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Associations among body energy status, feeding duration and activity with respect to diet energy and protein content in housed dairy cows

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Abstract

The study in this research paper was undertaken with a hypothesis that accelerometer data can be used to improve monitoring of energy balance in dairy cows. Animals of high (select, S) and average (control, C) genetic-merit lines were allocated to two feeding systems, by-product (BP) and homegrown (HG). This culminated in four production systems referred to as BPS, BPC, HGS and HGC. Cows between their first and fourth lactations were included and a total of 8602 records were used. The target crude protein (CP) and metabolisable energy (ME) content in the BP diet was 185 g/kg DM and 12.3 MJ/kg DM while it was 180 g/kg DM, and 11.5 MJ/kg DM for the HG diet, respectively. Milk yield, body energy content (BEC) and animal activity were monitored while the animals were all housed for winter. Results showed that cows on homegrown feeds were significantly ($P < 0.05$) more active than cows on by-product feeds as indicated by higher motion index and number of steps per day. Feeding duration was not significantly different ($P > 0.05$) between cows under by-product feeding system irrespective of the energy balance of the cows. However, there were significant differences for cows under homegrown feeding system. Cows in negative energy balance had a longer feeding duration per day than cows in positive energy balance. Milk yield was negatively correlated ($P < 0.05$) to motion index and number of steps per day but not to lying time and feeding duration. The results showed differences in cow activity were related to diet content and body energy status. This is useful in precision farming where feeds are provided according to specific animal behaviour and feed requirements.

Increased interest in precision agriculture and use of monitoring equipment on farms necessitates an in-depth understanding between the available data, animal biology and environmental factors. Monitoring of energy balance is an important aspect of dairy cow production. High producing cows are usually unable to consume adequate feed to meet the requirements for maintenance and milk production during early lactation (Patton *et al.*, 2007; Weber *et al.*, 2013). Hence, during this period cows mobilise energy from body fat which leads to negative energy balance (NEB) and loss of body condition. Early lactation energy deficit is normal in many mammals, however, in cattle rapid losses or prolonged periods of body energy deficit have negative effects on milk yield, cow health and reproduction (Chagas *et al.*, 2007; Leroy, *et al.*, 2008; Aguilar-Perez *et al.*, 2009). It is, therefore, important to monitor energy balance in order to ensure appropriate management of dairy cows.

Energy balance may not be directly measurable on farm but is usually monitored through change in body condition score (BCS: Roche *et al.*, 2009; Friggens *et al.*, 2010). The NEB that occurs during early lactation is reflected through BCS loss (Pryce *et al.*, 2001). Besides BCS change, energy balance can be estimated based on changes in body weight and BCS (NRC, 2001; Banos *et al.*, 2006) or based on the differences between energy intake and energy requirements for maintenance and milk production (Patton *et al.*, 2007; Aguilar-Perez *et al.*, 2009). Proxy measures such as BCS are useful for quick on farm assessment, however, estimates of actual energy balance are necessary for a better understanding of physiological changes.

Traditionally, accelerometers have been used to detect oestrus using within-animal variation in activity (Firk *et al.*, 2002; Lovendahl & Chagunda, 2010; Palmer *et al.*, 2010). Monitoring cow activity has also been used to study animal behaviour in relation to health and welfare status (O'Callaghan *et al.*, 2003; Barrientos *et al.*, 2011; Thorup *et al.*, 2015). O'Callaghan *et al.* (2003) and Thorup *et al.* (2015) used accelerometers in early detection of lameness while Barrientos *et al.* (2011) linked lying behaviour of dairy cows to presence and absence of deep-bedded stalls. However, if activity data were used across farms, it would be crucial to account for the variation that arises from environmental and other bio-physical factors. An example of this would be the comparison of cow feeding time and feed barrier design in different buildings.

The current study was undertaken to determine the association between energy status and cow activity monitored using accelerometers. This paper explores the use of accelerometer data to improve monitoring of energy balance in dairy cows and examines the interaction of three factors; cow energy status, energy content of ration and cow genetic merit.

Materials and methods

Data were obtained from a database available at Scotland's Rural College (SRUC) Dairy Research and Innovation Centre, Crichton Royal Farm, Dumfries, Scotland which was compiled as part of a long-term Langhill herd genotype by environment study. The herd consisted of Holstein Friesian cows from two genetic lines (Select (S) and Control (C) selected based on genetic merit for kilograms milk fat plus protein. Experimental design of the long-term study has previously been described in detail by Pryce *et al.* (1999), Chagunda *et al.* (2009) and Ross *et al.* (2014). The experiments were carried out in accordance with the U.K. Animals (Scientific Procedures) Act, 1986 and associated guidelines and was approved by SRUC Animal Experiments Committee.

Strict management protocols were operated both within and between systems. Cows were housed in the same building and managed by the same staff. Within a system, one complete diet was offered to all cows irrespective of milk yield and stage of lactation. The complete diet was offered at 1.05% of daily requirement and refusals removed daily. The diets had target crude protein (CP) and metabolisable energy (ME) content of 185 g/kg DM and 12.3 MJ/kg DM for the BP diet while it was 180 g/kg DM, and 11.5 MJ/kg DM for the HG diet, respectively. Table S1 in the online supplementary file provides details on the feed chemical composition of rations and target milk production.

Animals within S and C genetic lines were allocated to two different feeding systems, namely, by-product (BP) and a home-grown feeding systems (HG), making four experimental groups comprising two production systems (BP and HG) and within each feeding system two genetic lines (S and C). The four experimental groups constituted the four production systems herein referred to as BPS, BPC, HGS and HGC. Each production system was comprised of approximately 50 cows in their first 3 lactations. At the end of their third lactation the cows were replaced by heifers due to calve within 2 months. If there were no suitable replacements then cows remained on the system for an additional lactation (Roberts and March, 2013).

Data recording and management

Data collected between December 2012 and February 2013 were retrieved from the SRUC Langhill database using the Microsoft SQL Server Management Studio 2008. The total period used was three months during which time all the cows were housed for winter. Cows included had at least 21 d from which daily activity and eating time were recorded. A total of 8602 records from 124 cows between their first and fourth lactations were available for analysis. Cows in their first, second and third or more lactation accounted for 34, 31 and 35% of the study population, respectively. There were 33, 37, 31 and 23 cows from BPC, BPS, HGC, and HGS, respectively.

Herd management followed strict disease control management where vaccination and routine treatments such as deworming and hoof trimming were followed. There were also on-going checks for mastitis and infected animals were treated accordingly. All vaccinations and treatments were carried out by qualified veterinary surgeons or experienced farm staff. A veterinary surgeon visited the farm on a weekly basis for routine veterinary work, mainly related to fertility. If required, the veterinary surgeon would also visit the farm within an hour to attend to difficult calvings or other urgent veterinary issues. Routine foot-trimming was once every 6 months and cows walked through a footbath containing copper sulphate twice a week. Severely lame animals were examined as soon as possible by the head dairyman otherwise the veterinary surgeon visited fortnightly and cows locomotion scored 4 and above were walked around an enclosure and those considered lame were examined and any findings recorded and loaded to the database. The locomotion score was on a scale of 1–5. Sick animals were isolated and kept in a sick bay where they received treatment and were returned to the feeding groups upon recovery. Hence, the data used in this study are from cows that were considered healthy.

The data collected included animal identification, genetic group, feeding system and lactation number as well as calving date, milk yield, weights and body condition score (BCS), activity and feeding duration. Milk yields of individual cows were recorded at each milking and individual cow milk samples taken weekly for analysis of fat, protein and somatic cell contents. Live weights were measured after each milking. Body condition score was estimated weekly using the tail head system with a score of between 0 and 5 (with 0 being thinnest and 5 the fattest) (Mulvaney, 1977). The individual feed and water feed intake was recorded on 3 d out of six using Hoko gates (Insentec BV, Marknesse, The Netherlands). Individual time budgets (weekly averages of duration of lying and standing, motion index, number of steps and lying bouts) were monitored in cows using accelerometers (IceQube Sensors®, Icerobotics Ltd, UK).

Weekly body energy content (BEC) was calculated using weights and body condition score according to formulae described by Banos *et al.* (2006) as summarised in the online Supplementary file. Energy corrected milk yield was calculated using the formula reported by Sjaunja *et al.* (1990) given as:

$$\text{Kg ECM} = \text{kg milk} \times (0{:}25 + 0.122 \times \text{Fat \%} + 0.077 \times \text{Protein \%})$$

Data analysis

Data were analysed using descriptive statistics, crosstabs, frequencies and mixed models using Statistical Analysis System (SAS 9.3). All data on milk yield, fertility, body energy content (BEC), motion index, number of steps, standing, lying and feeding durations were subjected to the generalised mixed linear model (GLIMMIX) procedure of SAS 9.3 where differences in the response variables were determined between the feeding systems, genotypes and other management practices. The normally distributed data on milk yield were analysed using generalised mixed linear models (GLMM) with a normal error distribution and a log link function, while the data on activity and BEC were analysed using GLMM with negative binomial error distribution and a logit link function. A negative binomial error distribution was opted for in the count data analysis as a Poisson error distribution resulted in over-dispersion. Spearman correlation analysis was used to determine the relationship between milk yield, BEC, cow activity and feeding duration.

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Results

The results showed that there were differences in productivity, energy status and activity of the cows associated with feeding system as well as genotype. Cows on by-product feeding system had significantly ($P < 0.05$) higher average daily milk yield and body energy content (BEC) than cows on home-grown feeding system (Table 1). Both within the by-product and home feeding systems, there was significant difference in milk yield between select (higher yield) and control cows. However, there was no significant difference in energy corrected milk yield (ECM) between control cows on by-product diet and select cows fed home grown feeds. This suggests that control cows were able to mobilise energy from by-product diet which had relatively higher energy similar to select cows on home-grown feed. The results can be related to the higher ($P < 0.05$) feed intake by select cows on home grown diet compared to control cows on by-product diet. This higher feed intake probably enabled mobilisation of energy similar to the control cows on by-product feed. Cows on by-product diet generally had lower feed intake and higher BEC than cows on homegrown diet (Table 1).

Although select cows on by-product diet and control cows on homegrown diet had similar BEC, their milk yield was significantly different suggesting that select cows on by-product diet had the ability to mobilise more nutrients towards milk production than control cows on homegrown diet. This is further confirmed by the fact that control cows on homegrown diet had similar BEC compared to select cows on the same diet, but there was a significant difference ($P < 0.05$) in their milk yield. This is most likely demonstrating the interaction between feeding system and genotype.

Cow activity varied with the feeding system used. Cows on home grown feeds were significantly ($P < 0.05$) more active than cows on by-product feeds as indicated by higher motion index and number of steps per day (Table 1). Within feeding systems, high genetic merit cows were more active than average genetic merit cows. All the cows had a similar number of lying bouts as well as a similar minimum lying bout duration. However, cows on by-product feeds had significantly ($P < 0.05$) longer duration of maximum lying bouts (2.47 h) than cows on home grown feeds (2.03 h). Cows on home grown feeds also stood almost 1 h longer than those on by-product feeds for both genetic groups. The activity data compared well with feeding duration data, where cows on home grown feeds also spent more time feeding than cows on by-product feeds. However, there was no significant difference in the feeding time between select and control cows on by-product and homegrown diets, respectively. This aspect was also reflected in that these cows had similar average daily BEC content.

Production system had an effect on energy balance, cow activity and milk production. The results showed that the same cows that had negative balance were also those that had high milk yield, while cows in positive energy balance generally had low milk yield. This was the case in both feeding systems (Table 2) However, there was an interaction between feeding system and energy balance with regard to activity and feeding duration. Cows in NEB on the by-product feeding system were significantly less active than cows in positive energy balance (PEB) while on home-grown feeding systems all cows had similar activity. Control cows on by-product diet that were in NEB had longer feeding duration (4.9 h) than the same cows in PEB (4.2 h). Select cows on homegrown diet that were in NEB had a shorter duration (5 h) of feeding than the same cows in PEB (6 h).

Generally, cow activity, energy status and feeding durations varied widely within production systems as evidenced by coefficients of variation ranging from 38 to 49%. This may suggest that there were other differences in cow activity, energy balance and feeding duration associated with individual cows within systems. Correlation analysis showed that both milk yield and BEC were significantly positively correlated to some aspects of cow activity and feeding duration ($P < 0.05$, Table 3). Milk yield was significantly correlated with motion index and number of steps per day but not lying time and feeding duration. There was a negative correlation between milk yield and motion index as well as number of steps per day. This implies that cows with higher milk yield were less active than cows with lower milk yield. There was no significant correlation between milk yield and feeding duration and this could reflect the interaction between genetic merit and milk yield. Regardless of feeding duration and BEC, select cows seemed to maintain higher milk yield than control cows. It is likely that select cows were able to mobilise additional nutrients from body reserves to sustain milk production. This is further reflected in that there was no significant correlation between BEC and milk yield.

BEC was positively and negatively correlated to lying time and feeding duration, respectively. Cows that had longer lying durations had higher BEC than those with shorter lying durations. Cows with higher BEC also had shorter feeding durations. Standing durations were positively correlated with feeding duration indicating that part of the time that cows stood was spent feeding. However, a correlation analysis by feeding system showed some differences in some of the relationships in Table 3. For instance, online Supplementary Tables S2 and S3 show that BEC was negatively correlated with milk yield in cows on by-product diet while it was positively correlated to the same trait in cows on homegrown. This result further shows the interaction between genotype and feeding systems.

Discussion

Both high and average genetic merit cows had distinct and consistent patterns of milk production and activity which were related to the feeding systems. The results showed an interaction between genetic merit and feeding system where cows of average genetic merit fed BP diets with higher crude protein (CP) and ME produced higher milk yields than high genetic merit cows fed HG diets. These results are similar to earlier findings on the same herd by Pollott and Coffey (2008) and other herds (Nielsen *et al.*, 2003; Horan *et al.*, 2005; Windig *et al.*, 2008) and demonstrate that productivity is a function of both genetic merit and feeding systems. Such responses in productivity are related to feeding efficiency which is a ratio of output to intake (Brody, 1945). Apart from feed quality, feed efficiency is also dependent on genotype and physiological state (Blake and Custodio, 1984). The genotype effect is through the genetically determined potential for milk yield as shown by higher milk yields in cows of high genetic merit.

The results also showed an association between production system, energy status and cow activity. HGS were the most active while BPC cows were least active. This could be associated with the quality of the feeds in the systems and the genetic merit of the cows. HG feeds were less dense in terms of metabolisable energy and crude protein than BP feeds. Hence high genetic merit cows on HG spent more time standing and feeding to increase feed intake to match with their high milk production while average genetic merit cows on BP feeds were less active as

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Table 1. Average daily body energy content, milk production and activity of high and average genetic merit cows on either home grown or by-product feeds

Variable	Production system (mean ± SEM)			
	*BPC (*n* = 33)	BPS(*n* = 37)	HGC (*n* = 31)	HGS (*n* = 23)
Milk yield (kg/day)	32.0 ± 0.45a	38.0 ± 0.44b	26.1 ± 0.39c	27.0 ± 0.49d
ECM (kg/day)	27.4 ± 0.40a	35.7 ± 0.38b	24.9 ± 0.39c	26.8 ± 0.45a
Feed intake (kg/day)	41.2 ± 0.28a	44.5 ± 0.35b	49.5 ± 0.54c	49.7 ± 0.66c
BEC (MJ/day)	4902 ± 144[a]	4356 ± 149[b]	4284 ± 173[bc]	3938 ± 103[c]
No of steps/day	1336 ± 25[a]	1324 ± 46[a]	1644 ± 62[b]	1612 ± 50[b]
Motion index/day	5028 ± 105[a]	4900 ± 153[a]	6204 ± 249[b]	6125 ± 221[b]
Lying duration (hrs)	11.10 ± 0.29[a]	11.39 ± 0.26[a]	10.44 ± 0.25[b]	10.36 ± 0.33[b]
Standing duration (hrs)	12.90 ± 0.29[a]	12.61 ± 0.25[a]	13.54 ± 0.25[b]	13.63 ± 0.33[b]
No. of lying bouts/day	10.1 ± 0.5	10.9 ± 0.4	10.6 ± 0.4	10.5 ± 0.5
Minimum lying bout (hrs)	0.25 ± 0.02	0.22 ± 0.01	0.20 ± 0.01	0.22 ± 0.02
Maximum lying bout (hrs)	2.47 ± 0.09[a]	2.42 ± 0.08[a]	1.97 ± 0.06[b]	2.03 ± 0.08[b]
Feeding duration (hrs/day)	4.39 ± 0.32[a]	4.83 ± 0.34[ab]	5.05 ± 0.37[b]	5.13 ± 0.54[b]

[a,b]Means with different superscripts within the same row are significantly different ($P < 0.05$); *BPC, by-product control; BPS, by-product select; HGC, home-grown control; HGS, home-grown select; ECM, energy corrected milk; BEC, body energy content.

Table 2. The cow activity and milk yield of cows in positive and negative energy balance in high and average genetic merit cows on either home grown or by-product feeds

	By-product feeding system				Home-grown feeding system			
	Positive energy balance		Negative energy balance		Positive energy balance		Negative energy balance	
Variable	BPC	BPS	BPC	BPS	HGC	HGS	HGC	HGS
Number of steps	1404 ± 32[a]	1535 ± 17[b]	1242 ± 43[c]	1384 ± 115[ac]	1542 ± 72[b]	1298 ± 178[ac]	1668 ± 73[b]	1517 ± 64[b]
Motion index	5330 ± 88[a]	5841 ± 132[b]	4694 ± 135[c]	4723 ± 122[c]	5874 ± 369[bd]	5779 ± 680[bd]	6187 ± 192[d]	5911 ± 143[bd]
Standing duration (hrs)	12.1 ± 0.3[a]	12.5 ± 0.4[a]	12.3 ± 0.4[a]	12.6 ± 0.3[a]	13.5 ± 0.5[b]	12.9 ± 0.3[b]	11.3 ± 0.4[c]	13.0 ± 0.6[b]
Feeding duration (hrs)	5.3 ± 0.5[a]	5.8 ± 1.4[ab]	5.1 ± 0.5[a]	5.2 ± 0.2[a]	4.4 ± 0.3[b]	4.1 ± 0.1[c]	6.9 ± 0.6[d]	4.5 ± 0.1[b]
Daily milk yield (litres)	22.4 ± 0.7[a]	31.1 ± 1.6[b]	26.6 ± 1.6[c]	34.1 ± 0.7[d]	17.8 ± 1.0[e]	24.7 ± 0.2[f]	26.2 ± 1.2[c]	28.1 ± 0.5[g]

[a,b]Means with different superscripts within the same row are significantly different ($P < 0.05$); *BPC = by-product control; BPS = by-product select; HGC = home-grown control; HGS = home-grown select

Table 3. Correlation between milk yield, body energy content, cow activity and feeding duration in dairy cows under home grown and by-product feeding systems

Productivity factors and correlation coefficients						
	Milk yield (litres/day)	Body Energy Content (MJ//day)	No of steps/day	Motion index/day	Lying duration (hrs/day)	Standing Duration (hrs/day)
Body Energy Content (MJ/day)	−0.008 (0.931)					
No of steps/ day	−0.468 (<0.0001)	−0.115 (0.205)				
Motion index	−0.486 (<0.0001)	−0.056 (0.5416)	0.909 (<0.0001)			
Lying duration (hrs/day)	−0.109 (0.229)	0.198 (0.028)	−0.172 (0.057)	−0.052 (0.564)		
Standing duration (hrs/day)	0.113 (0.215)	−0.195 (0.030)	0.169 (0.062)	0.049 (0.588)	−0.9997 (<0.0001)	
Feeding duration (hrs/day)	−0.062 (0.498)	−0.302 (0.0007)	0.293 (0.001)	0.216 (0.0165)	−0.198 (0.028)	0.198 (0.028)

Figures within parentheses show the *P* value.

their feed quality was better and milk production relatively lower. However, there was no significant difference in time spent standing and lying. Heublein *et al.* (2017) found similar results in dairy cattle in pasture-based systems where cows that are supplemented with concentrates are less active than those that are solely on pasture.

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The results showed that there were differences in cow activity that could be attributed to body energy status. Cows fed diets with relatively lower ME and CP were more active and spent more time standing and eating than those on diets with higher ME and CP. Although ME and CP levels were different, these differences may not have been large in relation to much wider differences that exist in different production systems. However, the diets represent two different acceptable feeding levels that demonstrate that accelerometers can potentially detect and be used to appropriately address subtle management differences. This suggests, therefore, that when such a technology is used as a tool for management it may be able to quickly detect even more adverse problems that may otherwise take too long to detect using conventional management techniques.

The high activity may also imply that the cows were restless. Their greater activity was probably to increase feed intake to counter negative energy balance. Hence, there is an association between energy status and cow activity that could be determined using accelerometers. There is need for further analysis to investigate more details on cow activity in terms of time budgets such as feeding bouts and their durations. This may be useful in precision farming where feeds may need to be provided in accordance with specific animal behaviour and requirements.

In conclusion, the implication of the findings is that activity monitoring can be used beyond oestrus detection and animal welfare management to include diet quality and body energy status. When setting up the baseline activity for each cow, there may be a need to account for the cow's feeding system. Secondly, if cow activity is being used to evaluate building design then feed system, milk yield and the general well-being of the animals all need to be considered. This could be achieved through either having integrated or complementary technologies. For example, a combination of data from cow activity meters and BCS imaging cameras may further improve management approaches in dairy cows.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0022029922000267

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References

Aguilar-Pérez C, Ku-Vera J, Centurión-Castro F and Garnsworthy PC (2009) Energy balance, milk production and reproduction in grazing crossbred cows in the tropics with and without cereal supplementation. *Livestock Science* **122**, 227–233.

Banos G, Coffey MP, Wall E and Brotherstone S (2006) Genetic relationship between first lactation body energy and later life udder health in dairy cattle. *Journal of Dairy Science* **89**, 2222–2232.

Barrientos AK, Weary DM, Galo E and von Keyserlingk MAG (2011) Lameness, leg injuries and lying times on 122 North American freestall farms. *Journal of Dairy Science* **94**(suppl. 1), 414.

Blake RW and Custodio AA (1984) Feed efficiency: a composite trait of dairy cattle. *Journal of Dairy Science* **67**, 2075.

Brody S (1945) *Bioenergetics and growth, with special reference to the efficiency complex in domestic animals*. Reinhold Publishing Corporation, New York.

Chagas LM, Bass JJ, Blache D, Burke CR, Kay JK, Lindsay DR, Lucy MC, Martin GB, Meier S, Rhodes FM, Roche JR, Thatcher WW and Webb R (2007) New perspectives on the roles of nutrition and metabolic priorities in the subfertility of high-producing dairy cows. *Journal of Dairy Science* **90**, 4022–4032.

Chagunda MGG, Ross D and Roberts DJ (2009) On the use of a laser methane detector in dairy cows. *Computers and Electronics in Agriculture* **68**, 157–160.

Firk R, Stamer E, Junge W and Krieter J (2002) Automation of oestrus detection in dairy cows: A review. *Livestock Production Science* **75**, 219–232.

Friggens NC, Disenhaus C and Petit HV (2010) Nutritional sub-fertility in the dairy cow: towards improved reproductive management through a better biological understanding. *Animal* **4**, 1197–1213.

Heublein C, Dohme-Meier F, Südekum K-H, Bruckmaier RM, Thanner S and Schori F (2017) Impact of cow strain and concentrate supplementation on grazing behaviour milk yield and metabolic state of dairy cows in an organic pasture-based feeding system. *Animal: An International Journal of Animal Bioscience* **11**, 1163–1173.

Horan B, Dillon P, Faverdin P, Delaby L, Buckley F and Rath M (2005) The interaction of strain of Holstein-Friesian cows and pasture-based feed systems on milk yield body weight and body condition score. *Journal of Dairy Science* **88**, 1231–1243.

Leroy JLMR, Vanholder T, van Knegsel ATM, Garcia-Ispierto I and Bols PEJ (2008) Nutrient prioritization in dairy cows early postpartum: mismatch between metabolism and fertility? *Reproduction in Domestic Animals* **43** (suppl. 2), 96–103.

Lovendahl P and Chagunda MGG (2010) On the use of physical activity monitoring for estrus detection in dairy cows. *Journal of Dairy Science* **93**, 249–259.

Mulvaney P (1977) Dairy cow condition scoring. Handout No 4468 National Institute for Research in Dairying, Reading, UK.

Nielsen U, Pedersen OM and Toivonen M (2003) Time dependent effects as source of bias is estimating breeding values for longevity and fertility traits. *Interbull Bulletin* **30**, 29–34.

NRC (2001) *Nutrient requirements of dairy cattle*. 7th edition. National Academy Press, Washington DC, USA.

O'Callaghan KA, Cripps PJ, Downham DY and Murray RD (2003) Subjective and objective assessment of pain and discomfort due to lameness in dairy cattle. *Animal Welfare* **12**, 605–610.

Palmer MA, Olmos G, Boyle LA and Mee JF (2010) Estrus detection and estrus characteristics in housed and pastured Holstein-Friesian cows. *Theriogenology* **74**, 255–264.

Patton J, Kenny DA, McNamara S, Mee JF, O'Mara FP, Diskin MG and Murphy JJ (2007) Relationships among milk production, energy balance, plasma analytes and reproduction in Holstein-Friesian cows. *Journal of Dairy Science* **90**, 649–658.

Pollott GE and Coffey MP (2008) The effect of genetic merit and production system on dairy cow fertility measured using progesterone profiles and on-farm recording. *Journal of Dairy Science* **91**, 3649–3660.

Pryce JE, Coffey MP and Simm G (2001) The relationship between body condition score and reproductive performance. *Journal of Dairy Science* **84**, 1508–1515.

Pryce JE, Nielsen BL, Veerkamp RF and Simm G (1999) Genotype and feeding system effects and interactions for health and fertility traits in dairy cattle. *Livestock Production Science* **57**, 193–201.

Roberts DJ and March M (2013) Feeding systems for dairy cows: Homegrown *vs*. by-product feeds. 45th University of Nottingham Feed Conference 25–26 June 2013 Nottingham United Kingdom.

Roche JR, Friggens NC, Kay JK, Fisher MW, Stafford KJ and Berry DP (2009) Invited review: Body condition score and its association with dairy cow productivity, health and welfare. *Journal of Dairy Science* **92**, 5769–5801.

Ross SA, Chagunda MGG, Topp CFE and Ennos R (2014) Effect of cattle genotype and feeding regime on greenhouse gas emissions intensity in high producing dairy cows. *Livestock Science* **170**, 158–171.

Sjaunja LO, Baevre L, Junkkarinen L, Pedersen J and Setala J (1990) A Nordic proposal for an energy corrected milk (ECM) formula. In 27th session of the International Commission for Breeding and Productivity of Milk Animals, Paris.

Thorup V, Munksgaard L, Robert P, Erhard H, Thomsen P and Friggens N (2015) Lameness detection *via* leg-mounted accelerometers on dairy cows on four commercial farms. *Animal: An International Journal of Animal Bioscience* **9**, 1704–1712.

Weber C, Hametner C, Tuchscherer A, Losand B, Kanitz E, Otten W, Singh SP, Bruckmaier RM, Becker F, Kanitz W and Hammon HM (2013) Variation in fat mobilization during early lactation differently affects feed intake body condition and lipid and glucose metabolism in high-yielding dairy cows. *Journal of Dairy Science* **96**, 165–180.

Windig JJ, Beerda B and Veerkamp RF (2008) Relationship between milk progesterone profiles and genetic merit for milk production milking frequency and feeding regimen in dairy cattle. *Journal of Dairy Science* **91**, 2874–2884.