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Prevalence of lameness in dairy cows: A literature review

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ABSTRACT

Lameness in dairy cows has major negative impacts on animal welfare and production economy. While previous studies have evaluated the prevalence of lameness in single countries, the present literature review is the first overview of the prevalence of lameness in dairy cows globally. This literature review identified 53 studies reporting prevalence of lameness among representative samples of dairy cows and fulfilling a number of specified inclusion criteria (e.g., at least 10 herds and 200 cows, and locomotion scoring by trained observers). A total of 414,950 cows from 3945 herds were included in these 53 studies, which spanned a 30-year period (1989–2020) and included herds from six continents, with the majority from Europe and North America. Across the studies, the mean prevalence of lameness (typically defined as score 3–5 on a 1–5 scale) was 22.8% with a median of 22.0% and a range between studies from 5.1% to 45%, and a within herd range from 0% to 88%. The mean prevalence of severely lame cows (typically defined as score 4–5 on a 1–5 scale) was 7.0% with a median of 6.5% and a range between studies from 1.8% to 21.2%, and a within herd range from 0% to 65%. Over time, it appears that the prevalence of lameness has changed very little. Several different locomotion scoring systems and definitions of (severe) lameness were used across the 53 studies, and this may have affected the reported lameness prevalence. Sampling of herds and cows, inclusion criteria and representativeness also differed between studies. This review offers recommendations for the future capture of information on lameness in dairy cows and identifies potential knowledge gaps.

1. Introduction

Lameness in dairy cows has major negative impacts on animal welfare and production economy, and has been described as '*second only to mastitis in terms of its detrimental effect on herd productivity*' (Booth et al., 2004, based on Esslemont and Kossaibati, 1996). Shearer et al. (2017) reported that lameness is '*the third most common cause of culling or premature removal from the herd*', while Kofler et al. (2022) similarly found a high proportion of culling due to locomotor disorders and the associated lameness. The economic losses associated with lameness include reduced milk production, treatment costs, reduced reproductive performance, and increased risk of death and culling (as reviewed by Huxley, 2013, and Dolecheck and Bewley, 2018). Thomsen (2022) concluded that locomotor disorders were the most frequent reason for on-farm euthanasia in Danish dairy cows, accounting for approximately 40% of all cows being euthanized on-farm.

Farmers and veterinarians generally perceive hoof lesions causing lameness as painful for cows (Thomsen et al., 2012a; Tschoner et al., 2021). Tadich et al. (2013) demonstrated that the nociceptive threshold of cows decreased with increasing locomotion score. However, quantifying the impact of lameness on animal welfare is difficult, since the internal experience of an animal suffering pain from lameness (or other disorders) can only be imagined, but never fully known or understood. More often, the effect of lameness on an animal's welfare is framed within the context of its effect on animal function, affective states or its ability to perform normal behavior (Fraser, 2009), or described in terms of the Five Freedoms (Whay and Shearer, 2017). In an increasingly globalized food system, quantifying the prevalence of important production diseases such as lameness, with its negative welfare, production and economic effects, across regions and countries, is likely to become increasingly important. Comparisons of the prevalence of lameness between farms within and between countries relies upon the use of validated measures of locomotion. Information on the prevalence of lameness may be useful for research purposes, for on-farm health management including the identification of cows requiring treatment, and for assurance schemes.

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Few review papers on dairy cow lameness have been published. Among these, some have focused on risk factors for lameness (Oehm et al., 2019), or on treatment and prevention of hoof lesions causing lameness (Potterton et al., 2012). Two reviews reported lameness prevalence and incidence, but were restricted to the UK (Archer et al., 2010; Afonso et al., 2020). A review by Hirst et al. (2002) included papers on lameness and hoof lesions without any geographical restrictions, but only included papers published between 1981 and 2000. It focused on the methodology of the studies and did not present any information on the prevalence of lameness in those studies. The present review is thus the first to give an overview of the prevalence of lameness in dairy cows globally.

This paper sought to review the scientific literature on studies reporting the prevalence of lameness among representative samples of dairy cows, to estimate the overall prevalence of lameness and severe lameness, and to present the range of prevalence estimates among and between studies and herds. Additional objectives were to assess possible changes in prevalence over time (study year), and to describe the definitions and descriptions of study populations, locomotion scoring, study designs and sampling methods used in the included studies.

2. Literature review

A literature review was performed according to the most recent version of the PRISMA guidelines (Page et al., 2021). A literature search was undertaken using Scopus and Web of Science (as recommended by Grindlay et al., 2012) and the search terms (dairy* [all fields]) AND (cow* OR cattle* OR bovin* [all fields]) AND (locomot* OR gait* OR lame* OR mobilit* [title]). The literature search was repeated several times – most recently 2 May 2022. Additionally, relevant original articles identified via the reference list of other publications (e.g. reviews) could be included. No restrictions on year of publication were applied. The initial list of studies was scrutinized by the first author and their relevance for this review was evaluated based on the title and content in the abstract. The population of interest was defined as follows: only studies presenting data from at least 10 herds, and at least 200 cows, were included. Studies which included only selected herds with a high prevalence of lame cows (e.g., Sauter-Louis et al., 2004) and experimental intervention studies were not included. Observational studies with an evaluation of risk factors for lameness could be included if they fulfilled other inclusion criteria. To improve the generalizability of the results, studies including only cows of certain ages/parities or production stages (e.g., only dry cows [Foditsch et al., 2016] or only high-yielding, multiparous cows [Von Keyserlingk et al., (2012)]) were not included. Review articles were generally not considered, but could be used to identify publications on relevant original studies. In cases where (almost) identical data were presented in multiple publications, the publication with the most complete data set was included. In cases with two or more identical data sets, the oldest publication was included. The outcome of interest was defined as follows: only results from studies reporting prevalence of lame cows were included. Only studies with lameness evaluations undertaken by trained observers (researchers, veterinarians, etc.) were included. Studies where lameness evaluation was done exclusively by farmers or by a large number of hoof trimmers without specific training, as well as studies with all cows housed in tie stall barns and where lameness was evaluated in standing cows only (e.g., Stall Lameness Score, Leach et al., 2009), or publications in languages other than English, or conference abstracts were excluded. For each eligible study, the information presented in Table 1 was extracted and entered into an Excel spreadsheet.

Changes in lameness prevalence over time were evaluated by visual inspection of plots of lameness prevalence versus time (Figs. 3 and 4), and by comparing the mean and median lameness prevalence in studies with data collection before 2012 ('old studies') or in 2012 or later ('new studies'). A Wilcoxon rank sum test (PROC NPAR1WAY, SAS version 9.3) was used to compare median prevalence of (severe) lameness reported in 'old' and 'new' studies, with a non-significant test indicating no difference between the two groups. Using the same methodology, differences between median lameness prevalence between studies from Europe and North America were evaluated.

Table 1
Information recorded in a literature review of 53 studies of prevalence of lameness in dairy cows.

Variable	Information recorded
Country	Country where study was done
Region	Countries grouped into the following regional categories: Europe, North America, South America, Africa, Asia, Australia/New Zealand
Year	Year(s) of data collection
Prevalence of lameness	Prevalence of lameness and prevalence range across herds (where information available)
Prevalence of severe lameness	Prevalence of severe lameness and prevalence range across herds (where information available)
Locomotion scoring system	System used to assess lameness
Definition of lameness	Locomotion scores recorded as 'lameness'
Definition of severe lameness	Locomotion scores recorded as 'severe lameness'
Number of cows	Number of cows included in study
Number of herds	Number of herds included in study
Breed	Information on cow breeds (cow or herd level) included in study
Pasture	Information on use of pasture in study herds
Housing system	Information on housing system in study herds
Organic/conventional	Information on organic or conventional status of study herds
Milk yield	Information on daily or annual milk yield in study herds or cows
Study design	Categorized as: cross sectional or repeated cross sectional
Sampling of herds	Information on herd selection categorized as: random sampling, convenience sampling or no available information
Sampling of cows	Information on cow sampling within herds categorized as: random sampling, convenience sampling, entire herd sampling or no available information
Inclusion criteria	Information on specified inclusion or exclusion criteria for herds or cows

2.1. Identification of studies

The literature search identified 857 articles, and no additional articles were identified by other means. The initial scrutiny of the 857 articles by the first author identified 53 studies fulfilling the inclusion criteria specified above. The selection of studies is illustrated in a flow diagram (Fig. 1). The 53 studies are briefly presented in Table 2, and covered observations from 414,950 cows in 3945 herds. The mean number of cows per study was 7829 (range, 349–84,998), and the mean number of herds was 74 per study (range 10–751). A mean of 105 cows were assessed in each herd across the 53 studies. Studies spanned the years 1989–2020 and included herds from six continents. The majority of the studies were from Europe ($n = 29$) and North America ($n = 14$), with fewer studies from South America ($n = 4$), Australia ($n = 2$), Asia ($n = 3$) and Africa ($n = 1$).

Even though the literature search was done without any restrictions on year of publication, the oldest eligible article identified was published in 1993. Lameness in dairy cows has received increased scientific interest in recent years as shown by the increasing number of publications (Fig. 2). The international 'Lameness in Ruminants' conferences held regularly since 1994 may have contributed to an increased scientific awareness of lameness in dairy cows. The number of cows (and herds) included in published studies also increased over time; 12 of the 53 studies included more than 10,000 cows, and all these studies were published in 2009 or later, with nine of them published during the last five years.

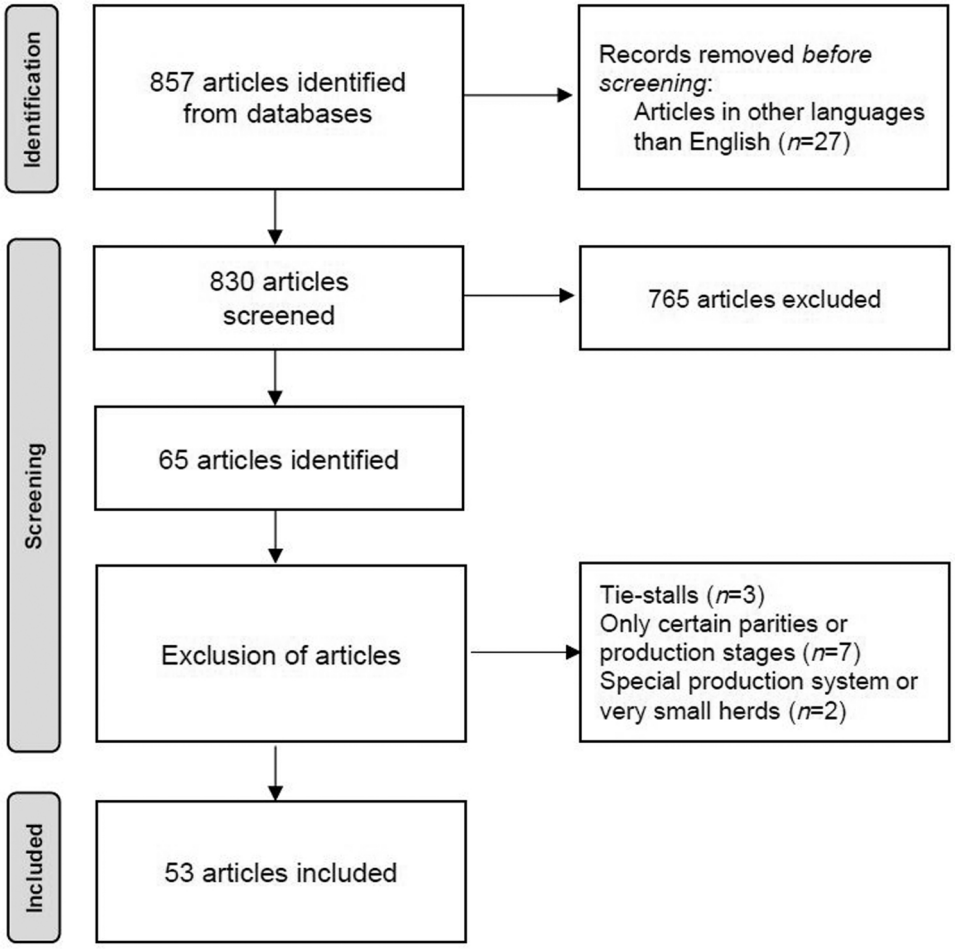

Fig. 1. Flow diagram illustrating the selection of studies for a literature review of prevalence of lameness in dairy cows.

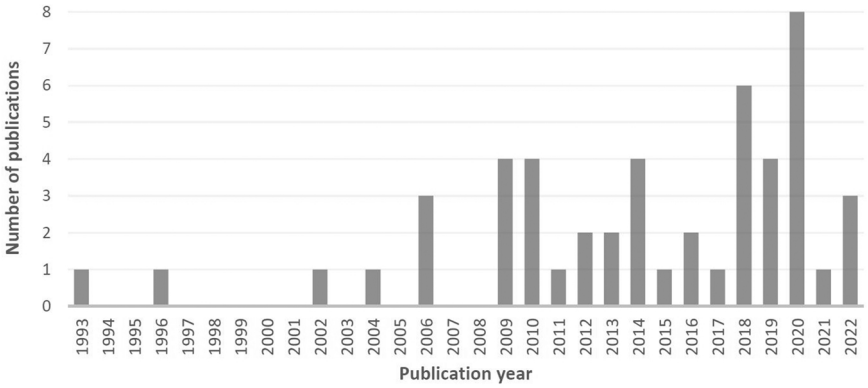

Fig. 2. Year of publication for 53 studies of prevalence of lameness in dairy cows.

2.2. Definition of lameness

In this review, the prevalence of lameness and severe lameness reported is based on the definitions given in the included papers, and may therefore vary between studies. Several different locomotion scoring systems and definitions of (severe) lameness were used across the 53 studies. Locomotion scores from 1 to 5 (e.g., Sprecher et al., 1997; Flower and Weary, 2006; Thomsen et al., 2008) were used in more than half (29 of 53) of the studies. In these cases, lameness was typically defined as score 3–5, and severe lameness as score 4–5. Less frequently, locomotion was scored on a scale from 0 to 3 (e.g., AHDB Dairy, 2017) with lameness typically defined as score 2–3, and severe lameness as score 3, or on a scale from 0 to 2 (e.g., Welfare Quality, 2009) with scores 1–2 typically defined as lame and 2 as severely lame. Finally, almost one fifth of the studies (9 of 53) did not use an already existing locomotion scoring system, but used a 'custom-made' scoring system specifically for the study. Table 3 presents detailed information on the locomotion scoring systems and the definitions of lameness and severe lameness used.

The many different locomotion scoring systems, and in some cases different definitions of 'lame' within the same locomotion scoring system, make comparisons between studies difficult. In a few studies, the

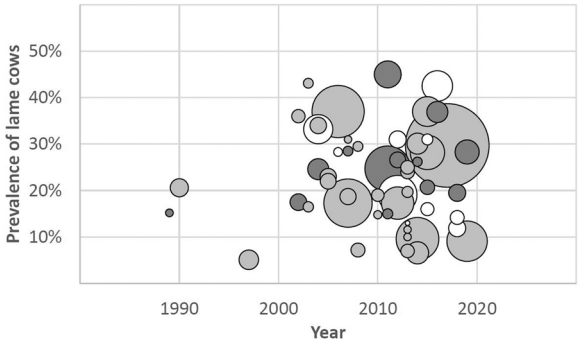

Fig. 3. Bubble diagram illustrating the association between prevalence of lameness, study year, number of cows included in the study, and geographical region. The area of each bubble illustrates the number of cows included in the study (larger bubbles=more cows). Dark grey, studies from North America; light grey, studies from Europe; white, studies from other regions or continents.

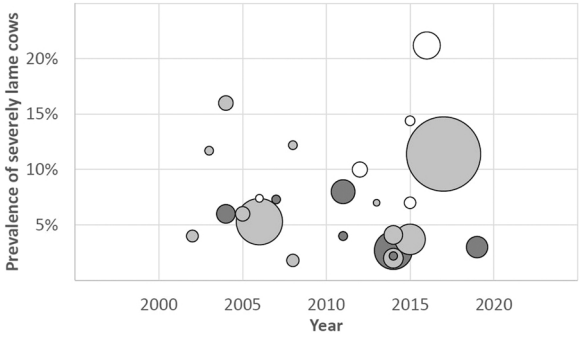

Fig. 4. Bubble diagram illustrating the association between prevalence of severe lameness, study year, number of cows included in the study, and geographical region. The area of each bubble illustrates the number of cows included in the study (larger bubbles=more cows). Dark grey, studies from North America; light grey, studies from Europe; white, studies from other regions or continents.

method for locomotion scoring or the definition of lameness was not stated (e.g., Manske et al., 2002; Dembele et al., 2006). We acknowledge that a 'one fits all' may not apply for locomotion scoring systems, and that the optimal choice of locomotion scoring system depends on a number of context-specific conditions. In some situations, it is important to be able to (at least to some extent) quantify the severity of lameness, and hence the use of a locomotion scoring system with an appropriate number of levels is warranted. In other situations, such quantification may not be needed, and a locomotion scoring system with fewer levels may suffice, and be faster and simpler to apply. We recommend that the method (locomotion scoring system) and the definition of lameness (e.g., scores defined as 'lame' or 'severely lame') are explicitly stated and described in all studies reporting lameness in dairy cows.

When a locomotion scoring system with the scores 1–5 was used, most studies defined severe lameness as scores 4 and 5. This is inconsistent with many 1–5 locomotion scoring systems where typically only score 5 is termed 'severely lame' (e.g., Sprecher et al., 1997; Flower and Weary, 2006; Thomsen et al., 2008). In many locomotion scoring systems, a 'severely lame' cow is defined as a cow with a degree of lameness that exceeds the threshold of 'clinically lame'. Typically, a locomotion score 4 out of 5 is defined as the lowest locomotion score where the cow is reluctant to bear weight on the affected leg(s), with locomotion score 5 being more lame than this (often with no or limited weight bearing on one or more legs) (Sprecher et al., 1997; Flower and Weary, 2006; Thomsen et al., 2008). The prevalence of severe lameness (defined as locomotion scores 4 and 5 on a 1–5 scale) reported in most of the studies included in this review may thus be seen as an overestimation, at least compared to a definition of 'severe lameness' as including only cows with a locomotion score 5 on a scale from 1 to 5.

Adequate training and standardization of observer scorings are very important for ensuring valid results when using visual locomotion scorings (Thomsen et al., 2008; Schlageter-Tello et al., 2015). Training of observers and evaluation of intra- and inter-observer agreement were described in some of the studies included in this review (e.g., Barker et al., 2010; Sjöström et al., 2018), whereas in other studies, this was not the case (e.g., King et al., 2016; Ali et al., 2021). Even though training does not guarantee unbiased recordings of the true lameness status of cows, we recommend that all observers participating in locomotion scoring as part of research studies are trained, with the aim to calibrate definitions of scores and maximize intra- and inter-observer agreement.

2.3. Prevalence of lameness

Across the 53 studies, the mean prevalence of lameness was 22.8% with a median of 22.0% and a range between studies from 5.1% to 45%, and a within herd range from 0% to 88%. Within herd range was reported in 35 of the 53 studies. The mean prevalence of severely lame cows was 7.0% with a median of 6.5% and a range between studies from 1.8% to 21.2%, and a within herd range from 0% to 65%. The prevalence of severely lame cows was reported in 24 of the 53 studies, and the range of severely lame cows was reported in 13 of these 24 studies. The association between lameness prevalence, study year, number of cows included in the study and geographical region is presented in Fig. 3 (lameness) and Fig. 4 (severe lameness).

Overall, the studies included in this review demonstrated a very large variation in the prevalence of lameness – both within and between studies. Between studies, the prevalence of lameness ranged from 5.1% (Sweden; Manske et al., 2002) to 45% (USA; Chapinal et al., 2013). When reported, the prevalence of severe lameness ranged from 1.8% (Norway; Sogstad et al., 2012) to 21.2% (Brazil; Costa et al., 2018). A Scientific Opinion from the European Food Safety Authority (EFSA) Panel on Animal Health and Animal Welfare has stated that '*when the prevalence of recognizable locomotor difficulties in dairy cattle is above 10%, this indicates that the prevention program is inadequate*' (EFSA, 2009). The mean lameness prevalence found in the present review was more than twice as high as the threshold for an 'acceptable' level of lameness suggested by the EFSA expert group. The large variation in lameness prevalence demonstrates that some herds have major problems with lame cows, whereas other herds seem to be able to control the problem. Further evaluations of the background of these differences are outside the scope of the present review, but have the potential to be useful for optimizing hoof health management in dairy herds. Knowing what those herds with a low lameness prevalence are 'doing right' may be useful for herds with a high lameness prevalence.

With changes in prevalence over time, no clear trend was evident (Fig. 3, Fig. 4). Comparing the lameness prevalence from the 28 studies with data collected during the last ten years (mean, 21.5%; median, 20.7%) with the lameness prevalence from the 25 older studies (mean, 24.3%; median, 23.0%), indicates that the prevalence of lameness among dairy cows has changed little during the last 20–30 years. This was supported by the results from the Wilcoxon rank sum test ($P = 0.37$). The same was observed for the prevalence of severe lameness: 12 newer studies with a mean prevalence of severe lameness of 7.0% (median, 5.6%), and 12 older studies with a mean prevalence of severe lameness of 7.0% (median, 6.7%). Also here, the result from the Wilcoxon rank sum test was non-significant ($P = 0.34$), supporting a conclusion that the prevalence of severe lameness has changed little with time.

No clear effect of geographical region was evident from Figs. 3 and 4. Comparing lameness prevalence among studies from Europe (mean, 22.0%; median, 20.6%) and North America (mean, 24.2%; median, 24.6%) also did not indicate any major geographical differences in lameness prevalence. This was supported by the results from the

Table 2
Information about 53 studies included in a literature review of prevalence of lameness in dairy cows.

Reference	Year (s) of study	Country	Prevalence of lameness	Range of prevalence of lameness	Prevalence of severe lameness	Range of prevalence of severe lameness	Number of cows included	Number of herds included
Wells et al. (1993)	1989–1990	USA	15.2%	-	-	-	853	17
Clarkson et al. (1996)	1989–1991	UK	20.6%	2–53.9%	-	-	4230	37
Manske et al. (2002)	1996–1998	Sweden	5.1%	0–33%	-	-	4899	101
Cook et al. (2004)	2002–2003	USA	17.5%	-	-	-	3610	12
Dembele et al. (2006)	-	Czech Republic	22%	6–42%	-	-	3240	24
Amory et al. (2006)	2003–2004	Netherlands	16.5%	3.8–30.8%	-	-	1450	19
Espejo et al. (2006)	2004	USA	24.6%	3.3–57.3%	6%	-	5626	50
Rutherford et al. (2009)	2006–2008	UK	17.3%	1.4–48.6%	-	-	28,698	80
Katsoulos and Christodoulopoulos (2009)	2007	Greece	18.7%	-	-	-	3400	40
Rouha-Mülleder et al. (2009)	2002–2003	Austria	36%	0–77%	4%	0–43%	2360	80
Dippel et al. (2009)	2004–2005	Germany/ Austria	34%	0–81%	16%	-	3514	103
Yaylak et al. (2010)	2006–2007	Turkey	28.3%	-	7.4%	-	1078	34
Olechnowicz et al. (2010)	2003–2004	Poland	43.1%	-	11.7%	-	1330	11
Tadich et al. (2010)	2004	Chile	33.2%	-	-	-	10,669	91
Ito et al. (2010	2007–2008	Canada	28.5%	-	7.3%	-	1319	28
Barker et al. (2010)	2006–2007	UK	37%	0–79.2%	5.3%	0–31%	33,415	205
Sarova et al. (2011)	2007	Czech Republic	31%	9–61%	7%	0–24%	807	14
Sogstad et al. (2012)	2008	Norway	7.2%	-	1.8%	-	2569	61
Thomsen et al. (2012b)	2007–2009	Denmark	29.5%	-	12.2%	-	1340	42
Sarjokari et al. (2013)	2005	Finland	23%	2–62%	6%	-	3459	87
Chapinal et al. (2013)	2010–2012	USA	45%	14–88%	8%	0–45%	9103	53
Becker et al. (2014)	2010–2011	Switzerland	14.8%	-	-	-	950	52
Burow et al. (2014)	2010	Denmark	19%	-	-	-	2084	36
Chapinal et al. (2014)	2012	China	31%	7–51%	10%	0–27%	3774	34
Somers et al. (2015)	2013	Ireland	11.6%	-	-	-	786	10
Westin et al. (2016)	2010–2012	Canada	15%	2.5–46%	4%	-	1378	36
King et al. (2016)	2014–2015	Canada	26.2%	2.5–57.5%	2.2%	0–12.2%	1218	41
Adams et al. (2017)	2014	USA	9.6%	0–47.9%	2.7%	0–25%	22,622	191
Sjöström et al. (2018)	2013	Sweden	7%	0–25%	-	-	2403	51
Sjöström et al. (2018)	2013	Spain	10%	0–27%	-	-	807	20
Sjöström et al. (2018)	2013	Germany	25%	0–79%	-	-	2450	60
Sjöström et al. (2018)	2013	France	24%	0–51%	-	-	2499	70
Costa et al. (2018)	2016	Brazil	42.5%	34–48%	21.2%	15.2–28.5%	11,675	50
Griffiths et al. (2018)	2015–2016	UK	28.2%	5.8–65.4%	3.7%	-	14,700	61
Salfer et al. (2018)	2012	USA	26.6%	-	-	-	3273	52
Bran et al. (2018)	2015	Brazil	31%	10–70%	14.4%	0–57%	1633	44
Klindworth et al. (2018)	2012	Germany	17.3%	-	-	-	13,112	159
Moreira et al. (2018)	2015–2016	Brazil	16%	3–42%	7%	0–30%	2267	48
Randall et al. (2019)	2014	UK	30.1%	7.3–60.6%	4.1%	0–14.4%	5620	43
Jewell et al. (2019)	2015–2016	Canada	20.7%	0–52.3%	-	-	2758	46
Somers et al. (2019)	2013–2014	Ireland	19.7%	-	-	-	1675	10
Warner et al. (2020)	2011–2012	Canada	24.7%	0–84%	-	-	25,617	229
Bonfati et al. (2020)	2018	Australia	11.9%	3.9–18.7%	-	-	3771	10
Dendani-Chadi et al. (2020)	2012–2015	Algeria	13%	-	-	-	349	14
Mineur et al. (2020)	2014–2015	Austria	6.6%	-	2%	-	6292	161
Ranjbar et al. (2020)	2011–2014	Australia	19.1%	5–44.5%	-	-	18,600	62
O'Connor et al. (2020)	2015	Ireland	37%	-	-	-	11,116	68
Denis-Robichaud et al. (2020)	2016–2017	Canada	36.9%	18.9–71.7%	-	-	5682	93
van Huyssteen et al., 2020)	2018	Canada	19.5%	2–56%	-	-	3759	65
Ali et al. (2021)	2018–2019	Pakistan	14.2%	3.1–33.1%	-	-	2555	15
Jensen et al. (2022)	2016–2019	Germany	29.7%	0–81%	11.4%	0–65%	84,998	751
Browne et al. (2022)	2019–2020	Ireland	9.1%	0–31.4%	-	-	20,208	99
Matson et al. (2022)	2019	Canada	28.3%	10–66.7%	3%	0–13.3%	7350	75

-, No information available from study.

Wilcoxon rank sum test ($P = 0.51$). It should be noted that within both Europe and North America, herds may be very different with respect to characteristics which may potentially influence the risk of lameness (e.g., herd size, housing system, and access to pasture).

2.4. Study design and representativeness

The majority ($n = 42$) of the studies were observational, cross-sectional studies with locomotion scoring of cows on a single occasion. The remaining 11 studies had a repeated cross-sectional design with locomotion scorings on two or more occasions; in some cases scoring the same cows repeatedly and in others scoring a new sample of

Table 3
Locomotion scoring systems and definitions of lameness used in 53 studies included in a literature review of prevalence of lameness in dairy cows. One of the 53 studies did not describe the locomotion scoring system used.

Number of levels in locomotion scoring system	Locomotion scoring systems and levels (number of studies)	Levels defined as 'lameness' (number of studies)	Levels defined as 'severe lameness' (number of studies)
2	Custom-made[a]: 0–1 (2)	1 (2)	NA (2)
3	Welfare quality (2009): 0–2 (6)	1–2 (5), 2 (1)	2 (1), NA (5)
	Custom-made[a]: 1–3 (1)	2–3 (1)	3 (1)
4	Barker et al. (2010): 0-3 (2)	2-3 (2)	3 (1), NA (1)
	Dairy Australia (2015): 0-3 (1)	2-3 (1)	NA (1)
	Nordlund et al. (2004): 1-4 (1)	3-4 (1)	NA (1)
	AHDB Dairy (2017: 0-3 (4)	2-3 (3), 1-3 (1)	3 (2), NA (2)
	Cook (2003): 1-4 (1)	3-4 (1)	NA (1)
	Custom-made a: 0-3 (2), 1-4 (2)	2-3 (1), 1-3 (1), 3-4 (1), 4 (1)	3 (1), NA (3)
5	Lischer et al. (2000): 1-5 (1)	3-5 (1)	NA (1)
	Flower and Weary (2006): 1-5 (11)	3-5 (10), not defined (1)	4-5 (8), NA (3)
	Sprecher et al. (1997): 1-5 (10)	3-5 (8), 2-5 (2)	4-5 (4), NA (6)
	Thomsen et al. (2008): 1-5 (2)	3-5 (2)	4-5 (2)
	Winckler and Willen (2001): 1-5 (2)	3-5 (2)	4-5 (2)
	NFACC (2009): 1-5 (1)	3-5 (1)	NA (1)
	Custom-made a: 0-4 (1), 1-5 (1)	2-4 (1), 3-5 (1)	4-5 (1), NA (1)
9	Manson and Leaver (1988): 1-5 with 0.5 points (1)	3-5 (1)	NA (1)

NA, Not applicable
[a] Locomotion scoring system not based on a previously described system, but made specifically for the particular study.

cows at each visit.

In 42 of the studies, specific inclusion or exclusion criteria for the participating herds were stated, whereas 11 studies did not contain information on such criteria. Fig. 5 describes the sampling of herds and cows. Convenience sampling of herds followed by inclusion of all cows in selected herds was the most frequent sampling procedure, used in 48% of all studies.

Relevant background information was included in relatively few studies: only 27 of the 53 studies reported information on cow breed. Holstein was the predominant breed in 23 of the 27 studies with breed information. In 15 of the 53 studies, information on the use of pasture was included, 32 of the studies included a description of the housing systems, and seven of the studies indicated whether herds were organic or conventional. Finally, 35 of the 53 studies included information on daily or annual milk yield.

The inclusion criteria specified for this review was intended to include only studies that were relatively representative of a large population of dairy cows. Still, the majority of studies (77%) did not use random sampling of herds to be included. Specific details of the methodology used for randomization was only provided in five of 12 studies that reported to use randomization in their study design. All 12 studies that reported random sampling for herd selection based the sampling on databases with herd information. These databases were typically managed by farmer organizations or public authorities. Most of the 12 studies that reported random sampling of herds did not include herds from the whole country. Most often, only herds from certain regions of a country could be sampled and included in the study. In some situations, the inclusion of only certain regions of a country may affect the generalizability of results (in cases with major geographical differences within a country), whereas in other situations, this may not be the case. Only three studies reported random sampling of herds from the whole country under study (Denmark, Thomsen et al., 2012b; Finland, Sarjokari et al., 2013; Switzerland, Becker et al., 2014). Most sampling of cows within herds (87%) was either reported as random (11/52 studies) or involved all cows in the selected herds (34/52 studies).

In the selection of herds for a given study, random sampling may be difficult, as this type of research is done in commercial dairy herds where the owner normally cannot be 'forced' to participate. Therefore, a high proportion of convenience sampling of herds ($n = 40$) is not surprising. However, less than half of all studies included relevant information about breed, housing system, or milk yield. If herd characteristics are presented in a study, it is easier to evaluate the reliability of any convenience sample data for a given target population. In addition to providing information relevant to an evaluation of the generalizability and representativeness of the study population, many of these variables are also well-known risk factors for lameness (e.g., Sogstad et al., 2007; Adams et al., 2017; Thomsen et al., 2019). Therefore, we recommend that relevant characteristics of herds and cows (breed, housing system, walking and lying surface, milk yield, and parity) always be included in papers presenting data on prevalence of lameness in dairy cows.

2.5. Knowledge gaps

The studies included in this review all used prevalence as a measure to quantify lameness. For use in herd management, The International Committee for Animal Recording (ICAR) recommends frequent locomotion scorings (weekly or fortnightly) (ICAR, 2020). Studies with frequent locomotion scoring are labour intensive and costly, and few studies have presented data on lameness incidence. In most cases, incidence studies have been based on farmer recordings, treatment records, or equivalent measures, and have not included frequent locomotion scorings by trained observers (e.g., Clarkson et al., 1996; Chawala et al., 2013; Hudson et al., 2014). Because quantification of the duration of lameness requires precise definitions of when a case starts and ends, as well as very frequent (ideally daily) locomotion scorings of cows, little information exists on the duration of lameness. Few studies have thus estimated the duration of lameness, and the associated hoof lesions, and such estimates have typically been based on locomotion scorings repeated every second week (e.g., Groenevelt et al., 2014; Thomas et al., 2016; Mahendran et al., 2017). The relatively few herds where data on the duration of lameness events has been collected (often due to the high labour and other cost requirements) has limited the ability to extrapolate results to a larger target population. This knowledge gap should be addressed in future research.

During the last decade, automatic methods for locomotion scoring and lameness detection have been developed and tested. Many different techniques for automatic detection of lame cows have been proposed, including automatic image analysis of back arching (Poursaberi et al., 2010), automatic weight distribution measurements (Chapinal and Tucker, 2012), automatic recordings of lying or feeding behavior (Thomsen et al., 2012b; Solano et al., 2016; Barker et al., 2018), leg

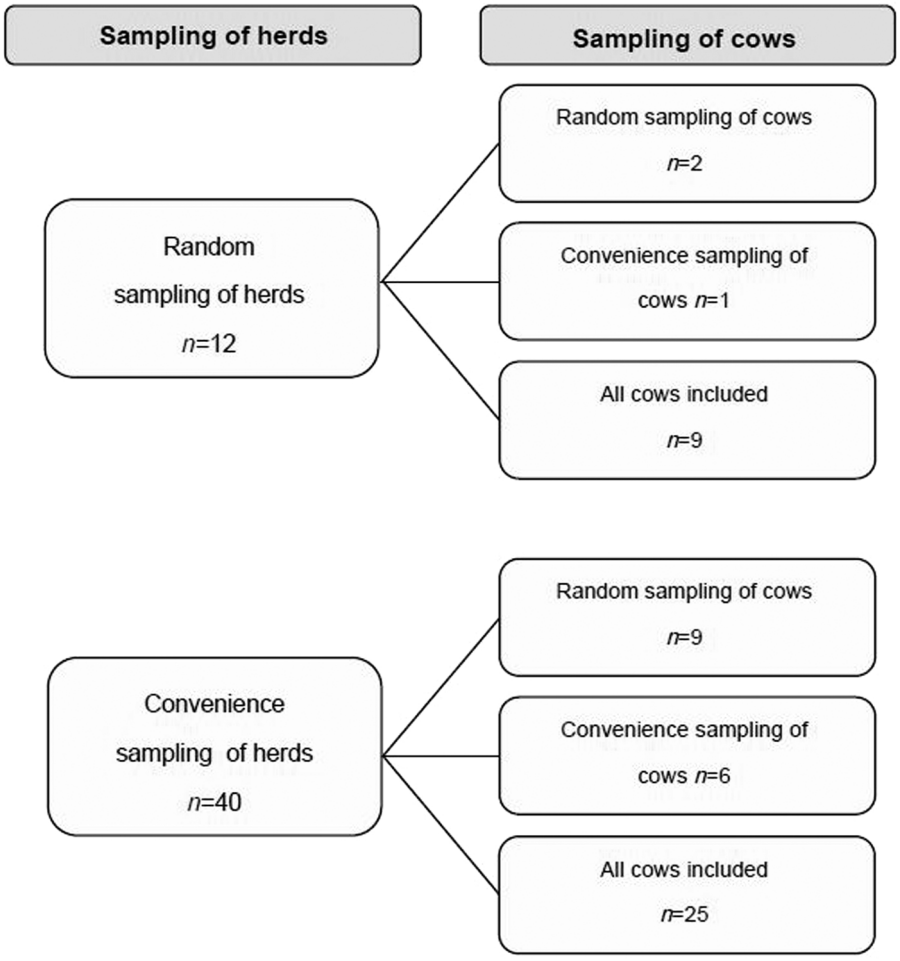

Fig. 5. Procedures for sampling of herds and cows in 52 studies included in a literature review of prevalence of lameness in dairy cows. One study provided no information on sampling procedures.

swing analysis with image processing techniques (Zhao et al., 2018), and radar sensing techniques (Busin et al., 2019). Such methods have the potential to allow very frequent scorings, and may thus be useful in future studies on incidence, and duration, of lameness – as well as in the daily hoof health management of dairy herds. However, to be useful in such settings, the automatic methods must be valid and accurate, which is presently not the case for many of them. In their review on automatic lameness detection in cattle, Alsaaod et al. (2019) concluded that most of the existing systems are still in the development phase and thus not ready for routine use.

3. Conclusions

Most studies reporting prevalence of lameness in dairy cows are relatively new. The number of studies has increased in recent years and no studies published before 1993 were identified. We found a large variation both within and between studies, with no indication of any major changes in lameness prevalence over time. Lameness among dairy cows thus remains a major problem. Mostly, all cows in the herds were included (or cows were selected randomly), but herds were often selected using convenience sampling. To facilitate better comparison between studies, and to enable generalization to larger target populations, we recommend that relevant herd and cow characteristics (i.e., milk yield, age/parity, housing system, and breed) are reported in all studies on lameness in dairy cows, that inclusion or exclusion criteria are specified, and that an exact definition of lameness is given.

Conflict of interest statement

None of the authors of this paper has a financial or personal relationship with other people or organisations that could inappropriately influence or bias the content of the paper.

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