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REVIEW

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Deviation of behavioural and productive parameters in dairy cows due to a lameness event: a synthesis of reviews

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ABSTRACT

Lameness is a widespread multifactorial condition affecting the health and performance of dairy cows. Despite the growing support by precision farming technologies, farmers still lack reliable data-driven tools to early identify lame cows. This study used a synthesis of reviews to identify cow's behavioural and productive parameters most related to lameness and estimate their deviation due to a lameness event. The methodological approach used reviews as starting point to identify the most pertinent studies with the intention of extracting and analysing data from these primary studies. The final dataset used information collected from 31 research papers, cited in 15 reviews, and involved more than 25,000 dairy cows. Five parameters were suitable for the meta-analysis: one about eating behaviour (eating time), three regarding activity and resting behaviour (lying bouts, lying bout duration and lying time) and milk yield. The meta-analysis revealed that all parameters had a significant deviation in cows affected by lameness. The calculation of the pooled means allowed to quantify a mean value for the deviation imposed by a severe lameness event from the value recorded on nonlame cows. Compared to a nonlame animal, a lame cow had a significant negative deviation for eating time (−39 min/day), number of lying bouts (−0.5/day), and milk yield (−3 kg/day). Lame cows had positive deviations for lying bout duration (+12 min/bout) and daily lying time (+42 min/day). The individual or combined use of these mean deviation values as alarm reference thresholds could improve the accuracy of the current automated lameness detection systems.

HIGHLIGHTS

- Feeding and resting habits, and milk yield had a significant deviation in lame cows.
- Lame cows decreased their time spent eating, lying bouts frequency, and milk yield.
- Lame cows had prolonged lying bout duration and daily lying time.

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Introduction

Prevention of lameness remains a priority for dairy farmers due to both economic and welfare reasons (Whay et al. 2003; O'Leary et al. 2020). The identification and accurate recording of the lameness events are essential items of the health check of the dairy farm and the locomotion scoring system and the routine hoof trimming are still the most widely methods used by stockmen and veterinarians. However, to become effective preventive measures, both methods should be carried out by skilled personnel according to a regular schedule. Unfortunately, these guidelines are still disregarded in many dairy farms and therefore, the true prevalence of lameness in these herds is likely to be underestimated with only visibly severe lame animals being recorded (Bennett et al. 2014). Besides impairing the normal cows' locomotion, lameness significantly alters other behaviours, such as the daily eating and lying time budget, and the lying frequency (Galindo and Broom 2002; González et al. 2008; Walker et al. 2008) as well as lowers milk yield (Green et al. 2002; Bach et al. 2007). Therefore, abrupt deviations from the physiological trend of the lactation curve as well as from the daily pattern of certain behaviours may be associated with the risk of lameness onset and be a warning sign for its early detection, preventing some cases from becoming severe or even chronic.

Several sensor systems have been developed over the last few decades to help dairy farmers manage

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their herds (Steeneveld and Hogeveen 2015; Lora et al. 2020). Such systems can provide both data and alerts to several productive, behavioural, and physiological indicators on individual cows (Rutten et al. 2013; King and DeVries 2018). However, in case of lameness, the development of specific sensors for dairy cows has been discouraged by its inconsistent impact on behavioural and production parameters. Although some behaviours (e.g. lying time) have been considered useful to distinguish between lame and non-lame dairy cows (Ito et al. 2010; Solano et al. 2016), other authors suggest they are not overly helpful as predictive parameters (Olechnowicz and Jaskowski 2011; Blackie and Maclaurin 2019; Grimm et al. 2019). This disagreement is likely due to the fact that the effect of lameness on eating and resting behaviours, or on milk yield, is rather complex, depending on many other factors such as the presence of other health problems, the severity of the hoof problems, the resulting pain, and the interactions with the housing and flooring system (Magrin et al. 2019; Oehm et al. 2019; Cook 2020).

In front of this inconsistency, the synthesis of reviews carried out in the present study aimed at summarising the evidence from multiple research syntheses (Aromataris et al. 2015; Caird et al. 2015; Pollock et al. 2020). The reviews of reviews are referred to by several different terms in the scientific evidence, including umbrella reviews, overviews of reviews, metareview, a summary of systematic reviews and also a synthesis of reviews. A synthesis of reviews offers the possibility to address a broad area of issues related to the phenomena of interest and is ideal to present a wide scope of evidence related to a specific scientific question. Not knowing *a priori* which and how many possible parameters relating to foot disorders can be found in the scientific literature, an approach based on reviews seemed most appropriate and comprehensive to scan the most relevant research and identify the most studied indicators.

Through a meta-analysis of data from the scientific literature reported in review papers on lameness in dairy cattle, the present study performed a synthesis of reviews, aiming at (1) identifying the most studied behavioural and production variables related to severe lameness detection, and (2) assessing their variation induced by a lameness event. The individual or combined use of estimated mean deviation values for some behavioural and production parameters could help farmers and veterinarians to more carefully identify and early treat lame cows. The same results, used as alarm thresholds, could be useful to further improve the accuracy of the current automated lameness detection systems.

Materials and methods

Literature search and inclusion criteria

The work started by gathering the recently available reviews on the topic of interest. Specifically, the search was conducted using the search engine Scopus®, the bibliographic and citation database of Elsevier©. The time span considered for the reviews' selection was 10 years, from 2011 to 2020. Type of articles was searched as a review published in English and the two following strings were entered in the TITLE, ABSTRACT and KEYWORDS fields of the database:

> *string1: TITLE-ABS-KEY (lameness AND dairy AND cow AND milk) AND PUBYEAR > 2010 AND PUBYEAR < 2021 AND LANGUAGE (english) AND (LIMIT-TO (SUBJAREA, "AGRI") OR LIMIT-TO (SUBJAREA, "VETE")) AND (LIMIT-TO (DOCTYPE, "re"))*
>
> and
>
> string2*: TITLE-ABS-KEY (claw AND dairy AND cow AND milk) AND PUBYEAR > 2010 AND PUBYEAR < 2021 AND LANGUAGE (english) AND (LIMIT-TO (SUBJAREA, "AGRI") OR LIMIT-TO (SUBJAREA, "VETE")) AND (LIMIT-TO (DOCTYPE, "re"))*

The search strategy, screening process, eligibility criteria and the total number of reviews included were performed according to the flow chart of Moher et al. (2009) (Figure S1). Individual articles (cited inside each review) were retrieved online by a single author (L.M.) and were submitted to a full-text assessment. The target population was dairy cows diagnosed clinically lame. The outcomes of the screening of cited articles were all behavioural and productive parameters of lame cows versus nonlame ones (control). A severe lameness condition was defined by the poorest locomotion scores (the highest values) or by the presence of specific claw disruption lesions (i.e. sole ulcer). The nonlame condition was defined as a cow with a normal gait score or without any claw disorders. The inclusion criteria for the articles was the evaluation of quantitative parameters only. Only parameters for which at least five papers (thus, a minimum of five values) were available were considered for further analyses.

The search in the Scopus® databases using the previously described strings retrieved a total of 33 reviews. After combining the results of the two extractions and removing the repeated documents, 23 reviews were selected (two reviews were not found online). The eligibility process targeted 6 out of 21 published reviews as not pertinent since none of them estimated quantitative behavioural or productive parameters for lame and control cows (most of them dealt with cows' nutrition and feeding supplementation). Therefore, 15 reviews were retained (Table S1). These 15 reviews referred to 45 research papers in which a total of 21 behavioural and productive parameters associated with lameness were identified and entered into a complete database, as described in Table S2. According to the above-mentioned inclusion criteria, the meta-analysis was carried out on 31 papers based on experimental studies and considered 5 parameters: one about eating behaviour (eating time, min/day), three regarding activity and resting behaviour (lying bouts, n/day; lying bout duration, min/bout; and lying time, min/day) and milk yield (kg/day) (Table S3). The time span covered by the research papers was 15 years, from 2003 to 2018.

Data extraction and statistical analysis

For each behavioural and productive parameter identified, descriptive statistics (mean and SD) provided by each paper were retained for lame versus control cows as well as the published significance level of the statistical test. If SD was not reported in the paper, it was calculated from the standard error (SE), as reported in Higgins et al. (2022). Overall means and 95% confidence intervals (95% CI) for lame and control groups were calculated using the inverse variance method (Higgins et al. 2022). The meta-analysis outcome for each parameter consisted of an overall mean difference between lame and control cows along with a global statistical significance level.

Comparisons of the means between the two groups of cows were performed using the standardised mean difference (SMD). A positive SMD value indicates that mean values of the parameters were greater in the control cows, whereas a negative SMD indicates that mean values were higher in lame cows. Based on these aggregated results, it is possible to ascertain if a considered parameter is a significant predictive test for the lameness diagnosis. If the value 0 is not included in the 95% CI, the SMD is statistically significant at the 5% level ($p < 0.05$). According to Cohen's rule of thumb for interpretation of the SMD statistic (Cohen 1988), a value of 0.2 indicates a small effect, a value of 0.5 indicates a medium effect and a value $\geq$0.8 indicates a large effect. The agreement or disagreement among the studies was examined using different measures of heterogeneity: Choran's Q (chi-square test) and I^2 statistics (Higgins et al. 2003). When $Q > 0.1$ and $I^2 > 0.5$, there was a high heterogeneity. For each parameter, the forest plot graph was used to show each single study result with its 95% CI and the numerical estimate of the overall effect of interest (global SMD). In the forest plot, the boxes represent the relative contribution of each study to the summary SMD. The size of the boxes reports the effects of the studies according to the weights assigned to each of them. These weights depend on sample size and the model adopted (fixed or random). The pooled SMD value was represented using a diamond that fixes the location of the estimated effect and whose width reflects the estimate's precision. Publications' bias was assessed by examining funnel plot asymmetry and Egger's regression test. All the analyses were conducted using 'meta' package (Schwarzer et al. 2015; Shim and Kim 2019) of R-software (Version 4.0.2; R Core Team 2022).

Results

Descriptive statistics of the comparison lame versus nonlame dairy cows for the five parameters considered in meta-analysis are reported in Table 1. Most comparisons between lame and control cows were significant for the different parameters. The only exception was the number of lying bouts per day, for which the same comparison was not significant in several studies. Some dissimilarity was observed in the mean values reported in the different articles for the same parameter, for the eating time in particular, for which mean values ranged from 91 to 302 min/day in lame cows and from 104 to 379 min/day in control cows.

The forest plots of the meta-analysis are reported in Figure 1. Wide heterogeneity was found for all parameters ($I^2 > 50\%$). In particular, wide 95% CIs for the SMD were calculated for lying bouts (n/day), using data from the first six studies listed in Figure 1(c). As SMD indicator was calculated by the difference between lame versus control cows, so negative values are expected for eating time (Figure 1(a)) and milk yield (Figure 1(e)), whereas positive values are expected for lying bout duration (Figure 1(b)) and lying time (Figure 1(d)), and some uncertainty remained for the number of lying bouts (Figure 1(c)). All pooled SMD (light blue diamonds in Figure 1) did not overlap at the 0-line, so an overall significant difference was found for all parameters comparing lame *vs* control cows. All results of the meta-analysis are reported in Table 2 and Figure 2. According to the pooled means, lame cows spent less time eating (200

Table 1. Descriptive statistics of the comparison lame versus nonlame dairy cows for the five parameters considered for the meta-analysis (data from the 31 selected research papers).

Parameter (units)	Study[a]	Health status (mean ± SD)		Cows (*n*)		*p*-Value[b]
		Lame	Nonlame	Lame	Nonlame	
Eating time (min/day)	Bach et al. (2007)	240 ± 125	268 ± 213	38	111	<0.0500
	Beer et al. (2016)	302 ± 57	379 ± 71	41	12	0.0003
	Cook et al. (2004)	259 ± 66	259 ± 290	10	73	ns
	Gomez and Cook (2010)	227 ± 64	270 ± 55	35	104	0.0500
	Kramer et al. (2009)	171 ± 46	196 ± 48	17	17	NA
	Miguel-Pacheco et al. (2014)	192 ± 20	264 ± 17	110	40	NA
	Norring et al. (2014)	91 ± 17	104 ± 32	19	40	<0.0500
	Proudfoot et al. (2010)	213 ± 32	228 ± 32	13	13	ns
	Thorup et al. (2016)	119 ± 52	197 ± 54	9	7	0.0040
Lying bout duration (min/bout)	Beer et al. (2016)	92 ± 31	72 ± 18	41	12	0.0360
	Calderon and Cook (2011)	54.0 ± 3.6	45.1 ± 2.5	39	18	<0.0500
	Chapinal et al. (2009)	93.3 ± 21.3	71.0 ± 21.3	13	9	<0.0500
	Chapinal et al. (2010)	94.0 ± 24.5	78.2 ± 29.0	25	25	0.0300
	Ito et al. (2010)I	83.1 ± 38.8	80.2 ± 58.5	129	397	ns
	Ito et al. (2010)II	76.8 ± 44.1	74.2 ± 56.6	247	546	ns
	King et al. (2017)	87.6 ± 30.5	79.0 ± 25.8	352	857	0.0300
	Solano et al. (2016)	69 ± 32	61 ± 27	1073	4062	<0.0500
	Thomsen et al. (2012)	99.1 ± 62.0	59.9 ± 25.7	42	508	<0.0500
	Weigele et al. (2018)	89.9 ± 29.8	81.9 ± 26.5	111	253	0.0080
	Westin et al. (2016)	78.3 ± 31.1	70.7 ± 52.8	192	113	<0.0010
	Yunta et al. (2012)	89.3 ± 43.5	80.7 ± 43.6	125	125	<0.0500
Lying bouts (n/day)	Beer et al. (2016)	9.5 ± 3.4	9.8 ± 1.6	41	12	ns
	Calderon and Cook (2011)	16.6 ± 3.8	14.2 ± 2.5	39	18	ns
	Chapinal et al. (2009)	9.2 ± 1.8	10.9 ± 2.1	13	9	ns
	Chapinal et al. (2010)	8.2 ± 2	8.1 ± 2	25	25	ns
	Cook et al. (2004)	7.2 ± 4.1	10.8 ± 4.0	10	73	ns
	Gomez and Cook (2010)	10.9 ± 5.4	13.2 ± 4.8	35	104	ns
	Ito et al. (2010)I	8.0 ± 4.6	8.1 ± 7.6	129	397	ns
	Ito et al. (2010)II	8.6 ± 4.8	8.5 ± 6.0	247	546	ns
	King et al. (2017)	9.3 ± 3.8	9.3 ± 2.9	352	857	ns
	Solano et al. (2016)	9.7 ± 4.7	10.2 ± 4.5	1073	4062	<0.0500
	Westin et al. (2016)	9.3 ± 4.2	9.9 ± 7.7	192	1113	0.0200
	Yunta et al. (2012)	9.4 ± 5.5	9.8 ± 5.5	125	125	ns
Lying time (min/day)	Beer et al. (2016)	784 ± 131	680 ± 74	41	12	<0.0500
	Blackie et al. (2011)	666 ± 264	540 ± 334	5	8	<0.0500
	Calderon and Cook (2011)	831 ± 172	683 ± 97	39	18	<0.05
	Chapinal et al. (2009)	828 ± 105	756 ± 105	13	9	<0.0500
	Chapinal et al. (2010)	666 ± 120	618 ± 90	25	25	ns
	Charlton et al. (2016)	738 ± 160	746 ± 126	876	2773	ns
	Cook et al. (2004)	585 ± 111	714 ± 282	10	73	ns
	Gomez and Cook (2010)	650 ± 470	724 ± 467	35	104	<0.0500
	Ito et al. (2010)I	696 ± 509	672 ± 366	129	397	ns
	Ito et al. (2010)II	672 ± 217	654 ± 286	247	546	0.0500
	King et al. (2017)	727 ± 165	676 ± 129	352	857	<0.0010
	Thorup et al. (2015)	724 ± 166	684 ± 180	164	325	<0.050
	Solano et al. (2016)	666 ± 168	630 ± 162	1073	4062	<0.0500
	Thomsen et al. (2012)	766 ± 177	631 ± 128	42	508	<0.0500
	Westin et al. (2016)	714 ± 212	678 ± 357	192	1113	0.0010
	Yunta et al. (2012)	728 ± 271	714 ± 271	125	125	ns
Milk yield (kg/day)	Bach et al. (2007)	28.3 ± 6.3	30.7 ± 10.9	38	111	<0.0500
	Beer et al. (2016)	39.8 ± 7.6	47.1 ± 8.0	41	12	0.0050
	Bicalho et al. (2008)I	36.1 ± 5.2	37.5 ± 5.2	603	603	<0.0010
	Bicalho et al. (2008)II	35.1 ± 5.8	36.1 ± 5.8	846	2777	<0.0010
	Gudaj et al. (2012)	28.6 ± 8.6	32.9 ± 8.7	826	826	<0.0500
	Hernandez et al. (2005)	37.8 ± 6.6	38.8 ± 5.8	169	84	<0.0500
	Juarez et al. (2003)I	41.3 ± 27.3	46.8 ± 56.1	23	97	ns
	Juarez et al. (2003)II	38.1 ± 52.4	41.9 ± 73.7	74	146	ns
	King et al. (2017)	34.1 ± 1.0	34.9 ± 9.8	352	857	<0.0010
	Kramer et al. (2009)	39.6 ± 7.4	41.2 ± 7.9	17	17	NA
	Machado et al. (2010)	43.5 ± 5.4	44.1 ± 18	140	433	ns
	Mandel et al. (2018)	32.9 ± 8.1	37.1 ± 24.7	10	154	<0.0500
	Nechanitzky et al. (2016)	33.9 ± 7.3	36.6 ± 7.0	32	10	ns
	Norring et al. (2014)	35.3 ± 4.4	35.9 ± 4.8	19	65	ns
	Proudfoot et al. (2010)	42.9	41.9	13	13	ns
	Solano et al. (2015)	36.8 ± 9.7	37.4 ± 9.2	1094	4162	<0.0010
	Solano et al. (2016)	36 ± 10	37 ± 9	1073	4062	<0.0500
	Thorup et al. (2016)	25.9 ± 7.3	18.8 ± 7.5	9	7	ns
	Van Hertem et al. (2013)	37.7 ± 3.3	45.1 ± 4.3	44	74	<0.0010
	Yunta et al. (2012)	29.2 ± 8.7	30.8 ± 8.7	125	125	ns

[a]Different Roman numerals I, II indicate different sample sizes within the same study.
[b]NA: not assessed; ns: not significant.

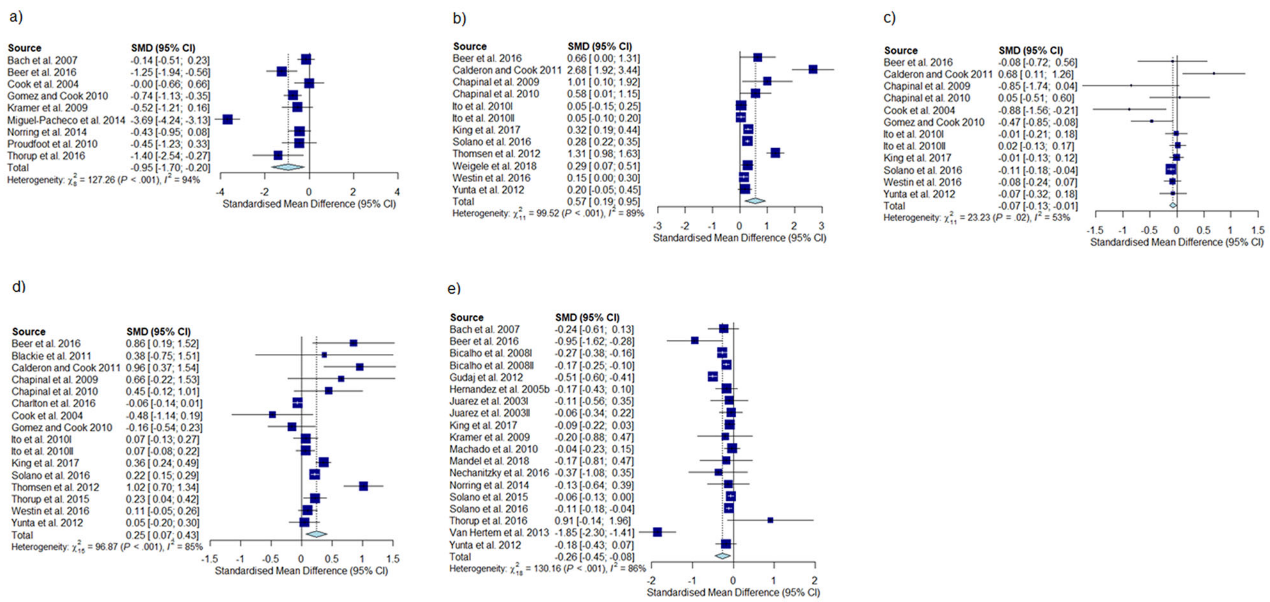

Figure 1. Forest plots of the five considered parameters: (a) eating time (min/day); (b) lying bout duration (min/bout); (c) lying bouts (*n*/day); (d) lying time (min/day); (e) milk yield (kg/day). The blue boxes represent the relative contribution of each study to the summary pooled standardised mean difference (SMD). The pooled SMD value was represented using a light blue diamond that fixes the location of the estimated effect and which width reflects the estimate's precision.

vs. 239 min/day, $p = 0.013$), had fewer lying bouts (9 vs. 10 n/day, $p = 0.019$), and a drop in milk yield (34 vs. 37 kg/day, $p = 0.006$) than control cows. On the contrary, lame cows had a prolonged lying bout duration (83 vs. 71 min/bout, $p = 0.003$) and daily lying time (720 vs. 678 min/day, $p = 0.006$) than control cows. The asymmetry funnel test confirmed a substantially reduced bias of publications (Table 2).

Discussion

So far, at least to the authors' knowledge, meta-analyses about lameness in dairy cows have been primarily focused on its risk factors (Oehm et al. 2019). No synthesis of reviews has been instead performed to assess the deviation of behavioural and productive parameters caused by the occurrence of a lameness event. This synthesis of reviews based on meta-analysis of primary studies aims at enriching the current knowledge about the impact of lameness on some behavioural and productive parameters in dairy cows. The review papers are one of the best available tools by apprising preliminary studies on a given issue and those retrieved from the available literature to be used as the starting point in this meta-analysis showed to be a promising approach for the selection of the most relevant research to quantify the behavioural and productive deviations caused by a lameness event in dairy cows. Despite the awareness that some relevant studies may not have been selected during the screening process adopted, the 15 selected reviews cite almost the same articles, proving that the 31 original research articles used to create the processed dataset actually represent a body of reference for this topic. Regarding the quality of the 31 selected original papers, 29 out of them were published in scientific journals ranked in the highest quartile of their class (Table S3). The outstanding contribution of these 31 articles to the topic of dairy cow lameness was also supported by their number of citations in the Scopus® databases (on average, 70 citations per each, Table S3) and in the extracted reviews (mostly cited 2–6 times, i.e., the 15 reviews tend to cite the same articles). Most of the 31 selected papers referred to trials involving a large number of animals under well-defined farming conditions, allowing for the identification of representative sample sizes of severely lame cows, moderately lame cows, and not-lame cows groups according to standard and referenced operating procedures. Moreover, the analysed articles reported detailed information about the dairy breed (only 6 exceptions out of 31) and the housing system (only 2 exceptions out of 31) of the study (Table S3). Overall, the meta-analysis involved more than 25,000 dairy cows, most lactating Holstein housed in free-stall barns with different flooring and/or bedding material. A single study by Charlton et al. (2016) dealt with behavioural measures for lameness assessment on tie-stall dairy farms.

Table 2. Meta-analysis results of the effect of lameness on behavioural parameters and milk production.

Item	Trial comparison		Pooled mean (95% CI)			SMD[a]		Heterogeneity[b]		
	studies (n)	cows (n)	Lame	Nonlame	Lame versus Nonlame	95% CI	*p*-Value	I^2 %	*p*-Value	*F* test[c]
Eating time (min/day)	9	734	200 (149–252)	239 (182–297)	−0.95	[−1.7; −0.2]	0.013	94	<0.001	0.603
Lying bout duration (min/bout)	12	10314	83 (75–91)	71 (64–78)	0.57	[0.19; 0.95]	0.003	89	<0.001	0.115
Lying bouts (n/day)	12	9622	9.7 (8.2–11.2)	10.2 (9.0–11.4)	−0.07	[−0.13; −0.01]	0.019	53	0.016	0.758
Lying time (min/day)	16	14323	720 (686–754)	678 (656–700)	0.25	[0.07; 0.42]	0.006	85	<0.001	0.252
Milk yield (kg/day)	19	20157	34.1 (32.8–37.3)	37.1 (34.1–40.2)	−0.26	[−0.45; −0.08]	0.006	86	<0.001	0.347

[a]SMD is the standardised mean difference of the lameness effect.
[b]I^2 is the proportion of total variation of size effect due to heterogeneity; *p*-value of chi-square (Q) test of heterogeneity.
[c]*p*-value of the Funnel (F) test asymmetry (Egger's regression asymmetry test).

Wide heterogeneity was found for each considered parameter: four parameters out of five showed an $I^2 > 80\%$, suggesting more than 80% of the variability in disease effect estimates is due to real study differences (heterogeneity) and only 20% due to chance. This high heterogeneity suggested the use of a random-effects model because high heterogeneity can be attributed to differences in study settings, populations, and other factors or chance in the course of sampling (Riley et al. 2011). In contrast, fixed-effects models are more adequate for the synthesis of a small number of well-controlled, functionally comparable studies with similar settings. Ignoring heterogeneity leads to an overly precise summary result (confidence interval is too narrow) which, in case of comparison across studies, may wrongly imply that an effect exists when actually there are no effective differences among groups. Based on these assumptions, the random-effects model was generally chosen (when $I^2 > 0.80$) to take into account the between-studies variation. The method is based on the inverse-variance approach, making an adjustment to the study weights according to the extent of variation, or heterogeneity, among the varying effects (DerSimonian and Laird 1986). Although real study differences (heterogeneity) existed, the studies were reasonably comparable as the same type of classification of disease was used, and population characteristics were similar.

The results of this synthesis revealed that all the considered behavioural parameters, along with milk yield, had significant deviations due to a lameness event. Thus, the methodological approach for the

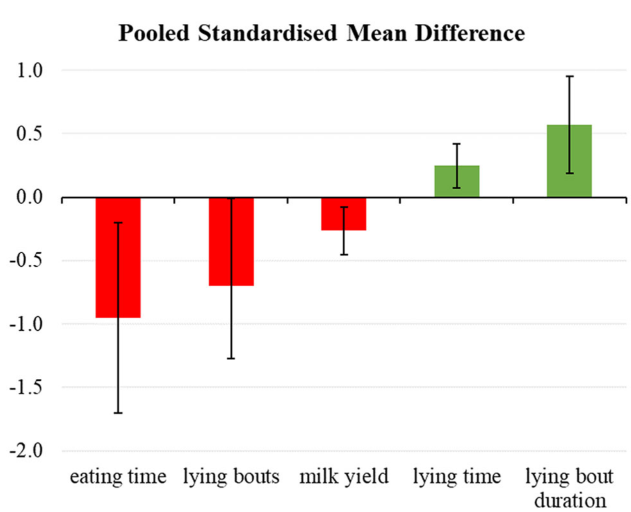

Figure 2. Pooled standardised mean difference (pooled SMD) with 95% confidence intervals of the five parameters considered for the comparison lame versus nonlame dairy cows. Negative values are represented by red bars and positive values by green bars in the histogram.

selection of the studies used in this work was effective in finding the most frequently measured parameters that are sensitive to lameness in dairy cows. Thirty-one out of 45 of the screened papers considered one or more of the five parameters selected for the meta-analysis. It is interesting to notice that for most of these parameters, data were recorded through electronic devices, such as accelerometers, noseband sensors, data loggers, milking systems, and so on, from 2007 onwards (Table S2). This was plausibly the reason why the data of these specific parameters were more frequently available in the literature as compared to other behavioural or productive traits. Looking at the trend of SMDs generated by the meta-analysis for lame and control cows and drawn in the forest diagrams, eating time, and lying bout duration are the parameters showing the most consistent trend across selected papers. In particular, all studies reported lame cows decreasing their time spent eating and prolonging the duration of their lying bouts. One of the study's limitations is that some parameters, particularly the daily number of lying bouts, showed a wide heterogeneity of SMDs (e.g. Chapinal et al. 2009; Beer et al. 2016), probably due to the low numbers of animals used for those comparisons. Although the pooled means for the daily number of lying bouts differed statistically between lame and control cows, the wide 95% CIs obtained for the two groups raise questions about the effective use of this parameter to characterise the lameness condition in dairy cows. Support for this assumption comes from the lack of statistical significance reported by most of the studies that compared SMDs for the number of daily lying bouts between lame and nonlame cows. Another limitation of a meta-analysis dealing with behavioural and productive parameters of lame cows might arise from the different locomotion scoring systems used in the selected studies. For example, Cook et al. (2004), Gomez and Cook (2010), and Calderon and Cook (2011) used a 4-point scale, that includes only non-lame (1), slightly lame (2), moderately lame (3), and severely lame (4), while Ito et al. (2010), Solano et al. (2015), and King et al. (2017) used a 5-point Numerical Rating System, where one corresponds to sound and 5 to severely lame. Nechanitzky et al. (2016) used a 13-point scale with 0 indicating a nonlame and 13 a severely lame cow. In order to avoid a bias due to the scoring system, the comparison lame versus control cows in the current meta-analysis used only data from cows graded with the extreme scores of the scoring scale applied in each study (lowest vs. highest scores). In this way, it was ensured that behavioural and productive data used in the meta-analysis for lame cows were recorded on animals with an evident inability or extreme reluctance to bear weight on one or more limbs. These cows appeared severely lame, and mostly showed an arched back while standing and walking (Bach et al. 2007; Gudaj et al. 2012; Mandel et al. 2018).

Both economic and welfare reasons indicate that the prevention of lameness in cows remains a priority for the dairy industry (Whay et al. 2003; O'Leary et al. 2020). The development of specific support tools to help farmers in early detecting cows affected by a lameness event becomes valuable, especially in face of the current increasing trend in herd size observed in the dairy world. Nowadays, a potential support might come from the large amount of information provided by the great number of sensor systems operating on many dairy farms (Steeneveld and Hogeveen 2015; Lora et al. 2020). These new technologies provide a constant flow of high-frequency repeated measures for parameters such as milk yield and cow's activity which have shown to be sensitive of changes in the physiological and health status of the animal (Rutten et al. 2013; King and DeVries 2018). Recent models have been proposed for predicting lameness in dairy cattle based on automatically recorded data on cows' behavioural metrics and milk yield (O'Leary et al. 2020; Borghart et al. 2021). Moreover, recent innovative, cost-effective and rapid approaches for identifying and predicting lameness incidence at cow level are also increasingly being applied based on phenotyping technologies such as MIR spectrometry (Bonfatti et al. 2020; Contla Hernández et al. 2021) or machine learning predictive algorithms (Warner et al. 2020; Shahinfar et al. 2021) that use routinely measured production and behavioural traits on farms. The pooled means calculated in the present meta-analysis for behavioural parameters and milk yield allowed to quantify the magnitude of the deviations imposed by a lame event from the values recorded on nonlame cows. The individual or combined use of these mean deviation values as alarm reference thresholds could further improve the accuracy of the most recent lameness detection systems. From a farmer's perspective, the early identification of cows affected by lameness problem through the automatic monitoring of their behavioural and productive deviations could allow preventive targeted interventions that might reduce or replace the use of medical treatments.

Conclusions

As the dairy industry is facing increasing pressure from society to improve the ethical sustainability of the current production systems, farmers need to optimise their housing and management strategies to reduce the outbreak of painful conditions for the cows, such as lameness events. Despite the growing support of precision livestock farming technologies, to date, there is still a lack of robust data-driven tools that assist farmers in early identifying lame cows. The methodological approach used in this work was effective in finding the most frequently measured parameters that are sensitive to lameness in dairy cows: one about eating behaviour (eating time), three regarding activity and resting behaviour (lying bouts, lying bout duration, and lying time) and milk yield. The meta-analysis revealed that all these parameters had a significant deviation in cows affected by lameness. The calculation of the pooled means allowed to quantify a mean value for the deviation imposed by a severe lameness event from the value recorded on nonlame cows. Compared to a nonlame animal, a lame cow had a significant negative deviation for eating time, number of lying bouts, and milk yield, and positive deviations for lying bout duration, and daily lying time. These calculated mean deviations could be proposed as alarming thresholds to improve the accuracy of the automated lameness detection systems. Integrating these detection systems into the existing digital herd monitoring devices could be particularly valuable for farmers and veterinarians in the face of the growing trend in herd size observed in the dairy world.

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Ethical approval

Ethical review and approval were not required because this study did not involve animals for experimental or other scientific purposes.

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Data availability statement

The data that support the findings of this study are available from the corresponding author, Cozzi G., upon reasonable request.

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