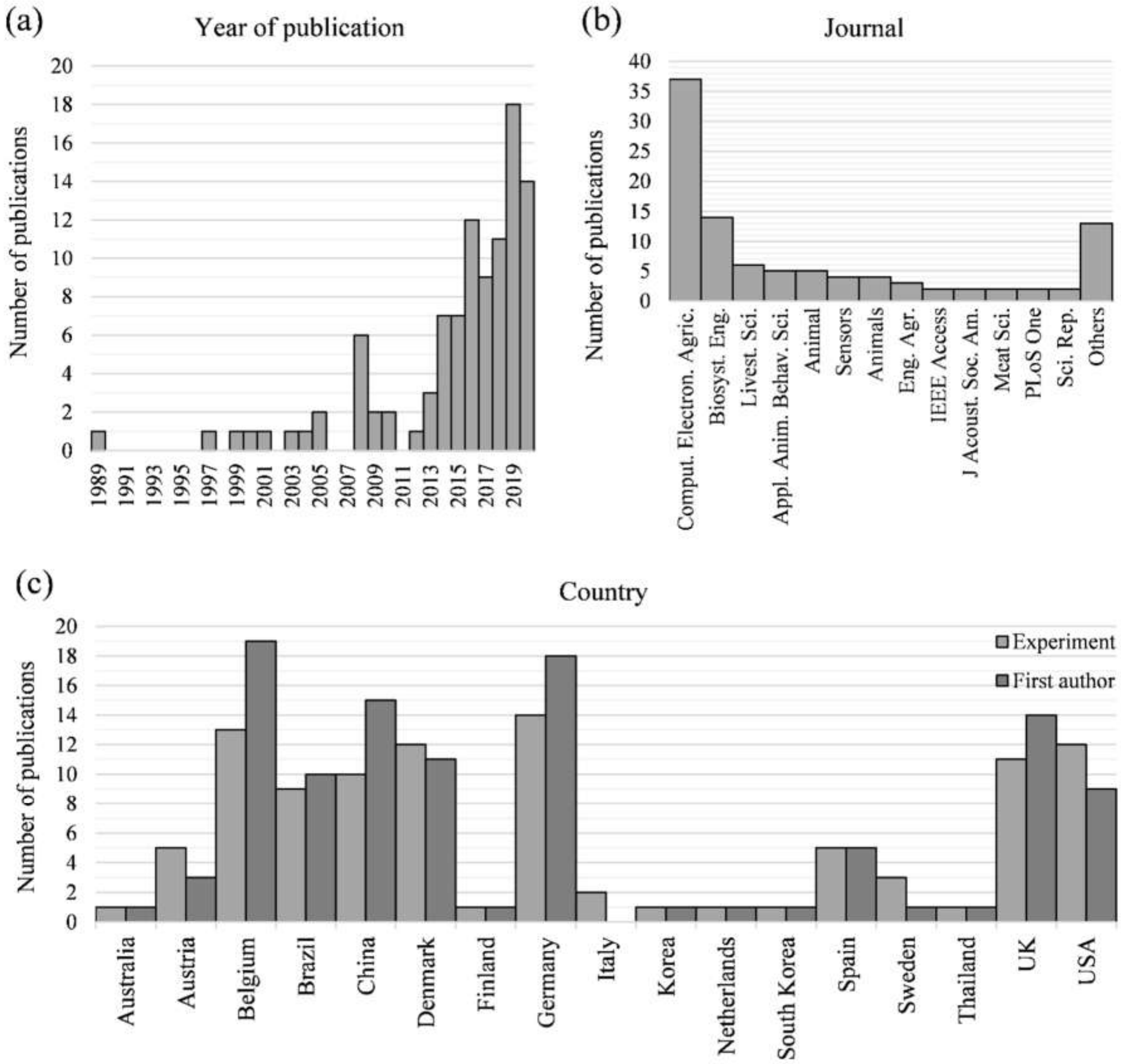

Figure 3. General characteristics of the 101 publications included in the systematic literature analysis including (**a**) year of publication, (**b**) journal and (**c**) country of experiment, first author origin. The 'Others' category in Figure (**b**) includes journals only represented once.

3.2.2. Sensor Technology

An overview of sensor technologies applied to measure animal biomarkers in the development of ITs for welfare monitoring in pigs can be seen in Table 3. Most publications used camera technology (49%), followed by microphones (18%) and animal attached sensors (15%) including accelerometers and RFID tags. Sensor technology used to measure environmental biomarkers include thermometers (n = 8, [12–19]), an EMK ('Environmental Monitoring Kit', n = 1, [20]), an anemometer (n = 1, [18]), an air-speed transmitter (n = 1, [15]), and a weather station (n = 1, [21]) used to measure temperature, relative humidity, air velocity, ventilation rate, CO_2, and ammonia.

Table 3. Overview of sensor technology used to measure animal biomarkers in the development of information technologies for animal welfare monitoring in pigs.

Sensor Technology	Type	Biomarker Type	Biomarker	Citation
Camera (n = 49)	2D image (n = 14)	Behavioural	Activity	[22]
			Posture, position and lying pattern	[23–30]
			Visual stance measures	[31]
		Physiological	Contour, area, volume and body size	[32]
			Face and eye recognition	[33]
			Lesions (claw, tail, ear)	[34–36]
	3D image (n = 6)	Behavioural	Activity	[37,38]
			Drinking and feeding behaviour	[37,38]
			Posture	[39]
		Physiological	Contour, area, volume and body size	[40–42]
			Inter-birth interval	[43]
	2D video (n = 21)	Behavioural	Activity	[44–50]
			Aggression	[51,52]
			Drinking behaviour	[53–55]
			Feeding behaviour	[49]
			Mounting	[49,56]
			Object engagement	[57]
			Posture, position and lying pattern	[50,58–60]
			Tail biting behaviour	[61]
		Physiological	Contour, area, volume and body size	[62,63]
	3D video (n = 7)	Behavioural	Activity and feeding behaviour	[64]
			Aggression	[65]
			Freeze/startle behaviour	[66]
			Gait measures	[67]
			Pig posture	[68]
			Tail posture	[69]
	IR thermography (n = 1)	Physiological	Surface temperature	[18]
Microphone (n = 18)	Sound (n = 18)	Behavioural	Cough	[70–73]
			Scream	[74–77]
			Squeals	[78]
			Vocalisation, general	[79–87]
Animal attached sensors (n = 15)	Accelerometer (n = 9)	Behavioural	Activity	[88–96]
			Feeding behaviour	[88–91]
			Rooting	[88,89]
	HF/UHF RFID (n = 6)	Behavioural	Drinking behaviour	[97]
			Feeding behaviour	[98–101]
		-	Identification	[40]
Other sensors (n = 16)	Force plates/pressure mats (n = 3)	Behavioural	Asymmetry indices	[102]
			Force stance measures	[31]
			Gait measures	[103]
	Light barriers	Behavioural	Activity	[104]

	(n = 1)			
	Load platform (n = 1)	Behavioural	Freeze/startle behaviour	[66]
	Passive IR detectors (n = 4)	Behavioural	Activity	[105–108]
	Portable Raman device (n = 1)	Physiological	Androsterone, Skatole	[109]
	Water-flow meters (n = 6)	Behavioural	Drinking behaviour	[13,14,19,110–112]

3.2.3. Variables, Biomarkers and Pig Production Stage

Characteristics of variables and biomarkers investigated can be seen in Table 4 whereas the types of biomarkers studied are presented in Table 3. Most publications investigated feature variables on individual or pen level of behavioural animal biomarkers.

Table 4. Characteristics of variables and biomarkers investigated in the development of information technologies for animal welfare monitoring in pigs.

Variable Type	No. Publications	Citation
Feature variable	79	[15–18,20–22,25,27,29–42,44–49,51–60,62,64–66,68–76,79–94,97–100,104–108,110,112]
Target variable	18	[12-14,19,43,50,61,63,67,77,78,95,96, 101–103,109,111]
Both	4	[23,24,26,28]
Variable level		
Individual	38	[18,27,31,33-41,43,48,54,62,67,68, 75,82,88-104,109]
Pen	42	[12–14,17,19,22–24,26,29,30,44,45,49–53,55–61,63–65,69,71,73,76–79,84,86,106–108,111,112]
Room/batch	10	[15,16,20,21,28,46,47,105,110,111]
Laboratory setting	11	[25,42,66,70,72,74,80,81,83,85,87]
Not reported	1	[32]
Biomarker characteristics		
Animal	97	
Behavioural	83	[13,14,19,21–31,37–39,44–61,64–108,110–112]
Physiological	14	[15,18,32–36,40–43,62,63,109]
Environmental	10	[12–21]

The stages of pig production investigated can be seen in Table 5. Most publications have investigated ITs for welfare monitoring in growing pigs (piglets, weaner pigs and finisher pigs) and lactating sows, whereas almost no publications have investigated pigs during transport or sows in the insemination unit.

Table 5. Pig production stages investigated in the development of information technologies for animal welfare monitoring in pigs.

Production Stage	No. Publications	Citation
Piglets	15	[17,20,27,70,74,75,77–79,81–83,85–87]
Weaner pigs	40	[15,20–24,26,29,30,41,45,51–55,62,64–66,69,72–74,76,79,80,86,87,97–99,102,103,105–107,110–112]
Finisher pigs	45	[12–14,19,20,22,28–30,32,40–42,44,45,50,53,54,56–60,61–64,66,69,71–73,76,79,84,87,97–101,105,108,111,112]
Sows	21	
Insemination	0	-
Gestation	1	[34]
Lactation	14	
Crated	6	[33,37,38,43,94,104]
Loose-housed	5	[39,68,90–92]
Both	3	[93,95,96]
Group-housed	2	[88,89]
Individual-housed	3	[18,31,103]
Full period	1	[36]
Boars	1	[43]
Transport	1	[46]
Abattoir	5	[35,36,43,46,109]
Artificial pigs	1	[25]
Not reported	3	[16,48,49]

3.2.4. Welfare Issues and IT Stage

The animal welfare issues investigated for IT monitoring within each IT development stage can be seen in Table 6. Ninety-seven publications investigated the welfare issues in real-time, whereas two publications investigated the welfare issue retrospectively at the abattoir (tail and ear lesions) [35,36], one publication used both evaluation methods [47] and for one publication, this categorisation was not applicable [109].

3.2.5. Relation to the Welfare Quality Assessment Protocol

The number of publications and ITs investigated related to each of the four WQ principles and the 12 WQ criteria can be seen in Tables 7 and 8.

3.2.6. Missing Publications

It is known to the authors that not all publications relevant to the objective of the current review could be identified by the systematic literature search. These include for example publications on remote weight estimation (e.g., [113–115]) and farrowing prediction (e.g., [116]), although both types of ITs where represented in other included publications. A possible explanation to this is the strong correlation between animal welfare, productivity and health. If the focus of the publication was not animal welfare, but instead on productivity, health, or similar, the authors may not have included the terms welfare or wellbeing in the title, abstract, or keywords, and thus the publication will not appear in the current systematic literature search. This illustrates the importance in the choice of keywords. It was not possible to include additional terms in the concept map of the current systematic literature search as the search already resulted in a large number of publications.

Table 6. Animal welfare issues investigated for IT monitoring within each IT development stage.

Welfare Issue	IT Development Stage (No. Publications)				Total	Citation
	Development	Validation	Dev. and val.	Implementation		
General [a]	29		9		38	[22,27,30,32,33,37–42,44,45,48,49,53–55,57,60,62,64,68,88–91,93,97–100,105–108,110,112]
Thermal environment	13	1	1		15	[15–18,23–26,28,29,58,59,83,84,86]
Disease	6		5		11	[12,13,18,19,47,70,71–73,101,111]
Stress	9		1		10	[51,52,65,75,76,79–82,87]
Farrowing management	3		3		6	[91,92,94–96,104]
Tail biting	4		2		6	[14,19,35,36,61,69]
Pen fouling	1		4		5	[12,13,19,50,111]
Lameness	5				5	[31,34,67,102,103]
Piglet crushing	2		1	1	4	[39,68,77,78]
Body injuries	2		1		3	[34,47,101]
Hunger	3				3	[83–85]
Air quality	2				2	[20,21]
Castration	2				2	[75,109]
Pain	2				2	[85,86]
Thirst	2				2	[84,86]
Undergrown pigs	1		1		2	[63,101]
Asphyxia in sows	1				1	[43]
Ear biting	1				1	[36]
Negative affective state	1				1	[66]
Negative social behaviour	1				1	[56]
Tripping and stepping	1				1	[46]

Total [b]	78	1	21	1
Citation	[17,18,20–29,31,32,34–37,39,41–49,51–54,56,58–61,63–67,69–72,74–77,80–91,93–95,97,98,100,102,103,105–111]	[15]	[12–14,16,19,30,33,38,40,50,55,57,62,68,73,79,92,96,99,101,104]	[78]

[a] Publications with welfare issue unspecified, but reporting general measures of welfare such as pig activity, positioning, posture, weight estimation, face recognition, drinking and feeding behaviour. [b] Number of publications within each IT development stage; each publication could investigate multiple welfare issues.

Table 7. The number of publications and ITs investigated related to the Welfare Quality® (WQ) principles 'Good feeding' and 'Good housing' and their respective WQ criteria. A publication could relate to multiple principles and criteria.

WQ Principle	**No. Pubs**	**WQ Criteria**	**No. Pubs.**	**WQ Measures**	**ITs Investigated** [a]	**Citation**
Good feeding	28	Absence of prolonged hunger	22	Body condition, age of weaning	Body dimension (G), weight (G), undergrown pigs (G), feeding behaviour (G, S), hunger vocalisation (G, P)	[32,37,38,40–42,49, 62–64,83,84,86, 88–91,98–101,108]
		Absence of prolonged thirst	10	Water supply (places, function, cleanliness)	Drinking behaviour (G, S), water usage (G), thirst vocalisation (G, P)	[37,38,53–55,84, 86,97,108,112]
Good housing	42	Comfort around resting	6	Pressure injuries, manure on the body	Pen fouling prediction (G)	[12,13,19,50,111,112]
		Thermal comfort	25	Shivering, panting, huddling	Respiration frequency (P), lying posture and location (G, P), cold/heat vocalisation (G, P), pen/room temperature (G), rectal temperature (P, S), pen fouling prediction (G)	[12,13,15–19,22–30, 50,58–60,83,84, 86,111,112]
		Ease of movement	17	Space allowance, farrowing crates (presence and size)	Body dimension (G), weight (G), movement (G, S), farrowing alarms (S)	[32,38–42,45,49,62,64,68,88–91,93,96]

[a] A: abattoir, G: growing pigs, P: piglets, S: sows.

Table 8. The number of publications and ITs investigated related to the Welfare Quality® (WQ) principles 'Good health' and 'Appropriate behaviour' and their respective WQ criteria. A publication could relate to multiple principles and criteria.

WQ Principle	No. Pubs.	WQ Criteria	No. Pubs.	WQ Measures	ITs Investigated [a]	Citation
Good health	78	Absence of injuries	25	Lameness, vulva lesions, body lesions	Lameness (G, S), tail/ear lesions (A), tail biting (G), crushing (P), aggression/mounting (G), tripping and stepping at unloading (A), pain vocalisation (P)	[14,19,31,34-36,39,46, 47,51,52,56,61,65, 67–69,77,78,83,86,91, 101–103}
		Absence of diseases	57	Mortality, multiple diseases	Crushing (P), asphyxia (S), farrowing management (S), posture changes (S), respiratory disease (G), diarrhoea prediction (G), general biomarkers [b] (G, P, S)	[12,13,18–22,30,32,37–45,47–49,53–55,60,62–64,68,70,71–73,77,78,88–101,104–108,110–112]
		Absence of pain induced by management procedures	4	Castration, tail docking, teeth clipping	Pain vocalisation during procedures (P), boar taint detection (A)	[75,82,85,109]
Appropriate behaviour	25	Expression of social behaviour	11	Negative and positive social behaviour	Aggression (G), mounting (G), tail biting (G), lowered tails (G) tail/ear lesions (A)	[14,19,35,36,49,51,52,56,61,65,69]
		Expression of other behaviour	7	Stereotypies, explorative behaviour	Rooting behaviour (S), nest building behaviour (S), scratching (G), object manipulation (G), drinker manipulation (G)	[49,55,57,88, 89,92,108]
		Good human-animal relationship	0	Fear of humans	-	-
		Positive emotional state	9	Qualitative behaviour assessment	Stress vocalisation (G, P), object manipulation (G), defence cascade response (G), pig face recognition (S)	[33,57,66,74,76, 79,80,81,87]

[a] A: abattoir, G: growing pigs, P: piglets, S: sows. [b] General biomarkers: activity, weight, feeding behaviour, drinking behaviour, rectal temperature, air quality.

4. Discussion

The systematic review identified 101 international peer-review publications written in English that investigated the development of ITs for welfare monitoring in the pig production chain. Although the search results date back three decades, only three publications were identified before the year of 2000 and all performed in the USA. Thus, the research field is still relatively young and a growing body of research is becoming available, which has originated from developed countries in particular. Further, an increasing trend in publications has been seen the last decade, probably as an effect of the large EU-PLF project initiated in 2012 [117] with the focus to investigate PLF technologies not only at laboratory scale, but also on-farm as the technology has become available and the industry is willing to adopt. Originally, the journals chosen for publication were mainly animal welfare journals such as *"Applied Animal Behaviour Science"* but it did not take long before more field-specific journals took the lead including 'Computers and Electronics in Agriculture' and later also 'Biosystems Engineering'. However, within the recent years, an increasing number of journals have published on open-access platforms. With an open-access publication policy, an open-data policy may follow, which is likely to advance the PLF field by enhancement of data sharing and algorithm development.

4.1. Robustness of Remote Sensor Technologies and Measurement Indicators

Recent research focus has been on using sensor technology and developing ITs for animal-based variables (96%), which is well in-line with both the WQ assessment protocol [6] and the PLF principles [9]. Most of these evaluates animal behavioural biomarkers (82%) rather than physiological biomarkers as behavioural change can be a sensitive indicator of compromised health or welfare [118]. Further, physiological biomarkers often demand invasive or disturbing measures to be performed on individuals which possibly impact on welfare and measurement robustness. The pre-dominance of such non-invasive technologies was clearly demonstrated in the methodologies reported in this study—over 80% of the publications used non-invasive monitoring with cameras and microphones being most represented, but also including water flow-meters, pressure mats, force plates, light barriers and passive infrared detectors. Technologies such as cameras and microphones have the advantage of being completely detached from the animals, meaning that the sensor does not disturb the animals, but also that the animals cannot disturb the sensor, which is especially important in the case of the curious and exploring pig. However, a disadvantage of such detached sensors is that it is not yet possible to observe on the individual level in group-housed animals; definitely not in the case of the pig where each animal look very much alike. Thus, a high proportion of the publications identified monitored on pen level (42%). The use of individual-level sensors, such as RFID technology or accelerometers, may not be cost-effective for the farmer, especially not for the little-valued growing pig, which is why research projects which develop camera-based algorithms for individual tracking are useful e.g., [61]. Further development of state-of-the-art technologies and this technique may make it possible in the future to make observations on the individual pig using detached sensors observing many animals per sensor, making the technology more available to the farmer.

4.2. Current Direction of IT Development

The majority of the identified publications studied feature variables (77%). To develop an IT to extract the feature variables from the field data is the first step in developing a PLF system and thus, it is a natural starting point. Such work should be preceded by research investigating which feature variables are connected to the chosen welfare issue. However, a high proportion of the included publications studying feature variables did not mention a specific welfare issue, thus no specific target variable, and was labelled 'General' for the welfare issue studied (38%). Included in this category are the biomarkers *activity, weight estimation, feeding behaviour, and drinking behaviour*. Although activity has been investigated as a feature variable for farrowing management, and drinking behaviour as a feature variable for undesirable events including tail biting, fouling and diarrhoea, more work seems needed on how these 'general' and other feature variables can be related to detection or prediction of specific welfare issues. This now seems possible as feature variables can be automatically and continuously detected.

For usable on-farm welfare monitoring IT development, validation needs to occur across environments. Surprisingly, only 23% of the identified publications properly validated their developed ITs, some internally on independent data and others externally in other environments. Several publications mentioned using cross-validation and described this as validation of the IT. Cross-validation is a valid method to initially test whether the IT works on the data or for parameter estimation, and therefore should not be considered as actual validation. Preferably, studies should be designed to isolate an independent part of the data for proper validation. Surprisingly, none of the identified publications (except one published in 1989) described the detailed implementation of the developed IT. One known example of implemented ITs include the development of the pig cough monitor systems to evaluate respiratory diseases [119]. It may be that there is merely a lack of robustly detailed documentation in the international peer-reviewed society, or possibly the non-implementation at farm or commercial level. Such a trend is unfortunate as it makes it difficult for the research community to replicate the development of different ITs and PLF systems. However, it may also be the case that prototypes are not being validated in practice because of individual or on-site needs. Ultimately, the more scientific validation and collaboration between companies and academic research, the greater the usefulness and robustness of such systems will be.

4.3. Relevance to the Welfare Quality® Protocol

The WQ protocol monitors animal welfare instantaneously and not continuously; thus, the assessment for each criteria is limited to what is possible in the moment and with the human eye. The use of ITs expand the assessment possibilities and thus also the measures to assess each criteria within each principle. This is for example seen within the 'good feeding' principle where absence of hunger and thirst evaluated with ITs can be assessed by direct physical measurement of pig eating and drinking volumes. This is also seen within the 'good housing' principle and 'ease of movement' criteria where space allowance can be more correctly assessed by the actual space taken up by the pigs instead of merely the number of pigs per floor space provided, and by measuring pigs' actual movement. Thus, the use of ITs in welfare assessment do have potential to not only improve the current welfare assessment by continuous, real-time and objective/reliable measures, but also to include more direct measures of the single criteria.

The 'good health' principle was related to the highest number of publications. However, with the 'absence of diseases' criterion, only diarrhoea and respiratory diseases has been directly investigated, and only in growing pigs. Considering the high number of diseases evaluated in the WQ assessment protocol, much work is still needed to identify feature variables for the specific diseases and develop ITs for these diseases. The same apply to the 'absence of injuries' criterion with lameness being the only injury directly investigated on-farm, primarily in sows using force plates, pressure mats and cameras to measure gait, stance and weight distribution. However, due to the use of these mats and the angle needed on the camera, none of these can yet detect lameness in the home pen, but instead needs to disturb and confine the animal being assessed. Together with the low number of publications representing the 'absence of pain induced by management procedures' criterion, probably due to this criterion being measurable through simple questions to the herd manager, the 'good health' principle is much less covered than first assumed.

The 'good housing' principle is mainly represented by the 'Thermal comfort' criterion. Shivering, panting, and huddling are best assessed in resting animals, as stated in the WQ assessment protocol, and thus ITs are an especially suitable tool within this criterion making it possible to observe the animals without human disturbance. However, no ITs have been developed for shivering and panting. Within this criterion, only one IT has been developed for sows measuring the surface temperature using infrared thermography and only three ITs have been developed for piglets measuring multiple variables using cameras, microphones and thermometers. This is surprising, as sows are prone to heat stress, especially when housed in crates [120] and as climate is a major conflict in the farrowing unit with piglets needing high temperatures above 30 °C and sows having an upper critical temperature of approximately 25 °C. Instead, the focus within the 'thermal comfort' criterion has so far been on the growing pigs, perhaps because the housing conditions for growing pigs give the animals more opportunity to show thermoregulatory behaviour (change in lying posture and position) and because the thermoregulatory behaviour of growing pigs is related to the undesirable event of pen fouling [121], and thus may be used as an indicator to predict and prevent such an event [50]. ITs developed for prediction and prevention of pen fouling are also the only ones representing the criterion 'Comfort around resting', although not being a direct measure of manure on the body and with no ITs developed to measure pressure injuries.

The 'appropriate behaviour' principle is the least represented one in the current systematic literature analysis, perhaps because this principle includes the detection of more complicated behaviour patterns often also demanding tracking of the single animals such as for tail biting [61] or of single objects such as for object engagement [57]. Further, the 'positive emotional state' criterion is currently being assessed by the qualitative behaviour assessment (QBA) protocol, indicating that objective measures are lacking, making it difficult to develop ITs for this criterion. ITs have so far been developed within the 'Expression of social behaviours' criterion for direct assessment of negative social behaviours, but not for positive social behaviour such as play behaviour or prosocial behaviours [122]. Further, ITs have been developed within the 'Expression of other behaviours' criterion for object engagement and drinker manipulation for growing pigs, and for rooting and nest building in sows, but not for stereotypies such as sham chewing, tongue rolling and teeth grinding. Most surprisingly is the complete lack of ITs developed for the 'good human-animal relationship' criterion, as the animals are being confronted with humans multiple times each day and thus, the character of the animals relationship to humans is important to their welfare on a daily basis [123]. Further, with increased automation and digitalisation of production, the overall human-animal contact may decrease, possibly decreasing the animals' habituation to humans [123] and making an easy, continuous, and objective measure of the human-animal relationship that more important.

Overall, the WQ principle 'good feeding' is best represented when considering welfare assessment with ITs in real-time and on-farm, although the lactating sow is not represented within this principle. The fact that lactating sows are housed individually, and thus do not experience the competition for feed and water resources as the group-housed animals, could be the reason. The other principles either have criteria with a complete lack of developed ITs or only few of their included measures covered. Although the current systematic literature analysis identified 101 publications, many of these cannot directly replace measures of the WQ assessment protocol and thus, much work is still needed to replace the manual welfare assessment with a remote solution. The current review identified such knowledge gaps to help future research projects choose their focus to cover the welfare assessment as widely as possible. In that context, it should also be mentioned that most focus so far has been put on the pigs intended for slaughter, although these being the animals experiencing the production environment for the shortest time. Further, only few studies investigated ITs for welfare monitoring at the abattoir, and no studies focused on ITs for welfare assessment during transport, although major welfare issues have been identified during this part of the production [124]. ITs seem to have high potential for welfare assessment inside the lorry, an environment where humans cannot observe manually. This could for example be monitoring the water consumption, the climate or the vocalisations of the animals during transport, whereas it may be difficult to use cameras with the low ceiling height and often several layers of animals in the lorry.

5. Conclusions

The current systematic review identified 101 publications investigating ITs for welfare monitoring within the pig production chain. Based on the systematic analysis, it was obvious that this research field is young and growing as shown not only by the year of publication, but also by the fact that the majority of publications identified reported ITs for feature variables still lacking proper validation. Most focus has so far been on growing pigs intended for slaughter, while only very few ITs were identified to monitor the welfare of pigs during transport and at the abattoir. ITs intended for many different welfare issues have been studied, although a high number of publications did not specify a welfare issue and instead studied a general biomarker such as activity and feeding and drinking behaviour. The 'good feeding' principle of the WQ assessment protocol was the most frequently represented by ITs for real-time on-farm welfare assessment, while for the other principles only few of the included WQ measures are so far covered. No ITs have yet been developed for the 'comfort around resting' and the 'good human-animal relationship' criteria. Thus, the potential to develop ITs for welfare assessment is high, and much work is still needed to end up with a remote solution for welfare assessment on-farm and in real-time.

Supplementary Materials: The following are available online at www.mdpi.com/2071-1050/13/2/692/s1. Excel file S1: the raw systematic analysis data.

Author Contributions: Conceptualization, M.L.V.L., M.W., and T.N.; methodology, M.L.V.L., M.W., and T.N.; formal analysis, M.L.V.L. and M.W.; investigation, M.L.V.L.; data curation, M.L.V.L; writing—original draft preparation, M.L.V.L.; writing—review and editing, M.L.V.L., M.W. and T.N.; visualization, M.L.V.L.; supervision, T.N.; funding acquisition, M.L.V.L. and T.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 842555.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Definition of terms used in the systematic literature search and systematic analysis of the relevant publications.

Term	Definition
Information technology (IT)	The use of sensor technology to develop an algorithm providing information to the stakeholder.
Variable type	
Target	Directly related to a welfare challenge and thus, the purpose of the PLF system being developed.
Feature	An alternative variable that represents or can give an early warning of the target variable.
Variable level	
Individual	The variable studied is measured at the individual animal level.
Pen	The variable studied is measured at pen level.
Batch	The variable studied is measured at room or batch level.
Laboratory	The variable studied is measured in a laboratory setting outside production conditions. An example is the isolation of

	group-housed animals to measure the feature variable at an individual level and under very controlled conditions.
IT stage	
Development	The study concerns the development of the algorithm for either the feature or the target variable.
Validation	The study concerns the validation of the developed algorithm on new data, either by assigning specific animals/groups for this validation (not just random data points) or by performing external validation. Does not include cross validation.
Implementation	The study concerns the implementation of the developed and validated algorithm/PLF system including evaluation of the algorithm/PLF system in a real-time production setting.
Production stage	
Piglet	The pig is being housed with a sow.
Weaner	The pig has been weaned from the sow and weighs below 30 kg.
Finisher	The pig weighs above 30 kg and is being produced for slaughter.
Growing pigs	Including both weaners and finishers.
Sow, insemination	The sow/gilt is in the reproduction stage of being inseminated.
Sow, gestation	The sow/gilt is pregnant, has not yet farrowed and is housed in a gestation unit.
Sow, lactation	The sow are housed in a farrowing pen either prior to farrowing or after farrowing with her piglets.
Sow, group housed	The sow/gilt is group-housed, but it is not specified whether the sow/gilt is in the insemination, gestation or lactation stage.
Sow, individual	The sow/gilt is housed individually, but it is not specified whether the sow/gilt is in the insemination, gestation or lactation stage.
Boar	An adult male pigused for breeding.
Transport	The animal is studied in a transport setting.
Abattoir	The animal is studied or the variable is captured at the abattoir.
Biomarker	Variable measured in the study. Can either be an animal or environmental based biomarker, and an animal based biomarker can either be behavioural or physiological.
Welfare issue	The animal welfare challenge experienced by the farmer and the reason for conducting the study and developing the algorithm/PLF system. If not specified, 'General' is noted.
Evaluation method	
Real-time	The algorithm/PLF system evaluates the welfare issue in real-time, meaning evaluating the present animal welfare and with the opportunity to also improve in the present.
Retrospectively	The algorithm/PLF system evaluates the welfare issue respectively, meaning evaluating past animal welfare to use for future improvements.

References

1. OECD/FAO. *OECD-FAO Agricultural Outlook 2020–2029*; OECD Publishing: Paris, France; FAO: Rome, Italy, 2020.
2. Harrison, R. *Animal Machines: The New Factory Farming Industry*; Vincent Stuart Publishers LTD: London, UK, 1964.
3. Keeling, L.; Tunón, H.; Antillón, G.O.; Berg, C.; Jones, M.; Stuardo, L.; Swanson, J.; Wallenbeck, A.; Winckler, C.; Blokhuis, H. Animal Welfare and the United Nations Sustainable Development Goals. *Front. Vet. Sci.* **2019**, *6*, 336, doi:10.3389/fvets.2019.00336.
4. Tucker, C.; Mench, J.; von Keyserlingk, M. Animal welfare: An integral component of sustainability. In *Sustainable Animal Agriculture*; Kebreab, E., Ed.; CAB International: Oxfordshire, UK, 2013; pp. 42–52.
5. Pedersen, L.J. Overview of commercial pig production systems and their main welfare challenges. In *Advances in Pig Welfare*; Špinka, M., Ed.; Woodhead Publishing: Cambridge, UK, 2018; pp. 3–25.
6. Welfare Quality®. *Welfare Quality® Assessment Protocol for Pigs (Sow and Piglets, Growing and Finishing Pigs)*; Lelystad, The Netherlands, 2009.
7. Blokhuis, H.J.; Veissier, I.; Miele, M.; Jones, B. The Welfare Quality® project and beyond: Safeguarding farm animal well-being. *Acta Agric. Scand Sect. A* **2010**, *60*, 129–140, doi:10.1080/09064702.2010.523480.
8. Berckmans, D. General introduction to precision livestock farming. *Anim. Front.* **2017**, *7*, 6–11, doi:10.2527/af.2017.0102.
9. Norton, T.; Chen, C.; Larsen, M.L. V.; Berckmans, D. Precision livestock farming: Building 'digital representations' to bring the animals closer to the farmer. *Animal* **2019**, *13*, 3009–3017, doi:10.1017/S175173111900199X.
10. Berckmans, D. Basic principles of PLF: Gold standard, labelling and field data. In Proceedings of the Precision Livestock Farming 2013—Papers Presented at the 6th European Conference on Precision Livestock Farming, ECPLF, Leuven, Belgium, 10–12 September 2013; pp. 21–29.
11. Rios, H.V.; Waquil, P.D.; de Carvalho, P.S.; Norton, T. How are information technologies addressing broiler welfare? A systematic review based on the welfare quality® assessment. *Sustainability* **2020**, *12*, 1413, doi:10.3390/su12041413.
12. Jensen, D.B.; Kristensen, A.R. Temperature as a predictor of fouling and diarrhea in slaughter pigs. *Livest. Sci.* **2016**, *183*, 1–3, doi:10.1016/j.livsci.2015.11.007.
13. Jensen, D.B.; Toft, N.; Kristensen, A.R. A multivariate dynamic linear model for early warnings of diarrhea and pen fouling in slaughter pigs. *Comput. Electron. Agric.* **2017**, *135*, 51–62, doi:10.1016/j.compag.2016.12.018.
14. Larsen, M.L.V.; Pedersen, L.J.; Jensen, D.B. Prediction of tail biting events in finisher pigs from automatically recorded sensor data. *Animals* **2019**, *9*, 9070458, doi:10.3390/ani9070458.
15. Ortega, J.A.; Losada, E.; Besteiro, R.; Arango, T.; Ginzo-Villamayor, M.J.; Velo, R.; Fernandez, M.D.; Rodriguez, M.R. Validation of an AutoRegressive Integrated Moving Average model for the prediction of animal zone temperature in a weaned piglet building. *Biosyst. Eng.* **2018**, *174*, 231–238, doi:10.1016/j.biosystemseng.2018.07.012.
16. Sarnighausen, V.C.R. Estimation of thermal comfort indexes for production animals using multiple linear regression models. *J. Anim. Behav. Biometeorol.* **2019**, *7*, 73–77, doi:10.31893/2318-1265jabb.v7n2p73-77.
17. Alves Damasceno, F.; Alves Oliveira, C.E.; Pedrozo Abreu, L.H.; Osorio Saraz, J.A.; Ferreira Ponciano Ferraz, P. Fuzzy system to evaluate performance and the physiological responses of piglets raised in the farrowing house with different solar heating systems. *Rev. Fac. Nac. Agron. Medellin* **2019**, *72*, 8729–8742, doi:10.15446/rfnam.v72n1.67736.
18. Feng, Y.-Z.; Zhao, H.-T.; Jia, G.-F.; Ojukwu, C.; Tan, H.-Q. Establishment of validated models for non-invasive prediction of rectal temperature of sows using infrared thermography and chemometrics. *Int. J. Biometeorol.* **2019**, *63*, 1405–1415, doi:10.1007/s00484-019-01758-2.
19. Domun, Y.; Pedersen, L.J.; White, D.; Adeyemi, O.; Norton, T. Learning patterns from time-series data to discriminate predictions of tail-biting, fouling and diarrhoea in pigs. *Comput. Electron. Agric.* **2019**, *163*, 104878, doi:10.1016/j.compag.2019.104878.
20. Banhazi, T.M.; Rutley, D.L.; Pitchford, W.S. Validation and fine-tuning of a predictive model for air quality in livestock buildings. *Biosyst. Eng.* **2010**, *105*, 395–401, doi:10.1016/j.biosystemseng.2009.12.011.
21. Besteiro, R.; Arango, T.; Ortega, J.A.; Rodríguez, M.R.; Fernández, M.D.; Velo, R. Prediction of carbon dioxide concentration in weaned piglet buildings by wavelet neural network models. *Comput. Electron. Agric.* **2017**, *143*, 201–207, doi:10.1016/j.compag.2017.10.025.
22. Nasirahmadi, A.; Sturm, B.; Edwards, S.; Jeppsson, K.-H.; Olsson, A.-C.; Mueller, S.; Hensel, O. Deep Learning and Machine Vision Approaches for Posture Detection of Individual Pigs. *Sensors* **2019**, *19*, s19173738, doi:10.3390/s19173738.
23. Shao, J.; Xin, H.; Harmon, J.D. Neural network analysis of postural behavior of young swine to determine the IR thermal comfort state. *Trans. Am. Soc. Agric. Eng.* **1997**, *40*, 755–760, doi:10.13031/2013.21306.
24. Xin, H. Assessing swine thermal comfort by image analysis of postural behaviors. *J. Anim. Sci.* **1999**, *77*, 1–9, doi:10.2527/1999.77suppl_21x.
25. Hu, J.; Xin, H. Image-processing algorithms for behavior analysis of group-housed pigs. *Behav. Res. Methods Instruments Comput.* **2000**, *32*, 72–85, doi:10.3758/BF03200790.
26. Shao, B.; Xin, H. A real-time computer vision assessment and control of thermal comfort for group-housed pigs. *Comput. Electron. Agric.* **2008**, *62*, 15–21, doi:10.1016/j.compag.2007.09.006.
27. Navarro Jover, J.M.; Alcañiz-Raya, M.; Gómez, V.; Balasch, S.; Moreno, J.R.; Grau Colomer, V.; Torres, A. An automatic colour-based computer vision algorithm for tracking the position of piglets. *Span. J. Agric. Res.* **2009**, *7*, 535–549, doi:10.5424/sjar/2009073-438.

28. Nasirahmadi, A.; Hensel, O.; Edwards, S.A.; Sturm, B. A new approach for categorizing pig lying behaviour based on a Delaunay triangulation method. *Animal* **2017**, *11*, 131–139, doi:10.1017/S1751731116001208.
29. Nasirahmadi, A.; Sturm, B.; Olsson, A.-C.; Jeppsson, K.-H.; Mueller, S.; Edwards, S.; Hensel, O. Automatic scoring of lateral and sternal lying posture in grouped pigs using image processing and Support Vector Machine. *Comput. Electron. Agric.* **2019**, *156*, 475–481, doi:10.1016/j.compag.2018.12.009.
30. Riekert, M.; Klein, A.; Adrion, F.; Hoffmann, C.; Gallmann, E. Automatically detecting pig position and posture by 2D camera imaging and deep learning. *Comput. Electron. Agric.* **2020**, *174*, doi:10.1016/j.compag.2020.105391.
31. Pluym, L.M.; Maes, D.; Vangeyte, J.; Mertens, K.; Baert, J.; Van Weyenberg, S.; Millet, S.; Van Nuffel, A. Development of a system for automatic measurements of force and visual stance variables for objective lameness detection in sows: SowSIS. *Biosyst. Eng.* **2013**, *116*, 64–74, doi:10.1016/j.biosystemseng.2013.06.009.
32. Buayai, P.; Piewthongngam, K.; Leung, C.K.; Saikaew, K.R. Semi-automatic pig weight estimation using digital image analysis. *Appl. Eng. Agric.* **2019**, *35*, 521–534.
33. Marsot, M.; Mei, J.; Shan, X.; Ye, L.; Feng, P.; Yan, X.; Li, C.; Zhao, Y. An adaptive pig face recognition approach using Convolutional Neural Networks. *Comput. Electron. Agric.* **2020**, *173*, 105386, doi:10.1016/j.compag.2020.105386.
34. van Riet, M.M.J.; Vangeyte, J.; Janssens, G.P.J.; Ampe, B.; Nalon, E.; Bos, E.J.; Pluym, L.; Tuyttens, F.A.M.; Maes, D.; Millet, S. On-Farm claw scoring in sows using a novel mobile device. *Sensors* **2019**, *19*, 1–14, doi:10.3390/s19061473.
35. Brünger, J.; Dippel, S.; Koch, R.; Veit, C. "Tailception": Using neural networks for assessing tail lesions on pictures of pig carcasses. *Animal* **2019**, *13*, 1030–1036, doi:10.1017/S1751731118003038.
36. Blömke, L.; Volkmann, N.; Kemper, N. Evaluation of an automated assessment system for ear and tail lesions as animal welfare indicators in pigs at slaughter. *Meat Sci.* **2020**, *159*, 107934, doi:10.1016/j.meatsci.2019.107934.
37. Leonard, S.M.; Xin, H.; Brown-Brandl, T.M.; Ramirez, B.C. Development and application of an image acquisition system for characterizing sow behaviors in farrowing stalls. *Comput. Electron. Agric.* **2019**, *163*, 104866, doi:10.1016/j.compag.2019.104866.
38. Lao, F.; Brown-Brandl, T.; Stinn, J.P.; Liu, K.; Teng, G.; Xin, H. Automatic recognition of lactating sow behaviors through depth image processing. *Comput. Electron. Agric.* **2016**, *125*, 56–62, doi:10.1016/j.compag.2016.04.026.
39. Zheng, C.; Zhu, X.; Yang, X.; Wang, L.; Tu, S.; Xue, Y. Automatic recognition of lactating sow postures from depth images by deep learning detector. *Comput. Electron. Agric.* **2018**, *147*, 51–63, doi:10.1016/j.compag.2018.01.023.
40. Li, Z.; Du, X.; Mao, T.; Teng, G. Pig dimension detection system based on depth image. *Trans. Chinese Soc. Agric. Mach.* **2016**, *47*, 311–318, doi:10.6041/j.issn.1000-1298.2016.03.044.
41. Condotta, I.C.F.S.; Brown-Brandl, T.M.; Silva-Miranda, K.O.; Stinn, J.P. Evaluation of a depth sensor for mass estimation of growing and finishing pigs. *Biosyst. Eng.* **2018**, *173*, 11–18, doi:10.1016/j.biosystemseng.2018.03.002.
42. Shuai, S.; Ling, Y.; Shihao, L.; Haojie, Z.; Xuhong, T.; Caixing, L.; Aidong, S.; Hanxing, L. Research on 3D surface reconstruction and body size measurement of pigs based on multi-view RGB-D cameras. *Comput. Electron. Agric.* **2020**, *175*, 105543, doi:10.1016/j.compag.2020.105543.
43. Okinda, C.; Lu, M.; Nyalala, I.; Li, J.; Shen, M. Asphyxia occurrence detection in sows during the farrowing phase by inter-birth interval evaluation. *Comput. Electron. Agric.* **2018**, *152*, 221–232, doi:10.1016/j.compag.2018.07.007.
44. Ott, S.; Moons, C.P.H.; Kashiha, M.A.; Bahr, C.; Tuyttens, F.A.M.; Berckmans, D.; Niewold, T.A. Automated video analysis of pig activity at pen level highly correlates to human observations of behavioural activities. *Livest. Sci.* **2014**, *160*, 132–137, doi:10.1016/j.livsci.2013.12.011.
45. Kashiha, M.A.; Bahr, C.; Ott, S.; Moons, C.P.H.; Niewold, T.A.; Tuyttens, F.; Berckmans, D. Automatic monitoring of pig locomotion using image analysis. *Livest. Sci.* **2014**, *159*, 141–148, doi:10.1016/j.livsci.2013.11.007.
46. Gronskyte, R.; Clemmensen, L.H.; Hviid, M.S.; Kulahci, M. Pig herd monitoring and undesirable tripping and stepping prevention. *Comput. Electron. Agric.* **2015**, *119*, 51–60, doi:10.1016/j.compag.2015.09.021.
47. Gronskyte, R.; Clemmensen, L.H.; Hviid, M.S.; Kulahci, M. Monitoring pig movement at the slaughterhouse using optical flow and modified angular histograms. *Biosyst. Eng.* **2016**, *141*, 19–30, doi:10.1016/j.biosystemseng.2015.10.002.
48. Cowton, J.; Kyriazakis, I.; Bacardit, J. Automated Individual Pig Localisation, Tracking and Behaviour Metric Extraction Using Deep Learning. *IEEE Access* **2019**, *7*, 108049–108060, doi:10.1109/ACCESS.2019.2933060.
49. Zhang, K.; Li, D.; Huang, J.; Chen, Y. Automated video behavior recognition of pigs using two-stream convolutional networks. *Sensors* **2020**, *20*, 1085, doi:10.3390/s20041085.
50. Jensen, D.B.; Larsen, M.L.V.; Pedersen, L.J. Predicting pen fouling in fattening pigs from pig position. *Livest. Sci.* **2020**, *231*, 103852, doi:10.1016/j.livsci.2019.103852.
51. Chen, C.; Zhu, W.; Ma, C.; Guo, Y.; Huang, W.; Ruan, C. Image motion feature extraction for recognition of aggressive behaviors among group-housed pigs. *Comput. Electron. Agric.* **2017**, *142*, 380–387, doi:10.1016/j.compag.2017.09.013.
52. Chen, C.; Zhu, W.; Steibel, J.; Siegford, J.; Wurtz, K.; Han, J.; Norton, T. Recognition of aggressive episodes of pigs based on convolutional neural network and long short-term memory. *Comput. Electron. Agric.* **2020**, *169*, 105166, doi:10.1016/j.compag.2019.105166.
53. Kashiha, M.; Bahr, C.; Haredasht, S.A.; Ott, S.; Moons, C.P.H.; Niewold, T.A.; Odberg, F.O.; Berckmans, D. The automatic monitoring of pigs water use by cameras. *Comput. Electron. Agric.* **2013**, *90*, 164–169, doi:10.1016/j.compag.2012.09.015.
54. Zhu, W.; Guo, Y.; Jiao, P.; Ma, C.; Chen, C. Recognition and drinking behaviour analysis of individual pigs based on machine vision. *Livest. Sci.* **2017**, *205*, 129–136, doi:10.1016/j.livsci.2017.09.003.

55. Chen, C.; Zhu, W.; Steibel, J.; Siegford, J.; Han, J.; Norton, T. Classification of drinking and drinker-playing in pigs by a video-based deep learning method. *Biosyst. Eng.* **2020**, *196*, 1–14, doi:10.1016/j.biosystemseng.2020.05.010.
56. Nasirahmadi, A.; Hensel, O.; Edwards, S.A.; Sturm, B. Automatic detection of mounting behaviours among pigs using image analysis. *Comput. Electron. Agric.* **2016**, *124*, 295–302, doi:10.1016/j.compag.2016.04.022.
57. Chen, C.; Zhu, W.; Oczak, M.; Maschat, K.; Baumgartner, J.; Larsen, M.L.V.; Norton, T. A computer vision approach for recognition of the engagement of pigs with different enrichment objects. *Comput. Electron. Agric.* **2020**, *175*, 105580, doi:10.1016/j.compag.2020.105580.
58. Nilsson, M.; Herlin, A.H.; Ardo, H.; Guzhva, O.; Astrom, K.; Bergsten, C. Development of automatic surveillance of animal behaviour and welfare using image analysis and machine learned segmentation technique. *Animal* **2015**, *9*, 1859–1865, doi:10.1017/S1751731115001342.
59. Nasirahmadi, A.; Richter, U.; Hensel, O.; Edwards, S.; Sturm, B. Using machine vision for investigation of changes in pig group lying patterns. *Comput. Electron. Agric.* **2015**, *119*, 184–190, doi:10.1016/j.compag.2015.10.023.
60. Nasirahmadi, A.; Edwards, S.A.; Matheson, S.M.; Sturm, B. Using automated image analysis in pig behavioural research: Assessment of the influence of enrichment substrate provision on lying behaviour. *Appl. Anim. Behav. Sci.* **2017**, *196*, 30–35, doi:10.1016/j.applanim.2017.06.015.
61. Liu, D.; Oczak, M.; Maschat, K.; Baumgartner, J.; Pletzer, B.; He, D.; Norton, T. A computer vision-based method for spatial-temporal action recognition of tail-biting behaviour in group-housed pigs. *Biosyst. Eng.* **2020**, *195*, 27–41, doi:10.1016/j.biosystemseng.2020.04.007.
62. Kashiha, M.; Bahr, C.; Ott, S.; Moons, C.P.H.; Niewold, T.A.; Oedberg, F.O.; Berckmans, D. Automatic weight estimation of individual pigs using image analysis. *Comput. Electron. Agric.* **2014**, *107*, 38–44, doi:10.1016/j.compag.2014.06.003.
63. Lee, S.; Ahn, H.; Seo, J.; Chung, Y.; Park, D.; Pan, S. Practical Monitoring of Undergrown Pigs for IoT-Based Large-Scale Smart Farm. *IEEE Access* **2019**, *7*, 173796–173810, doi:10.1109/ACCESS.2019.2955761.
64. Matthews, S.G.; Miller, A.L.; Plotz, T.; Kyriazakis, I. Automated tracking to measure behavioural changes in pigs for health and welfare monitoring. *Sci. Rep.* **2017**, *7*, 17582, doi:10.1038/s41598-017-17451-6.
65. Lee, J.; Jin, L.; Park, D.; Chung, Y. Automatic Recognition of Aggressive Behavior in Pigs Using a Kinect Depth Sensor. *Sensors* **2016**, *16*, s16050631, doi:10.3390/s16050631.
66. Statham, P.; Hannuna, S.; Jones, S.; Campbell, N.; Robert Colborne, G.; Browne, W.J.; Paul, E.S.; Mendl, M. Quantifying defence cascade responses as indicators of pig affect and welfare using computer vision methods. *Sci. Rep.* **2020**, *10*, 1–13, doi:10.1038/s41598-020-65954-6.
67. Stavrakakis, S.; Guy, J.H.; Syranidis, I.; Johnson, G.R.; Edwards, S.A. Pre-clinical and clinical walking kinematics in female breeding pigs with lameness: A nested case-control cohort study. *Vet. J.* **2015**, *205*, 38–43, doi:10.1016/j.tvjl.2015.04.022.
68. Zheng, C.; Yang, X.; Zhu, X.; Chen, C.; Wang, L.; Tu, S.; Yang, A.; Xue, Y. Automatic posture change analysis of lactating sows by action localisation and tube optimisation from untrimmed depth videos. *Biosyst. Eng.* **2020**, *194*, 227–250, doi:10.1016/j.biosystemseng.2020.04.005.
69. D'Eath, R.B.; Jack, M.; Futro, A.; Talbot, D.; Zhu, Q.; Barclay, D.; Baxter, E.M. Automatic early warning of tail biting in pigs: 3D cameras can detect lowered tail posture before an outbreak. *PLoS ONE* **2018**, *13*, e0194524, doi:10.1371/journal.pone.0194524.
70. Van Hirtum, A.; Berckmans, D. Fuzzy approach for improved recognition of citric acid induced piglet coughing from continuous registration. *J. Sound Vib.* **2003**, *266*, 677–686, doi:10.1016/S0022-460X(03)00593-5.
71. Silva, M.; Ferrari, S.; Costa, A.; Aerts, J.-M.; Guarino, M.; Berckmans, D. Cough localization for the detection of respiratory diseases in pig houses. *Comput. Electron. Agric.* **2008**, *64*, 286–292, doi:10.1016/j.compag.2008.05.024.
72. Exadaktylos, V.; Silva, M.; Aerts, J.-M.; Taylor, C.J.; Berckmans, D. Real-time recognition of sick pig cough sounds. *Comput. Electron. Agric.* **2008**, *63*, 207–214, doi:10.1016/j.compag.2008.02.010.
73. Exadaktylos, V.; Silva, M.; Ferrari, S.; Guarino, M.; Taylor, C.J.; Aerts, J.-M.; Berckmans, D. Time-series analysis for online recognition and localization of sick pig (Sus scrofa) cough sounds. *J. Acoust. Soc. Am.* **2008**, *124*, 3803–3809, doi:10.1121/1.2998780.
74. Schön, P.-C.; Puppe, B.; Manteuffel, G. Linear prediction coding analysis and self-organizing feature map as tools to classify stress calls of domestic pigs (Sus scrofa). *J. Acoust. Soc. Am.* **2001**, *110*, 1425–1431, doi:10.1121/1.1388003.
75. Puppe, B.; Schön, P.C.; Tuchscherer, A.; Manteuffel, G. Castration-induced vocalisation in domestic piglets, Sus scrofa: Complex and specific alterations of the vocal quality. *Appl. Anim. Behav. Sci.* **2005**, *95*, 67–78, doi:10.1016/j.applanim.2005.05.001.
76. Vandermeulen, J.; Bahr, C.; Tullo, E.; Fontana, I.; Ott, S.; Kashiha, M.; Guarino, M.; Moons, C.P.H.; Tuyttens, F.A.M.; Niewold, T.A.; et al. Discerning Pig Screams in Production Environments. *PLoS ONE* **2015**, *10*, e0123111, doi:10.1371/journal.pone.0123111.
77. Manteuffel, C.; Hartung, E.; Schmidt, M.; Hoffmann, G.; Schoen, P.C. Online detection and localisation of piglet crushing using vocalisation analysis and context data. *Comput. Electron. Agric.* **2017**, *135*, 108–114, doi:10.1016/j.compag.2016.12.017.
78. Friend, T.; O'Connor, L.; Knabe, D.; Dellmeier, G. Preliminary trials of a sound-activated device to reduce piglet crushing of piglets by sows. *Appl. Anim. Behav. Sci.* **1989**, *24*, 23–29.
79. Schön, P.C.; Puppe, B.; Manteuffel, G. Automated recording of stress vocalisations as a tool to document impaired welfare in pigs. *Anim. Welf.* **2004**, *13*, 105–110.
80. Düpjan, S.; Schön, P.C.; Puppe, B.; Tuchscherer, A.; Manteuffel, G. Differential vocal responses to physical and mental stressors in domestic pigs (Sus scrofa). *Appl. Anim. Behav. Sci.* **2008**, *114*, 105–115, doi:10.1016/j.applanim.2007.12.005.

81. Moura, D.J.; Silva, W.T.; Naas, I.A.; Tolon, Y.A.; Lima, K.A.O.; Vale, M.M. Real time computer stress monitoring of piglets using vocalization analysis. *Comput. Electron. Agric.* **2008**, *64*, 11–18, doi:10.1016/j.compag.2008.05.008.
82. Oliveira, S.R.D.E.M.; Violaro, F.; Almeida, A.C.M.D.E. Efficiency of distinct data mining algorithms for classifying stress level in piglets from their vocalization. *Eng. Agric.* **2012**, *32*, 208–216.
83. da Silva Cordeiro, A.F.; de Alencar Nääs, I.; Oliveira, S.R.M.; Violaro, F.; de Almeida, A.C.M.; Neves, D.P. Understanding vocalization might help to assess stressful conditions in piglets. *Animals* **2013**, *3*, 923–934, doi:10.3390/ani3030923.
84. Moi, M.; Nääs, I. de A.; Caldara, F.R.; Paz, I.C. d. L.A.; Garcia, R.G.; Cordeiro, A.F.S. Vocalization data mining for estimating swine stress conditions. *Eng. Agric.* **2014**, *34*, 445–450, doi:10.1590/S0100-69162014000300008.
85. Cordeiro, A.F. d. S.; Nääs, I. de A.; Baracho, M. dos S.; Jacob, F.G.; de Moura, D.J. The use of vocalization signals to estimate the level of pain in piglets. *Eng. Agric.* **2018**, *38*, 486–490, doi:10.1590/1809-4430-Eng.Agric.v38n4p486-490/2018.
86. da Silva, J.P.; de Alencar Nääs, I.; Abe, J.M.; da Silva Cordeiro, A.F. Classification of piglet (Sus Scrofa) stress conditions using vocalization pattern and applying paraconsistent logic Eτ. *Comput. Electron. Agric.* **2019**, *166*, 105020, doi:10.1016/j.compag.2019.105020.
87. Cordeiro, A.F. d. S.; Nääs, I. de A.; da Silva Leitão, F.; de Almeida, A.C.M.; de Moura, D.J. Use of vocalisation to identify sex, age, and distress in pig production. *Biosyst. Eng.* **2018**, *173*, 57–63, doi:10.1016/j.biosystemseng.2018.03.007.
88. Cornou, C.; Lundbye-Christensen, S. Classifying sows' activity types from acceleration patterns—An application of the Multi-Process Kalman Filter. *Appl. Anim. Behav. Sci.* **2008**, *111*, 262–273, doi:10.1016/j.applanim.2007.06.021.
89. Cornou, C.; Lundbye-Christensen, S. Classification of sows' activity types from acceleration patterns using univariate and multivariate models. *Comput. Electron. Agric.* **2010**, *72*, 53–60, doi:10.1016/j.compag.2010.01.006.
90. Liu, L.S.; Ni, J.Q.; Zhao, R.Q.; Shen, M.X.; He, C.L.; Lu, M.Z. Design and test of a low-power acceleration sensor with Bluetooth Low Energy on ear tags for sow behaviour monitoring. *Biosyst. Eng.* **2018**, *176*, 162–171, doi:10.1016/j.biosystemseng.2018.10.011.
91. Thompson, R.J.; Matthews, S.; Plötz, T.; Kyriazakis, I. Freedom to lie: How farrowing environment affects sow lying behaviour assessment using inertial sensors. *Comput. Electron. Agric.* **2019**, *157*, 549–557, doi:10.1016/j.compag.2019.01.035.
92. Oczak, M.; Maschat, K.; Berckmans, D.; Vranken, E.; Baumgartner, J. Classification of nest-building behaviour in non-crated farrowing sows on the basis of accelerometer data. *Biosyst. Eng.* **2015**, *140*, 48–58, doi:10.1016/j.biosystemseng.2015.09.007.
93. Oczak, M.; Maschat, K.; Berckmans, D.; Vranken, E.; Baumgartner, J. Can an automated labelling method based on accelerometer data replace a human labeller?—Postural profile of farrowing sows. *Comput. Electron. Agric.* **2016**, *127*, 168–175, doi:10.1016/j.compag.2016.06.013.
94. Thompson, R.; Matheson, S.M.; Plotz, T.; Edwards, S.A.; Kyriazakis, I. Porcine lie detectors: Automatic quantification of posture state and transitions in sows using inertial sensors. *Comput. Electron. Agric.* **2016**, *127*, 521–530, doi:10.1016/j.compag.2016.07.017.
95. Pastell, M.; Flietaoja, J.; Yun, J.; Tiusanen, J.; Valros, A. Predicting farrowing of sows housed in crates and pens using accelerometers and CUSUM charts. *Comput. Electron. Agric.* **2016**, *127*, 197–203, doi:10.1016/j.compag.2016.06.009.
96. Oczak, M.; Maschat, K.; Baumgartner, J. Dynamics of sows' activity housed in farrowing pens with possibility of temporary crating might indicate the time when sows should be confined in a crate before the onset of farrowing. *Animals* **2020**, *10*, 10010006, doi:10.3390/ani10010006.
97. Maselyne, J.; Adriaens, I.; Huybrechts, T.; De Ketelaere, B.; Millet, S.; Vangeyte, J.; Van Nuffel, A.; Saeys, W. Measuring the drinking behaviour of individual pigs housed in group using radio frequency identification (RFID). *Animal* **2016**, *10*, 1557–1566, doi:10.1017/S1751731115000774.
98. Maselyne, J.; Saeys, W.; De Ketelaere, B.; Mertens, K.; Vangeyte, J.; Hessel, E.F.; Millet, S.; Van Nuffel, A. Validation of a High Frequency Radio Frequency Identification (HF RFID) system for registering feeding patterns of growing-finishing pigs. *Comput. Electron. Agric.* **2014**, *102*, 10–18, doi:10.1016/j.compag.2013.12.015.
99. Maselyne, J.; Saeys, W.; Briene, P.; Mertens, K.; Vangeyte, J.; De Ketelaere, B.; Hessel, E.F.; Sonck, B.; Van Nuffel, A. Methods to construct feeding visits from RFID registrations of growing-finishing pigs at the feed trough. *Comput. Electron. Agric.* **2016**, *128*, 9–19, doi:10.1016/j.compag.2016.08.010.
100. Adrion, F.; Kapun, A.; Eckert, F.; Holland, E.M.; Staiger, M.; Götz, S.; Gallmann, E. Monitoring trough visits of growing-finishing pigs with UHF-RFID. *Comput. Electron. Agric.* **2018**, *144*, 144–153, doi:10.1016/j.compag.2017.11.036.
101. Maselyne, J.; Van Nuffel, A.; Briene, P.; Vangeyte, J.; De Ketelaere, B.; Millet, S.; Van den Hof, J.; Maes, D.; Saeys, W. Online warning systems for individual fattening pigs based on their feeding pattern. *Biosyst. Eng.* **2018**, *173*, 143–156, doi:10.1016/j.biosystemseng.2017.08.006.
102. Meijer, E.; Oosterlinck, M.; van Nes, A.; Back, W.; van der Staay, F.J. Pressure mat analysis of naturally occurring lameness in young pigs after weaning. *BMC Vet. Res.* **2014**, *10*, 193, doi:10.1186/s12917-014-0193-8.
103. Abell, C.E.; Johnson, A.K.; Karriker, L.A.; Rothschild, M.F.; Hoff, S.J.; Sun, G.; Fitzgerald, R.F.; Stalder, K.J. Using classification trees to detect induced sow lameness with a transient model. *Animal* **2014**, *8*, 1000–1009, doi:10.1017/S1751731114000871.
104. Manteuffel, C.; Hartung, E.; Schmidt, M.; Hoffmann, G.; Schoen, P.C. Towards qualitative and quantitative prediction and detection of parturition onset in sows using light barriers. *Comput. Electron. Agric.* **2015**, *116*, 201–210, doi:10.1016/j.compag.2015.06.017.
105. Ni, J.Q.; Liu, S.; Radcliffe, J.S.; Vonderohe, C. Evaluation and characterisation of Passive Infrared Detectors to monitor pig activities in an environmental research building. *Biosyst. Eng.* **2017**, *158*, 86–94, doi:10.1016/j.biosystemseng.2017.03.014.
106. Besteiro, R.; Rodriguez, M.R.; Fernandez, M.D.; Ortega, J.A.; Velo, R. Agreement between passive infrared detector measurements and human observations of animal activity. *Livest. Sci.* **2018**, *214*, 219–224, doi:10.1016/j.livsci.2018.06.008.

107. Besteiro, R.; Arango, T.; Rodríguez, M.R.; Fernández, M.D.; Velo, R. Estimation of patterns in weaned piglets' activity using spectral analysis. *Biosyst. Eng.* **2018**, *173*, 85–92, doi:10.1016/j.biosystemseng.2017.06.014.
108. Von Jasmund, N.; Wellnitz, A.; Krommweh, M.S.; Büscher, W. Using passive infrared detectors to record group activity and activity in certain focus areas in fattening pigs. *Animals* **2020**, *10*, 1–20, doi:10.3390/ani10050792.
109. Liu, X.; Schmidt, H.; Mörlein, D. Feasibility of boar taint classification using a portable Raman device. *Meat Sci.* **2016**, *116*, 133–139, doi:10.1016/j.meatsci.2016.02.015.
110. Madsen, T.N.; Kristensen, A.R. A model for monitoring the condition of young pigs by their drinking behaviour. *Comput. Electron. Agric.* **2005**, *48*, 138–154, doi:10.1016/j.compag.2005.02.014.
111. Dominiak, K.N.; Hindsborg, J.; Pedersen, L.J.; Kristensen, A.R. Spatial modeling of pigs' drinking patterns as an alarm reducing method II. Application of a multivariate dynamic linear model. *Comput. Electron. Agric.* **2019**, *161*, 92–103, doi:10.1016/j.compag.2018.10.037.
112. Dominiak, K.N.; Pedersen, L.J.; Kristensen, A.R. Spatial modeling of pigs' drinking patterns as an alarm reducing method I. Developing a multivariate dynamic linear model. *Comput. Electron. Agric.* **2019**, *161*, 79–91, doi:10.1016/j.compag.2018.06.032.
113. Shi, C.; Teng, G.; Li, Z. An approach of pig weight estimation using binocular stereo system based on LabVIEW. *Comput. Electron. Agric.* **2016**, *129*, 37–43, doi:10.1016/j.compag.2016.08.012.
114. Pezzuolo, A.; Guarino, M.; Sartori, L.; González, L.A.; Marinello, F. On-barn pig weight estimation based on body measurements by a Kinect v1 depth camera. *Comput. Electron. Agric.* **2018**, *148*, 29–36, doi:10.1016/j.compag.2018.03.003.
115. Pezzuolo, A.; Milani, V.; Zhu, D.; Guo, H.; Guercini, S.; Marinello, F. On-barn pig weight estimation based on body measurements by structure-from-motion (SfM). *Sensors* **2018**, *18*, 3603, doi:10.3390/s18113603.
116. Aparna, U.; Pedersen, J.P.; Jørgensen, E. Hidden phase-type Markov model for the prediction of onset of farrowing for loose-housed sows. *Comput. Electron. Agric.* **2014**, *108*, 135–147, doi:10.1016/j.compag.2014.07.008.
117. Guarino, M.; Norton, T.; Berckmans, D.; Vranken, E.; Berckmans, D. A blueprint for developing and applying precision livestock farming tools: A key output of the EU-PLF project. *Anim. Front.* **2017**, *7*, 12–17, doi:10.2527/af.2017.0103.
118. Keeling, L.; Jensen, P. Abnormal Behaviour, Stress and Welfare. In *The Ethology of Domesticated Animals*, 2nd ed.; An introduction; CABI: Wallingford, UK, 2009; pp. 85–101.
119. Vandermeulen, J.; Decré, W.; Berckmans, D.; Exadaktylos, V.; Bahr, C.; Berckmans, D. The Pig Cough Monitor: From research topic to commercial product. In Proceedings of the Joint European Conference on Precision Livestock Farming, Leuven, Belgium, 10–12 September 2013; pp. 717–723.
120. Muns, R.; Malmkvist, J.; Larsen, M.L. V.; Sørensen, D.; Pedersen, L.J. High environmental temperature around farrowing induced heat stress in crated sows. *J. Anim. Sci.* **2016**, *94*, 377–384, doi:10.2527/jas.2015-9623.
121. Larsen, M.L.V.; Bertelsen, M.; Pedersen, L.J. Review: Factors affecting fouling in conventional pens for slaughter pigs. *Animal* **2018**, *12*, 322–328, doi:10.1017/S1751731117001586.
122. Rault, J.L. Be kind to others: Prosocial behaviours and their implications for animal welfare. *Appl. Anim. Behav. Sci.* **2019**, *210*, 113–123, doi:10.1016/j.applanim.2018.10.015.
123. Waiblinger, S.; Boivin, X.; Pedersen, V.; Tosi, M.V.; Janczak, A.M.; Visser, E.K.; Jones, R.B. Assessing the human-animal relationship in farmed species: A critical review. *Appl. Anim. Behav. Sci.* **2006**, *101*, 185–242, doi:10.1016/j.applanim.2006.02.001.
124. Bench, C.; Schaefer, A.L.; Faucitano, L. The welfare of pigs during transport. In *Welfare of Pigs: From Birth to Slaughter*; Schaefer, A., Faucitano, L., Eds.; Wageningen Academic Publishers: Wageningen, The Netherlands, 2008; pp. 161–195..