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Associating mobility scores with production and reproductive performance in pasture-based dairy cows

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ABSTRACT

Lameness in dairy cows can have significant effects on cow welfare, farm profitability, and the environment. To determine the economic and environmental consequences of lameness, we first need to quantify its effect on performance. The objective of this study, therefore, was to determine the associations of various production and reproductive performance measurements (including milk, fat, and protein yield, somatic cell count, calving interval, cow death, or cow slaughter), and mobility scores in spring-calving, pasture-based dairy cows. We collected mobility scores (0 = good, 1 = imperfect, 2 = impaired, and 3 = severely impaired mobility), body condition scores, and production data for 11,116 cows from 68 pasture-based dairy herds. Linear mixed modeling was used to determine the associations between specific mobility scores and milk, fat and protein yield, and somatic cell count and calving interval. Binomial logistic regression was used to determine the association between mobility score and cow death, or slaughter. Significant yield losses of up to 1.4% of the average yield were associated with mobility score 2 and yield losses of up to 4.7% were associated with mobility score 3 during the early scoring period. Elevated somatic cell count was associated with all levels of suboptimal mobility during the late scoring period. Cows with a mobility score of 2 during the early scoring period were associated with longer calving interval length, whereas only cows with a mobility score of 3 during the late scoring period were associated with longer calving interval length. Cows with a mobility score ≥1 were more likely to be culled during both scoring periods. Our study, therefore, shows an association between specific mobility scores and production and reproductive performance in spring-calving, pasture-based dairy cows scored during the summer grazing period.

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INTRODUCTION

Lameness has been identified as the third most important health-related economic loss, after fertility and mastitis (Bruijnis et al., 2010; Alawneh et al., 2011; Huxley, 2013). Lameness also has serious negative consequences on animal welfare (Leach et al., 2012; Navarro et al., 2013) and the environment; for example, increased greenhouse gas emissions (Mostert et al., 2018), acidification, eutrophication, and fossil fuel depletion (Chen et al., 2016). Lameness has the potential to reduce the overall lifetime performance of dairy cows due to milk production loss and culling (Huxley, 2013), as well as having the potential to further affect sustainability by increasing the total greenhouse gas emissions per unit of milk produced (Mostert et al., 2018). Lame cows are also more at risk for developing future mobility issues (Green et al., 2002; Hirst et al., 2002). Hence, lameness can be considered to be among the most significant disease challenges in current dairy production systems (Huxley, 2012).

In the majority of the northwest European pasture-based systems, cows are housed during the winter months but managed at pasture for the remainder of the year. Specifically in Ireland, the majority of milk production systems operate a spring-calving, pasture-based grazing system. In such a system feed demand and supply are synchronized by both calving pattern and stocking rate, with the vast majority of the feed consumed through grazing (Shalloo et al., 2014). In studies that examine mobility in these types of systems, it is generally the higher risk winter period that is prioritized. However, during the summer grazing period cows are exposed to a number potential risks, such as walking long distances between the milking parlor and pasture each day on varying types of roadway surfaces. In contrast, during the winter period, risk factors are similar to those of cows managed in non-pasture-based systems and mostly include risk factors such as availability of cubicle spaces (Fregonesi et al., 2007), shed flooring type, and exposure of claws to slurry (Cook et al., 2004; Alvergnas et al., 2019). Risk factors from both types of systems contribute to the development of claw disorders, of which up to 90% are found in the hind limbs (Somers and O'Grady, 2015).

Clinical lameness in systems other than spring-calving, pasture-based systems has been shown to be negatively associated with milk yield (Green et al., 2002), reproductive performance, additional labor, and treatment costs (Enting et al., 1997). Amory et al. (2008) reports substantial yield losses for up to 5 mo before a farmer's diagnosis of a claw disorder. This delay in diagnosis and subsequent treatment may result in cows having mobility problems for longer periods of time, which could potentially increase their stress levels due to the pain associated with lameness (O'Callaghan, 2002; Leach et al., 2012).

The consequences of lameness, especially more severe types of lameness, have been well researched for several management systems, such as year-round housing (Bicalho et al., 2008) and nonseasonal calving pasture-based systems (Archer et al., 2010). However, relatively fewer studies have examined the effect of less severe or mild types of lameness in spring-calving, pasture-based systems, like those in Ireland. In our study, we use the phrases optimal mobility (mobility score 0) and sub-optimal mobility (mobility score ≥1), referring to the UK Agriculture and Horticulture Development Board 4-point scale. Therefore, the aim of this study was to determine the associations between mobility scores and production and reproductive performance in spring-calving, pasture-based dairy cows.

MATERIALS AND METHODS

Cow Data

Using an existing database, herds were selected for inclusion based on the following criteria: (1) maximum of 100 km from Teagasc, Moorepark in Fermoy (Co. Cork, Ireland), (2) must have been registered to the Irish Cattle Breeding Federation (**ICBF**) milk recording system, (3) herd owners must have been willing to have their herd genomically tested, and (4) must have been operating a spring-calving, pasture-based system. The Irish pasture-based system refers to a system in which cows are turned out to pasture postcalving during the spring, once ground conditions allow and feed is available. Spring calving is the norm in such Irish pasture-based systems, whereby over 70% of such cows calve between January and March (Irish Cattle Breeding Statistics, 2018) and remain outside grazing for the summer and autumn months, and are partially or fully housed during the winter months (December to January). In this system, once cows calve they return to pasture with supplementary feed offered postcalving to individual cows as required. The system focus is to manage the interface between the cow and the pasture, with an ultimate focus of maximizing grass intake (managed through pregrazing herbage mass and postgrazing residuals) as well as grass utilization (Dillon et al., 2005).

Sixty-eight pasture-based dairy herds (11,116 cows) fit the criteria and were included in the analysis. The average herd size was 163 (SD = 110) cows, ranging from 40 to 640 cows per herd. The main breeds of the cows were Holstein, Jersey, and Friesian, making up 75%, 13%, and 9%, respectively, which is representative of the national population (Ring et al., 2018). Parity ranged from 1 through 13, whereby parity 1 cows made up 30% of all the cows, parity 2 cows made up 20% of all the cows, and parity 3+ cows made up 50% of all the cows. The mean calving date for the cows in this study was February 18, 2015 (median = February 23), ranging from January 2 through May 23, 2015, of which 1,404 cows calved in January, 6,047 cows calved in February, 2,503 cows calved in March, 929 cows calved in April, and the remaining 233 cows calved in May.

BCS and Mobility Score. Figure 1 presents the distribution of both the early and late scoring period mobility score and BCS for all cows analyzed. Each herd was visited twice by 2 trained technicians from Teagasc, Moorepark in 2015 (the same 2 technicians visited all farms). Both technicians were experienced herd personnel with experience using both scoring methods used in this study, as described below. The first visit (early scoring period) was conducted in March through May for each herd. The average date for the first visit was April 5, 2015 (ranging from March 2 through May 13, 2015). During the first visit, the average DIM for the lactating cows was 40, with a standard deviation of 31, ranging from 70 d precalving to 111 d postcalving. The second visit (late scoring period) was conducted in June through November for each herd. The average date for the second visit was August 3, 2015 (ranging from June 2 through November 26, 2015). During the second visit, the average DIM was 160, with a standard deviation of 49, ranging from 23 through 300 d postcalving. Cows were treated during a third herd visit by one commercial company (Farm Relief Services, Roscrea, Co. Tipperary, Ireland), if required. Treatment refers to the recommended actions as per the UK AHDB mobility scoring method, which recommends routine (preventative) trimming or treatment when/if required and cows that were treated between the first and second visits were not included in the analyses (i.e., cows that were treated after the first mobility scoring visit but before the second mobility scoring visit were not included). Body condition of each cow was scored as they walked through a chute, using both visual and tactile appraisal on a scale of 1 to 5 with 0.25 increments, as described by Edmonson et al. (1989). Cows were mobility scored on exit from the parlor on a concrete surface. Mobility of each cow was scored using the UK Agriculture and Horticulture Development Board 4-point scale (https://dairy.ahdb.org.uk/technical-information/animal-health-welfare/lameness/husbandry-prevention/mobility-scoring/#.WXnhULuFOr8; accessed December 16, 2017), using the following definitions:

- A score of 0 describes a cow with good mobility that walks with even weight bearing and rhythm on all 4 feet, with a flat back. Long and fluid strides are possible.
- A score of 1 describes a cow with imperfect mobility (any mobility score >0 is defined as suboptimal mobility) with uneven steps or shortened strides affecting one or more limbs and it may not be immediately identifiable.
- A score of 2 describes a cow with impaired mobility, which is a cow with uneven weight bearing on one or more limbs that is immediately identifiable, or shortened strides (or both), usually associated with an arched back.
- A score of 3 describes a cow with severely impaired mobility; a cow with this score is unable to walk as fast as the rest of the healthy herd due to more severely impaired symptoms compared with score 2.

Milk Production Data and SCC. Milk and production data were extracted retrospectively from the ICBF database for the complete lactation of cows that entered the study in spring 2015. Milk data included 305-d yield in kilograms for milk, fat, and protein, and

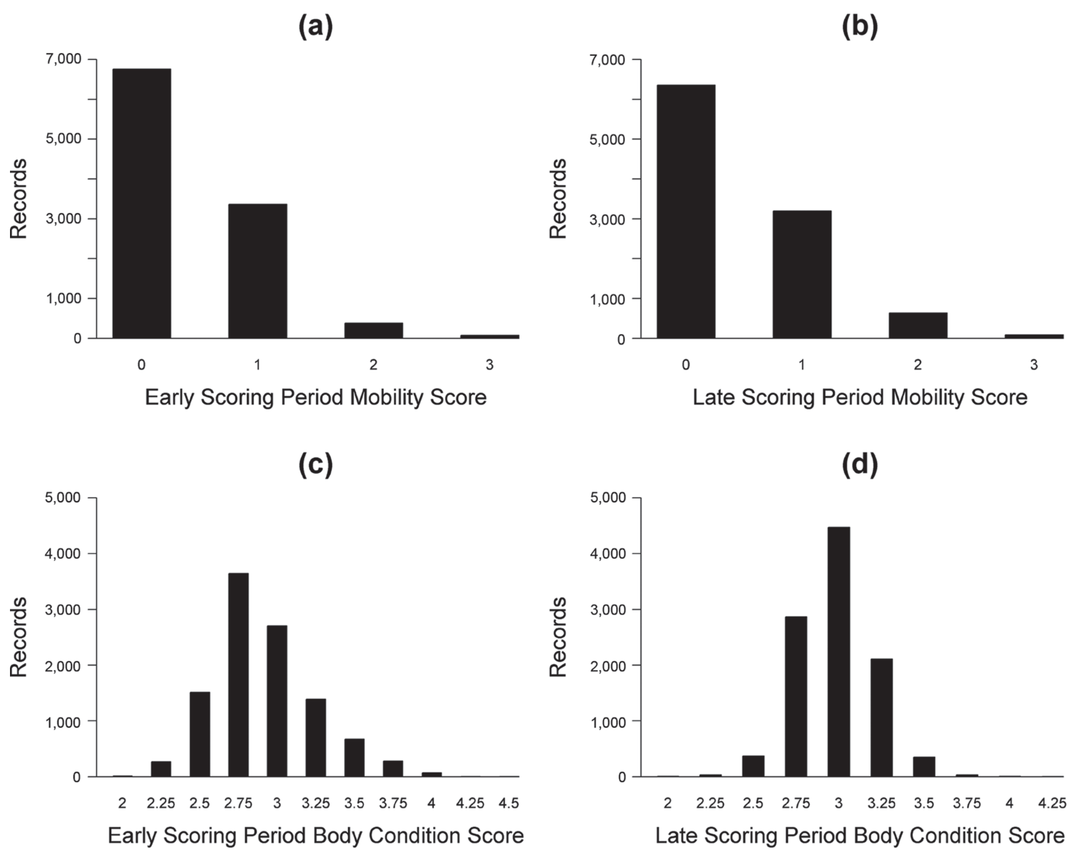

Figure 1. Distribution of (a) early and (b) late scoring period mobility score, and (c) early and (d) late scoring period BCS. Early scoring period refers to mobility scores recorded during March through May 2015. Late scoring period refers to mobility scores recorded during June through November 2015.

production data included stage of lactation during each scoring period (i.e., DIM), and the average SCC for the entire lactation. The output variable for both SCC models (for the early and late scoring period separately) was $\log_{10}$ SCC, which is a $\log_{10}$ transformation applied to normalize the SCC data (Ali and Shook, 1980).

Economic Breeding Index Data. The Economic Breeding Index (**EBI**) is a breeding index used to identify genetically superior animals to increase profitability within Irish dairy herds (Veerkamp et al., 2002). The EBI and its subindices are described in detail by Berry et al. (2007). The EBI subindices trait values for production, fertility, and health were extracted from the ICBF database for the year 2015 for all cows, to correct for a genetic predisposition for certain traits. The production subindex is made up of 3 traits representing the milk kilograms, fat kilograms, and protein kilograms. The fertility subindex is made up of 2 traits: calving interval and survival. The health subindex is made up of 3 traits: lameness, mastitis, and SCC. An animal's PTA indicates the amount of a particular trait an animal is expected to pass on to its progeny, relative to the base population. The base population refers to cows born in 2005, and then calved and were milk recorded in 2007. The base population performance figures are 5,743 kg of milk, 224 kg of fat (3.9%), 195 kg of protein (3.39%), a 400-d calving interval, and 82.5% survival.

Cow Death and Cow Slaughter Data. Cow death date refers to the date on which a cow died on farm (including cows euthanized on farm), and cow slaughter date refers to the date on which a cow exited the herd specifically to be slaughtered. These data were available and extracted from the ICBF database for all the animals in the data set.

Calving Interval. Calving interval data were extracted from the ICBF database for all the animals in the data set. Calving interval in our study is calculated using each cow's calving date in 2015 and in 2016, thus parity 1 cows (in 2015) become parity 2 cows in 2016 (and so on) and are used as the reference value in the statistical models.

Data Edits

Cows were only included in each of the analysis if all predictor variables were available and recorded correctly to the best of our knowledge. Supplemental Figures S1, S2, S3, and S4 (https://doi.org/10.3168/jds.2019-17103) describe the edits made for the milk, fat, and protein analysis; the SCC analysis; the calving interval analysis; and the cow death and cow slaughter analyses, respectively.

Statistical Analysis

Descriptive statistics and modeling were performed using the R statistical software (RStudio Team, 2016), using linear mixed-effects models (function 'lmer') and binomial logistic regression models (function 'glm').

Analysis for Milk, Fat, and Protein Production, SCC Performance, and Calving Interval Length. A linear mixed model analysis was used to model the relationship between specific mobility scores and milk, fat, and protein production, SCC, and calving interval length:

$$Y_{ijklm} = \beta_0 + \text{MOS}_k + \text{BCS}_l + \text{PAR}_m + \beta_1 \times \text{PTA}_{ij} + \beta_2 \times \text{DIM}_{ij} + \beta_3 \times \text{SCC}_{ij} + \text{Farm}_j + \varepsilon_{ijklm},$$

where Y_{ijklm} corresponds to the 305-d milk, fat, or protein for cow i, of farm j, with mobility score k, BCS_l, and parity m. MOS_k is the corresponding early or late scoring period mobility score for $ijklm$, BCS_l is the corresponding early or late scoring period BCS for $ijklm$, PAR_m is the corresponding parity for $ijklm$, PTA_{ij} is the corresponding PTA for milk kilograms, fat kilograms, or protein kilograms for cow i of farm j. DIM_{ij} is the corresponding DIM for cow i of farm j, and SCC_{ij} is the corresponding $\log_{10}$ transformation of SCC for cow i of farm j. The parameters β_0, β_1, β_2, and β_3 are the regression coefficients and ε_{ijklm} is the error term. When Y_{ijklm} corresponds to the $\log_{10}$ SCC, PTA_{ij} is the corresponding PTA for SCC, while all other fixed variables remain the same as for when Y_i corresponds to the 305-day milk, fat, or protein for $ijklm$, except for SCC_{ij}, which is replaced with MKG_{ij}, which is the corresponding 305-day milk yield in kilograms for $ijklm$. Farm was also included in each model as a random effect. Random error terms ε_{ijklm} and random farm effects Farm_j are assumed to be independently normally distributed around 0 with variances σ^2 and $\sigma^{2/\text{f}}$, respectively. Only significant variables were kept in all the models, except for BCS, which was forced into all models regardless of its statistical significance, due to its proven strong association with suboptimal mobility (O'Connor et al., 2019).

Six models were run in total to determine the association between milk, fat, and protein production performance and mobility scores: 3 using early scoring period mobility score and BCS and the remaining 3 for late scoring period mobility score and BCS. Body condition score was inputted as a categorical variable with 3 classes: BCS <3.00, BCS = 3.00, and BCS >3.00 (i.e., less than the median, the median, and greater than the median BCS, respectively). Two models were run in total to determine the associations between SCC and mobility scores, one using early scoring period mobility score and BCS, and one with late scoring period mobility score and BCS. Similarly, 2 models were run in total to determine the association between calving interval length and mobility scores, one for early scoring period mobility score and BCS, and one for late scoring period mobility score and BCS. The distribution of standard residuals of the model was plotted and assessed to check the model fitting.

Analysis for Cow Death or Slaughter. Binomial logistic regression was used to model nominal outcome variables, in which the log odds of the outcomes are modeled as a linear combination of the predictor variables. The model was run 4 times (2 times using the early scoring period mobility score and BCS, and 2 times using the late scoring period mobility score and BCS) with the outcome variables cow death or cow slaughter (categorical variables, coded as cow did not die = 0 and cow died = 1, and cow not slaughtered = 0 and cow slaughtered = 1). The associations between the predictor variables (early or late scoring period mobility score, early or late scoring period BCS, cow parity, DIM, health, and calving interval length PTA) on cow death or slaughter were assessed individually. Farm was also included in each model as fixed predictor variable because the model was unable to converge with farm as a random variable.

RESULTS

Mobility Score and Milk, Fat, and Protein Production Performance

Model results from the linear mixed models analyzing the association between 305-d milk, fat, and protein yield and the early or late scoring period mobility and BCS are reported in Table 1. Early scoring period mobility score 1 (imperfect mobility) tended to be associated with increased 305-d milk and protein yield, whereas late scoring period mobility score 1 was associated with an increased 305-d milk, fat, and protein yield (1% higher 305-d milk yield compared with the average yield) when compared with the reference value, mobility score 0 (good i.e., optimal mobility). Early scoring period mobility 2 (impaired mobility) was associated with a decreased 305-d milk and protein yield (102 kg reduced 305-d milk yield), whereas late scoring period mobility score 2 had no significant association with 305-d milk, fat, or protein yield. Both early and late scoring period mobility score 3 (severely impaired mobility) were associated with decreased 305-d milk yield (299 kg reduction of milk in the early scoring period and 356 kg reduction of milk in the late scoring period) and decreased 305-d protein yield (10 kg reduction in the early scoring period and 15 kg reduction in the late scoring period). Late scoring period mobility score 3 was associated with decreased fat yield (13 kg reduction), whereas the early scoring period mobility score 3 was not associated with fat yield.

As reported in Table 1, early scoring period BCS >3 (compared with BCS <3) tended to be associated with decreased milk yield and was associated with protein yield, but had no significant associations with fat yield. Late scoring period BCS = 3 also had no significant association with performance, whereas late scoring period BCS >3 was significantly negatively associated with milk, fat, and protein yield. Higher parity cows were associated with higher milk, fat, and protein 305-d yield. The PTA for milk, fat, and protein, as well as stage of lactation during each scoring period (DIM), also had significant positive associations with milk, fat, and protein yield, whereas $\log_{10}$ SCC increased as milk, fat, and protein yield decreased in both scoring periods.

Mobility Score and SCC Performance

Model results from the linear mixed models analyzing the effect of early and late scoring period mobility score on the log SCC are reported in Table 2 (estimate of coefficients on the transformed SCC scale) and Table 3 (estimated marginal means on the untransformed SCC scale). Elevated SCC was associated with all levels of suboptimal mobility (mobility score 1, 2, and 3) in the late scoring period, whereas mobility score 1 (imperfect mobility) and mobility score 2 (impaired mobility) were associated with elevated SCC in the early scoring period. Both early and late scoring period BCS had no associations with SCC. Parity 2 and parity >3 cows were significantly associated with elevated SCC compared with the reference category, parity 1 cows, during the analyses of both scoring periods. The PTA for SCC was associated with increased SCC during both scoring periods, whereas stage of lactation was only associated with SCC during the late scoring period and as 305-d milk yield increased SCC decreased during both scoring periods.

Calving Interval

Model results from the linear mixed models analyzing the effect of early and late scoring period mobility score on calving interval length (in days) are reported in Table 4. Both early and late scoring period mobility score 1 (imperfect mobility) had no significant association with calving interval length. However, early scoring period mobility score 2 (impaired mobility) was associated with an increase in calving interval length by 3.5 d, whereas late scoring period mobility score 2 had

Table 1. Estimates and the 95% CI of the effect on 305-d milk, fat, and protein yield, using the early (n = 9,680) or late (n = 9,487) scoring period mobility score and BCS as predictor variables

	Early scoring period[2]						Late scoring period[3]					
	Milk (kg)		Fat (kg)		Protein (kg)		Milk (kg)		Fat (kg)		Protein (kg)	
Item[1]	Estimate	CI	Estimate	CI	Estimate	CI	Estimate	CI	Estimate	CI	Estimate	CI
Intercept	6,500.8***	6,246.7 to 6,755.0	254.0***	243.0 to 265.0	211.8***	202.8 to 220.9	5,893.0***	5,622.5 to 6,163.8	239.5***	227.6 to 251.4	188.4***	178.8 to 198.1
MOS 1[4]	29.8†	1.6 to 58.0	0.9	−0.3 to 2.2	1.1†	0.1 to 2.0	68.3***	40.3 to 96.4	2.5***	1.3 to 3.8	2.1***	1.2 to 3.1
MOS 2	−102.2*	−171.2 to −33.1	−1.3	−4.3 to 1.7	−4.5**	−6.9 to −2.1	−18.4	−72.0 to 35.1	1.1	−1.3 to 3.5	−1.6	−3.4 to 0.3
MOS 3	−298.6**	−453.4 to −143.9	−6.4	−13.3 to 0.4	−9.6**	−15.0 to −4.3	−356.4***	−492.4 to −220.4	−13.1***	−19.2 to −7.1	−14.8***	−19.5 to −10.1
BCS = 3[5]	2.3	−28.6 to 33.2	−0.2	−1.6 to 1.1	0.1	−0.9 to 1.2	−7.7	−38.2 to 22.8	0.4	−1.0 to 1.7	0.4	−0.6 to 1.5
BCS >3	−41.5†	−79.6 to −3.3	−0.5	−2.1 to 1.2	−2.1**	−3.4 to −0.8	−186.5***	−224.0 to −149.0	−7.2***	−8.8 to −5.5	−4.9***	−6.2 to −3.6
Parity 2[6]	974.2***	937.8 to 1,010.6	40.0***	38.4 to 41.6	38.6***	37.3 to 39.8	970.1***	934.2 to 1,006.0	39.6***	38.1 to 41.2	38.6***	37.3 to 39.8
Parity ≥3	1,629.1***	1,598.5 to 1,659.6	69.7***	68.3 to 71.0	62.1***	61.0 to 63.2	1,619.1***	1,588.5 to 1,649.5	69.2***	67.9 to 70.6	62.0***	60.9 to 63.0
PTA	3.0***	2.9 to 3.1	2.9***	2.8 to 3.0	3.2***	3.1 to 3.3	3.0***	2.9 to 3.0	2.9***	2.8 to 3.0	3.1***	3.0 to 3.2
DIM	4.3***	3.7 to 5.0	0.1***	0.1 to 0.2	0.2***	0.1 to 0.2	4.8***	4.3 to 5.3	0.1***	0.1 to 0.2	0.2***	0.2 to 0.2
Log_{10}SCC	−309.7***	−352.2 to −267.2	−11.3***	−13.2 to −9.5	−9.3***	−10.7 to −7.8	−294.3***	−337.4 to −251.2	−11.2***	−13.1 to −9.3	−8.9***	−10.4 to −7.4

[1]MOS = mobility score (1 = imperfect mobility; 2 = impaired mobility; 3 = severely impaired mobility); PTA = predicted transmitting ability for milk, fat, and protein yield; DIM = number of days in milk at either the early or late scoring period.

[2]Early scoring period refers to MOS recorded during March through May 2015.

[3]Late scoring period refers to MOS recorded during June through November 2015.

[4]MOS 1, 2, and 3 estimates refer to the reference category MOS 0 (good/optimal mobility).

[5]BCS = 3.00 and BCS >3.00 estimates refer to the reference category BCS <3.00.

[6]Parity 2 and parity ≥3 estimates refer to the reference category parity 1.

***, **, *, †Estimate is significantly or tends to be different from 1 ($P < 0.001$, 0.01, 0.05, and 0.10, respectively).

no association with calving interval length. Early scoring period mobility score 3 (severely impaired mobility) had no association with calving interval length, whereas late scoring period mobility score 3 was significantly associated with an increase in calving interval length by just over 6 d. Both early and late scoring period BCS >3 were associated with a decreased calving interval length, whereas BCS = 3 had no association with calving interval length compared with the reference category, BCS <3. Parity 2 cows (parity 2 in 2015/parity 3 in 2016) were associated with a shorter calving interval during the early scoring period analysis, whereas parity ≥3 had a tendency for an increased calving interval length when compared with parity 1 (parity 1 in 2015/parity 2 in 2016) cows. As the PTA for calving interval length increased (becomes less negative), calving interval length increased.

Cow Death and Cow Slaughter

Model results from the binomial logistic regression models analyzing the association between early and late scoring period mobility score on cow deaths and slaughters are reported in Table 5. All levels of suboptimal mobility (mobility score 1, 2, and 3) during both scoring periods had no significant association with cow deaths. However, all levels of suboptimal mobility during both scoring periods were associated with an increased log odds for a cow to be slaughtered, compared with the reference category of mobility score 0 (good, i.e., optimal mobility). Thus, as mobility score increased, so too did a cow's likelihood of being slaughtered. Early and late scoring period BCS = 3 and BCS >3 were associated with a decreased log odds for cow deaths, whereas early scoring period BCS had no association with cow slaughters, and BCS = 3 and BCS >3 during the late scoring period were associated with a decreased log odds for a cow to be slaughtered compared with BCS <3. Higher parity cows (parity ≥2) also had increased log odds for slaughter during both scoring periods, whereas only parity ≥4 cows had increased log odds for death during both scoring periods. As the PTA for lameness and calving interval increased so too did the log odds for being slaughtered during both scoring periods, whereas the PTA for mortality was not significantly associated with cow deaths or cow slaughters. As stated in the Materials and Methods section, farm was also included in each model as fixed predictor variable, because the model was unable to converge with farm as a random variable. As a result, a small number of farms were significant in both models for cow deaths and cow slaughters, but due to the large number of farms involved in this study the results are not reported in Table 5.

Table 2. Estimates and the 95% CI of the effect of mobility score on log SCC, using the early (n = 9,716) or late (n = 9,575) scoring period mobility score and BCS as predictor variables

	Log SCC			
	Early scoring period[2]		Late scoring period[3]	
Item[1]	Estimate	CI	Estimate	CI
Intercept	5.123***	5.082 to 5.164	5.140***	5.093 to 5.188
MOS 1[4]	0.030***	0.020 to 0.041	0.029***	0.018 to 0.039
MOS 2	0.057***	0.031 to 0.083	0.047***	0.027 to 0.067
MOS 3	0.062†	0.003 to 0.121	0.098**	0.046 to 0.150
BCS = 3[5]	0.002	−0.009 to 0.014	0.002	−0.009 to 0.014
BCS >3	0.001	−0.014 to 0.015	0.012	−0.002 to 0.026
Parity 2[6]	−0.030***	−0.045 to −0.016	−0.034***	−0.048 to −0.019
Parity ≥3	0.096***	0.082 to 0.110	0.092***	0.078 to 0.106
PTA	1.242***	1.174 to 1.311	1.205***	1.136 to 1.273
DIM	−0.000†	−0.001 to 0.000	−0.000*	−0.000 to −0.000
Milk (kg)	−0.000***	−0.000 to −0.000	−0.000***	−0.000 to −0.000

[1]MOS = mobility score (1 = imperfect mobility; 2 = impaired mobility; 3 = severely impaired mobility); PTA = predicted transmitting ability for SCC; DIM = number of days in milk at either the early or late scoring period.

[2]Early scoring period refers to MOS recorded during March through May 2015.

[3]Late scoring period refers to MOS recorded during June through November 2015.

[4]MOS 1, 2, and 3 estimates refer to the reference category MOS 0 (good/optimal mobility).

[5]BCS = 3.00 and BCS >3.00 estimates refer to the reference category BCS <3.00.

[6]Parity 2 and parity ≥3 estimates refer to the reference category parity 1.

***, **, *, †Estimate is significantly or tends to be different from 1 ($P < 0.001$, 0.01, 0.05, and 0.10, respectively).

	Antilog of log SCC model			
	Early scoring period[2]		Late scoring period[3]	
Item[1]	EMM	SE	EMM	SE
MOS 0	84,947	3,057	85,616	2,824
MOS 1	91,080	3,382	91,491	3,130
MOS 2	96,894	4,857	95,398	3,990
MOS 3	98,030	8,794	107,375	8,495

DISCUSSION

Milk, Fat, and Protein Production Performance

This analysis has identified an association between mobility score 2 (impaired mobility), mobility score 3 (severely impaired mobility), and reduced milk and protein 305-d yields during the early scoring period, and an association between mobility score 3 and reduced milk, fat, and protein yields during the late scoring period, compared with cows with mobility score 0 (optimal mobility) in a spring-calving, pasture-based system. However, there was no significant association between milk, fat, or protein yield, and mobility score 2 during the late scoring period, which could suggest that a cow with a mobility score 2 during the late scoring period (later in the lactation) has less potential to affect the yield for the lactation compared with a cow with a mobility score of 2 during the early scoring period (earlier in the lactation). Yield losses, specifically fat and protein yield losses, are of particular importance in milk production systems in Ireland as this is the basis for how farmers are paid for their milk (Geary et al., 2010); however, literature on the association between suboptimal mobility and fat and protein yield are less available. Many studies have reported on production losses (specifically milk yield) associated with lame cows, but focused on confinement type systems (Bicalho et al., 2008); wherein cows are housed all of the time, year-round calving, pasture-based systems (Archer et al., 2010); wherein calving pattern is not synchronized with feed demand, with cow grazing occurring when possible, and autumn calving, pasture-based systems (Green et al., 2002); wherein cows calving during the autumn months, with cows grazing occurring when possible. The comparison of the yield losses associated with impaired and severely impaired mobility in our study to the yield losses reported in other studies, requires consideration of the methods of data collection

Table 4. Estimates and the 95% CI of the effect of mobility score on calving interval, using the early (n = 8,599) or late (n = 8,500) scoring period mobility score and BCS as predictor variables

	Calving interval			
	Early scoring period[2]		Late scoring period[3]	
Item[1]	Estimate	CI	Estimate	CI
Intercept	347.55***	344.29 to 350.79	279.17***	273.55 to 284.75
MOS 1[4]	0.70	−0.27 to 1.68	0.82	−0.15 to 1.80
MOS 2	3.67*	1.21 to 6.13	1.34	−0.61 to 3.28
MOS 3	5.68	−0.07 to 11.44	6.08*	1.05 to 11.1
BCS = 3[5]	−0.78	−1.84 to 0.27	−0.46	−1.53 to 0.61
BCS >3	−1.77*	−3.12 to −0.43	−2.12**	−3.43 to −0.82
Parity 2[6]	−1.62*	−2.87 to −0.37	−1.14	−2.38 to 0.10
Parity ≥3	0.84	−0.21 to 1.88	1.19†	0.14 to 2.24
PTA	0.49***	0.26 to 0.72	0.49***	0.25 to 0.73
DIM	0.59***	0.57 to 0.61	0.61***	0.59 to 0.63

[1]MOS = mobility score (1 = imperfect mobility; 2 = impaired mobility; 3 = severely impaired mobility); PTA = predicted transmitting ability for calving interval length; DIM = number of days in milk at either the early or late scoring period.

[2]Early scoring period refers to MOS recorded during March through May 2015.

[3]Late scoring period refers to MOS recorded during June through November 2015.

[4]MOS 1, 2, and 3 estimates refer to the reference category MOS 0 (good/optimal mobility).

[5]BCS = 3.00 and BCS >3.00 estimates refer to the reference category BCS <3.00.

[6]Parity 2 and parity ≥3 estimates refer to the reference category parity 1.

***, **, *, †Estimate is significantly or tends to be different from 1 ($P < 0.001$, 0.01, 0.05, and 0.10, respectively).

Table 5. Odds ratios and the 95% CI for the binomial logistic regression models used to predict cow death and cow slaughter interval, using the early (n = 9,955) or late (n = 9,628) scoring period mobility score and BCS as predictor variables[1]

	Cow death or slaughter							
	Early scoring period[3]				Late scoring period[4]			
	Death		Slaughter		Death		Slaughter	
Item[2]	Odds ratio	95% CI	Odds ratio	95% CI	Odds ratio	95% CI	Odds ratio	95% CI
Intercept	0.02***	0.00–0.06	0.11***	0.07–0.18	0.01***	0.00–0.03	0.36**	0.20–0.62
MOS 1[5]	1.05	0.85–1.3	1.16*	1.04–1.29	1.04	0.82–1.31	1.17*	1.05–1.3
MOS 2	1.12	0.71–1.69	1.49**	1.18–1.86	0.88	0.57–1.32	1.58***	1.32–1.9
MOS 3	0.46	0.11–1.31	3.97***	2.55–6.22	1.12	0.41–2.52	3.46***	2.23–5.35
BCS = 3[6]	0.66**	0.51–0.84	0.85*	0.75–0.96	0.64**	0.5–0.82	1.06	0.94–1.19
BCS >3	0.49***	0.35–0.66	1.26**	1.09–1.45	0.48***	0.34–0.66	1.12	0.97–1.30
Parity 2[7]	0.77	0.54–1.07	1.29*	1.09–1.52	0.89	0.6–1.29	1.33**	1.13–1.58
Parity 3	1.03	0.75–1.41	1.68***	1.43–1.98	1.16	0.8–1.65	1.76***	1.49–2.08
Parity 4	1.51*	1.07–2.12	2.82***	2.38–3.35	1.79*	1.22–2.59	2.7***	2.26–3.23
Parity 5	2.08***	1.47–2.92	3.25***	2.71–3.9	2.49***	1.7–3.64	3.23***	2.67–3.91
Parity ≥6	2.59***	1.91–3.53	6.68***	5.68–7.87	3.49***	2.48–4.93	6.37***	5.37–7.57
Mortality PTA	0.99	0.78–1.24	0.97	0.86–1.09	0.97	0.75–1.24	0.96	0.85–1.09
Lameness PTA	4.00	0.10–162.69	64.86***	9.78–430.24	1.23	0.02–74.59	42.14**	5.98–296.9
CIN PTA	1.01	0.96–1.06	1.03*	1.01–1.06	1.00	0.95–1.05	1.03*	1.01–1.06
DIM	0.99*	0.99–1.00	0.99***	0.99–0.99	1.01*	1.00–1.01	0.99***	0.99–0.99

[1]Several farms were significant as fixed effect predictor variables.

[2]MOS = mobility score (1 = imperfect mobility; 2 = impaired mobility; 3 = severely impaired mobility); mortality PTA = predicted transmitting ability for cow death, lameness PTA = predicted transmitting ability for lameness; CIN PTA = predicted transmitting ability for calving interval length; DIM = number of days in milk at either the early or late scoring period.

[3]Early scoring period refers to mobility scores recorded during March through May 2015.

[4]Late scoring period refers to mobility scores recorded during June through November 2015.

[5]MOS 1, 2, and 3 estimates refer to the reference category mobility score 0 (good/optimal mobility).

[6]BCS = 3.00 and BCS >3.00 estimates refer to the reference category BCS <3.00.

[7]Parity 2, parity 3, parity 4, parity 5, and parity ≥6 estimates refer to the reference category parity 1.

***, **, *Odds ratio is significantly different from 1 ($P < 0.001$, 0.01, and 0.05, respectively).

and the way in which lameness is defined. First, the methods of data collection can vary from lame cows being pre-selected by farmers followed by diagnosis by a veterinarian (Green et al., 2002), to the method of data collection implemented in the present study whereby all cows were mobility scored without any preselection. Second, defining or classifying lameness can also vary significantly between studies. For example, using the 5-point scale developed by Sprecher et al. (1997), a cow is defined as lame when she had a score ≥3; however, using the same scoring method Olechnowichz and Jaskowski (2015) defined a cow as lame when she had a score ≥2, and Kovács et al. (2015) only referred to a cow as lame when her score was ≥4.

Hence, in our study, we only refer to varying levels of suboptimal mobility (mobility score 1, 2, and 3) and optimal mobility (mobility score 0) as defined by the UK Agriculture and Horticulture Development Board 4-point scale (https://dairy.ahdb.org.uk/technical-information/animal-health-welfare/lameness/husbandry-prevention/mobility-scoring/#.WXnhULuFOr8; accessed December 16, 2017).

In our study, milk yield losses of about 350 kg for a 305-d lactation were associated with cows with severely impaired mobility (mobility score 3) during the late scoring period. This result is comparable to the results of Archer et al. (2010), reporting milk yield losses of up to 350 kg for 305-d lactation associated with severely lame cows, using the same mobility scoring method. The study of Hernandez et al. (2002), however, reports much greater yield losses, with lame cows producing about 850 kg less milk compared with non-lame cows when referring to the mean yield. The relatively greater yield loss reported by Hernandez et al. (2002) could most likely be due to differences in production systems and that cows were milked 3 times per day, whereas cows in the present study were milked twice per day. Comparable results between our study and the study of Archer et al. (2010) were evident despite the slightly higher average milk yields in the study of Archer et al. (2010). Archer et al. (2010) reported that severely lame cows (equivalent to severely impaired cows in the present study) failed to achieve their potential 305-d milk yield, but that progressive yield losses did not occur until 4 mo after lameness was detected. This implies that the use of test day yield depending on the milk recording system and frequency and a lameness event relative to a milk recording event can result in suboptimal mobility having a poor association with test day milk yield. Daily milk yield allows for more prompt identification of yield losses; however, this type of data is rarely collected on commercial farms, therefore depending on the level of milk recording (i.e., every 4, 8, or 12 wk), the lameness event and its effects may be more difficult to pick up. In research settings wherein data are collected daily or for a full lactation setting, both the direct and indirect effects are captured across the lactation. However, it could also be a limitation of the present study having analyzed the effect of mobility score on an entire lactation using just 2 mobility scores per cow, whereby other events between both scoring periods could have been missed in the analysis. The reasoning for using just 2 mobility scores used in the present study was simply due to the large number of farms included in this study and the time availability of the technicians, which resulted in 2 measurements of both mobility score and BCS collected for each cow. Figures 1(a) and 1(b) illustrate the distribution of each mobility score for both scoring periods.

In our study there was a tendency for increased milk and protein yield associated with cows scored as mobility score 1 during the early scoring period and significantly increased milk, fat, and protein yield in cows scored as mobility score 1 during the late scoring period. Mobility score 1 (imperfect mobility) is a mild deviation from optimal gait; thus, we hypothesized that cows scored as mobility score 1 in our study could be comparable to what is often not included in the lame category throughout the literature, because mobility score 1 cows have imperfect mobility, thus are more difficult to identify by the untrained eye. Higher yielding cows being associated with lameness have been reported on throughout the literature (Green et al., 2002: Amory et al., 2008; Archer et al., 2010). The increase in yield reported in the present study associated with mobility score 1 is relatively small throughout the entire lactation in comparison to the reported increase reported, for example, by Green et al. (2002). Green et al. (2002) found that lame cows were associated with a higher milk yield by up to 342 kg over a 305-d lactation, whereas in the present study, mobility score 1 cows were associated with a higher milk yield by just 68 kg over a 305-d lactation (~1% increase in yield throughout the lactation). The mean 305-d yield in the present study (6,400 kg) is similar to that reported by Green et al. (2002). However, a key difference (other than type of system) is the use of repeated measures and specific test day record yields as the outcome variables by Green et al. (2002), whereas in the present study the average lactation yield was used as the outcome variable. The increase in yield reported by Green et al. (2002) is much greater compared with the reported yield in the present study. This difference could be explained by the difference in the type of data collected and analyzed in both studies, or could be due to the inclusion of a correction for a genetic predisposition for higher yields, by including each cow's PTA for milk, fat, and protein in our analysis, which was not included in the study of Green et al. (2002).

Regardless, the results of our study showing that early scoring period mobility score 2 is negatively associated with yield highlights the importance of regular mobility scoring on farm by trained professionals. Routine mobility scoring of entire herds, however, is quite labor intensive, thus automated sensor technology is needed to facilitate the identification of problem cows (specifically mobility score 1 cows that may progress to mobility score 2 or 3) at an earlier stage (Schlageter-Tello et al., 2018). Perhaps if farmers had regular updates of each cow's mobility score, it would be easier to identify mobility score 1 cows before they possibly progress to a more severe state of suboptimal mobility, which would also facilitate earlier treatment (Leach et al., 2012) and reduce the potential yield losses from occurring.

Somatic Cell Count

This study reports on elevated SCC on the $\log_{10}$ scale associated with suboptimal mobility (mobility score 1, 2, and 3) during both scoring periods, except for a tendency for elevated SCC for mobility score 3 cows during the early scoring period. The tendency reported in Table 2 could be explained by the relatively lower number of cows scored as mobility score 3 in the present study and the large variation in SCC among this group. As reported in the untransformed SCC scale in Table 3, however, cows with suboptimal mobility have higher SCC compared with cows with optimal mobility during both the early and late scoring periods. A biological explanation for the association between suboptimal mobility and elevated SCC could potentially be explained using the findings of Navarro et al. (2013) and Walker et al. (2008). Navarro et al. (2013) reported that lame cows (defined as cows scored as locomotion score 3 using the Sprecher et al., 1997 scale) stood on average for shorter periods compared with non-lame cows. The implied increased lying time potentially increases the risk of exposure to pathogens at the teat end. The study of Walker et al. (2008) confirms that lame cows do spend more time lying down. Another possible explanation for the association between elevated SCC and suboptimal mobility reported in the present study could be due to an immune response of cows with suboptimal mobility. O'Driscoll et al. (2015) identified a higher neutrophil percentage in lame cows compared with sound cows, and lame cows tended to have a higher neutrophil:lymphocyte ratio compared with sound cows. In the study of O'Driscoll et al. (2015), a lame cow was referred to as a cow with an obvious impairment of one or more limbs specifically due to sole ulcers, which have been shown to be associated with suboptimal mobility by O'Connor et al. (2019). The higher neutrophil:lymphocyte percentage found by O'Driscoll et al. (2015) associated with lame cows has been previously described in animals experiencing stress (Fell et al., 1999) and in cows with an increased genetic susceptibility for disease (Kulberg et al., 2002).

Calving Interval

It has been demonstrated in a review paper by Huxley (2013) that lameness negatively affects a wide range of measures of reproductive performance. To the best of our knowledge, the present study is the first to identify an increased calving interval length associated with specific mobility scores. Our study reports on the association between mobility score 2 during the early scoring period, and mobility score 3 during the late scoring period, with an increased calving interval length. Cows with a mobility score 3 during the early scoring period, however, were not significantly associated with an increased calving interval length, which could be a result of the relatively lower number of mobility score 3 cows. Similarly, cows with a mobility score 2 during the late scoring period were also not significantly associated with an increased calving interval, which could be explained by the fact that cows with a mobility score 2 during the late scoring period may have had optimal mobility during the early scoring period when they became pregnant. The findings of other studies compliment ours by reporting on longer calving intervals associated with the presence of sole ulcers (Hultgren et al., 2004), heel-horn erosions, and sole hemorrhages (Sogstad et al., 2006), which are all types of claw disorders shown to be associated with suboptimal mobility (O'Connor et al., 2019). Other factors linked to calving interval length have also been reported throughout the literature, with Sprecher et al. (1997) and Hernandez et al. (2001) reporting an increased number of days from calving to first service and from calving to conception for lame cows. The aim in spring-calving, pasture-based systems is to synchronize grass growth with nutrient requirements, thus calving pattern is used to synchronize feed supply and feed demand of the herd with the seasonal pattern of grass growth (Shalloo et al., 2014). Therefore, in such systems the calving pattern and the length of the calving interval is a key indicator of efficiency at the farm level and deviations from the seasonal pattern can result in various types of losses.

Cow Death and Slaughter

The effect of lameness on culling has been reported frequently throughout the literature, with the majority of published work reporting an association between lameness and increased risk to be culled. Booth et al. (2004) reports on the association between lameness and culling where culling refers to both cow deaths on farm and cow slaughters, whereas McConnel et al. (2008) reports on the association between lameness and cow mortality (cow deaths on farm). Sprecher et al. (1997) reports an association between lameness and culling. In the present study we analyzed cow deaths on farm and cow slaughters separately. We found no association between mobility score and cow deaths, which we expected because it is assumed that cows would be culled (sold) before succumbing to a severe enough state of lameness that they could die on farm. However, we identified an increased risk to be slaughtered associated with cows with suboptimal mobility (mobility score 1, 2 and 3) compared with cows with optimal mobility (mobility score 0). From this finding, we hypothesize that if there were a substantial proportion of cows with suboptimal mobility within a herd, this could potentially be associated with increased herd-level culling. Increased herd-level culling implies a requirement for an increase in replacement heifers in the herd or lower rates of expansion if this is what was happening on farm. Higher culling rates in herds would result in a younger age profile than is optimum and thus less potential for voluntary culling. The possibility of increased culling of cows within a herd due to suboptimal mobility also has the potential to reduce overall herd yield, due to milk yield being dependent on parity, whereby first parity cows produce less milk than mature cows (Hutchinson et al., 2013). However, it is important to note that the decision to cull a cow is a complex one in which many more factors are considered, including yield, gestation status, and even SCC levels, which were not analyzed for their association with culling in this study.

CONCLUSIONS

Our study shows that suboptimal mobility in spring-calving, pasture-based systems has negative associations with production (milk, fat and protein yield, and SCC) and reproductive performance (calving interval length), as well as being associated with a higher risk for premature culling. The results of the current study are in agreement and comparable with other dairy management systems, such as confinement type systems and year-round calving, pasture-based systems. Spring-calving, pasture-based systems are based on low inputs and low outputs where cost control is paramount to the success of the system; therefore, preventable losses associated with suboptimal mobility have significant economic impacts, despite the prevalence of suboptimal mobility in such systems being relatively lower.

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