Genetic Parameters for Digital Dermatitis and Correlations with Locomotion, Production, Fertility Traits, and Longevity in Holstein-Friesian Dairy Cows

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ABSTRACT

Heritability of digital dermatitis (DD) and correlations between DD and type traits related to legs and feet were estimated from a linear animal model. Data comprised 93,391 national type evaluation records of pedigreed first-lactation Holstein-Friesian cows that calved from 2002 through 2006. At the time of classification, cows were housed in different housing systems (i.e., cubicles, straw yards, slatted or loafing yards) and on pasture. The type traits evaluated were locomotion score (LOCO), rear legs side view (RLS), foot angle (FA), bone quality and leg and feet composite (L&F). In addition, cows were examined for DD lesions at classification. The relationships among these type traits, lifespan (LS), production (milk and fat), fertility (calving interval and 56-d nonreturn) and DD were examined by estimating the approximate genetic correlations from sire estimated breeding values. The study also evaluated the association between DD and the housing systems as well as the general conditions of the farm flooring where classification took place. In general, cows on pasture were less susceptible to DD than cows in other housing systems, whereas the association between DD and the flooring conditions was counterintuitive. Heritability estimate for DD was 0.011 on the 0/1 scale, which is equivalent to 0.029 on the assumed underlying normally distributed scale. Bone quality, LOCO, and L&F had moderate to high negative genetic correlations with DD, indicating that flatter, more refined bones, higher LOCO, and better L&F were associated with less incidence of DD. The genetic correlations between DD, RLS, and FA were not significantly different from zero. Digital dermatitis had moderate but negative genetic correlations with LS and milk and fat, suggesting that breeding for resistance to DD will result in an increase in both longevity and production. Cows affected with DD had a

slightly shorter calving interval than healthy cows, an association found to be mediated through the reduced milk yield of these cows. Generally, the type traits included in this study had low genetic correlations with production and fertility traits whereas the associations between these traits and LS ranged from moderate to high. This indicates that good locomotion, straighter RLS, steeper FA, better L&F, and flatter, more refined bones are associated with increased longevity.

Key words: genetic parameter, digital dermatitis, locomotion trait, dairy cow

INTRODUCTION

Digital dermatitis (DD) is an infectious skin disease of cattle that affects the heels and the skin between the digits. It is considered an important cause of lameness in dairy herds due to the associated pain, discomfort, and impaired performance (Read and Walker, 1998). Clarkson et al. (1996) surveyed 37 dairy farms in England and Wales and observed that DD constituted 8% of all the hoof lesions contributing to lameness.

Digital dermatitis has been associated with decreased milk yield, reduced reproductive performance, increased involuntary culling rate, and reduced general well-being of the animals (Nutter and Moffit, 1990; Argaez-Rodriguez et al., 1997; Garbarino et al., 2004). Wells et al. (1999) reported that 9.7% of DD resulted in lameness in affected cows. Hernandez et al. (2001) reported that calving to conception interval was significantly longer in lame cows with multiple lesions including DD, compared with healthy cows. Earlier, Argaez-Rodriguez et al. (1997) reported that cows affected by DD in a Mexican herd had a 20-d increase in calving to conception interval, resulting in reduced fertility and consequently a shorter lifespan. The same study also reported a decrease in the milk production of cows affected with DD compared with healthy cows, although the difference was not significant. Corrie et al. (2000) noted that papillomatous digital dermatitis was common among culled adult cattle with the incidence greater among dairy cattle compared with their beef counterparts.

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Table 1. Description of traits

Type traits and DD	Abbreviation	Score		Mean	SD
		1	9		
Locomotion score	LOCO	Lame	Normal	5.43	1.46
Rear leg, side view	RLS	Straight	Sickled	5.07	1.37
Foot angle	FA	Low	Steep	5.17	1.40
Bone quality	BONEQ	Thick and coarse	Flat and refined	6.29	1.31
Composite score					
		65	95		
Leg and feet	L&F	Poor	Excellent	79.96	4.92
Disease score					
		0	1		
Digital dermatitis	DD	Absent	Present	0.12	0.33

Estimates of genetic parameters between claw diseases including DD and locomotion traits were reported by van der Waaij et al. (2005). With threshold and linear models, they reported a heritability of 0.10 from both models for DD in Dutch Holstein-Friesian dairy cows. They also reported genetic correlations of 0.16 ± 0.13 , -0.22 ± 0.13 , -0.67 ± 0.19 , and -0.34 ± 0.12 between DD and rear legs, side view (RLS), foot angle (FA), locomotion score (LOCO), and leg and feet composite (L&F), respectively. Approximate genetic correlations reported by Koenig et al. (2005) between DD and linear type traits ranged from 0.03 (hocks) to -0.61 (FA).

Reports of genetic parameters of DD and genetic associations with locomotion, production, fertility, and longevity traits are few in the literature, yet these estimates are required to enable DD to be included in a genetic selection index. The genetic association of DD with longevity has not been reported so far in the literature.

Studies on environmental and management risk factors have associated the incidence of DD with herd size, stage of lactation, parity, damp floors, housing systems, and so on. (Frankena et al., 1991; Rodriguez-Lainz et al., 1996; Somers et al., 2005). Cows housed in cubicles and those with restricted access to pasture were observed to be at greater risk of DD compared with cows that had full access to pasture during summer (Frankena et al., 1991; Somers et al., 2005). Moist and unhygienic floor conditions as well as solid or grooved concrete floors have also been associated with a greater incidence of DD (Rodriguez-Lainz et al., 1996; Wells et al., 1999; Hultgren and Bergsten, 2001).

As part of the UK type classification scheme, field officers now routinely collect information on housing systems and flooring conditions (Onyiro and Brotherstone,

2008). In addition, the field officers record whether cows exhibit signs of DD during type classification. It is, therefore, now possible in the UK to investigate associations between DD and housing conditions and estimate genetic parameters for DD and associated traits using national data.

The objectives of this study were 1) to determine the influence of housing on the occurrence of DD in Holstein-Friesian dairy cows; 2) to estimate the heritability of DD and its genetic correlation with locomotion and other leg and feet traits; and 3) to estimate approximate genetic correlations among locomotion traits, lifespan (LS), production and fertility traits, and DD from sire EBV.

MATERIALS AND METHODS

Data

The data used for this analysis comprised 93,391 national type evaluation records of pedigreed first-lactation Holstein-Friesian cows inspected from 2002 through 2006. Data were taken from 2002 because the recording of DD commenced in that year. Digital dermatitis was scored by the field officers on the presence or absence of lesions in the interdigital spaces of the feet. Herd visits were undertaken once every 10 mo to avoid type classifying cows more than once per lactation.

Five type traits related to legs and feet were evaluated. The traits are LOCO, RLS, FA, and bone quality (BONEQ) measured on a scale of 1 to 9, which represents extreme biological values, and L&F, which was measured on a subjective scale of “poor” (65) to “excellent” (95). Table 1 gives a description of the traits scored with their means and standard deviations, and

Table 2 shows the locomotion scoring system used for UK national herds. Age of cows at inspection was between 19 and 50 mo.

Housing Information

Field officers subjectively assessed cow housing based on 3 criteria: 1) type of houses where cows were kept; 2) the length of time cows had spent in each housing type; and 3) the general condition of the farm flooring where type evaluation took place, which was scored between 1 (poor) and 5 (ideal). Detailed information on housing is described by Onyiro and Brotherstone (2008). The number of cows classified in cubicles, straw yards, on pasture, and in slatted or loafing yards was 60,838, 3,885, 27,901, and 767, respectively; whereas total numbers scored on flooring conditions 1, 2, 3, 4, and 5 were 16,411, 2,723, 9,047, 19,930, and 45,280, respectively.

Statistical Analysis

Data were first adjusted for field-officer differences in scores by scaling records such that the standard deviation of each field officer was equal to the mean standard deviation of all field officers (Brotherstone, 1994).

The model equation used to describe the data was

$$Y_i = \mu + hyv + \sum_{n=1}^2 \beta_n age^n + \sum_{n=1}^2 \chi_n stage^n + \alpha \cdot phols + moc + hcode.hmns + hfloor + a_i + e_i,$$

where Y_i = presence (1) or absence (0) of DD for animal i ; μ = overall mean; hyv = random herd-year-visit effect; β_1 and β_2 = linear and quadratic regression coefficients of DD on age of cow at inspection; χ_1 and χ_2 = linear and quadratic regression coefficients of DD on stage of lactation of cow (stage) at inspection; α = linear regression of DD on the proportion of Holstein genes; $phols$ = proportion of Holstein genes; moc = effect of month of

calving; $hcode.hmns$ = housing period effect nested in housing type; $hfloor$ = flooring condition at inspection of animal i ; a_i = random animal effect; and e_i = random error term.

The length of time cows spent in a particular housing was classified as 1, 2, 3, 4, 5 mo and then 6 or more due to small sample sizes recorded from 6 mo. The length of time cows spent in slatted or loafing yards was not accounted for because few animals were recorded in these housing types. Housing period was nested within housing type and the combined effect referred to as housing situation. Cow and herd-year-visit were fitted as random effects in the model. Fitting herd-year-visit as a random effect allowed us to estimate the effect of housing systems and flooring conditions as these factors are confounded with herd visit. Herd-year-visit in this model will account for residual differences after the fixed effects have been accounted for. Housing systems and flooring conditions are both indicative of the overall farm management conditions. Age of cow at inspection, stage of lactation at inspection, and mean proportion of Holstein genes (ranging from 91 to 100%) were included as covariates.

Heritability of DD was estimated from a linear model. The heritability obtained from the linear model was then transformed from the 0/1 scale to an assumed underlying continuous normally distributed scale (Robertson and Lerner, 1949). The transformation applied was

$$h_n^2 = h_{0/1}^2 \left[p(1-p)/z^2 \right],$$

where h_n^2 = heritability on the continuous normal scale; $h_{0/1}^2$ = heritability on the binomial scale; z = ordinate of the standardized normal distribution at the threshold point corresponding to p , and p = incidence of DD; that is, the proportion of cows that had DD.

Genetic and phenotypic correlations between DD and type traits were estimated from a multivariate REML

Table 2. Descriptions of locomotion scores

Locomotion score	Description
1	Lame
2	Severe ab-/adduction present, uneven gait, short strides
3	Ab-/adduction present, uneven gait
4	Slight ab-/adduction present, even gait, short strides
5	No ab-/adduction present, even gait, short strides
6	Slight ab-/adduction present, even gait, medium strides
7	Slight ab-/adduction present, even gait, long strides
8	No ab-/adduction present, even gait, medium strides
9	No ab-/adduction present, even gait, long strides

analysis using an animal model. The same model was applied to both DD and the linear traits.

A single multivariate analysis with DD and all 5 type traits was not feasible because insufficient computer memory was available. Therefore, a series of 2-trait analysis (i.e., 5 bivariate analyses) was performed with DD and one of the type traits in turn. No structure was imposed on the variance-covariance matrix. Phenotypic correlations between DD and the type traits ($r_{0/1}$) were also transformed to an assumed underlying normally distributed scale (r_n) by applying the method of Ollausson and Ronningen (1975):

$$r_n = r_{0/1} \left[p(1-p) / z^2 \right]^{1/2},$$

where p and z are as above. Genetic correlations on the 0/1 and underlying normal scale are expected to be similar, so no transformation is needed (Ollausson and Ronningen, 1975). The ASREML software was used for all analysis (Gilmour et al., 2000).

Estimation of Approximate Genetic Correlations Among Locomotion Traits and Production, Fertility Traits, and Lifespan

Sires' EBV were correlated to obtain approximate genetic correlations among type traits (LOCO, RLS, L&F, FA and BONEQ), production traits (milk and fat), fertility traits [calving interval in days (CI) and 56 d nonreturn (NR56), scored 0 if the cow returns to service within 56 d and 1 otherwise], and lifespan. Wall et al. (2003) describe the UK system to predict EBV for fertility and Brotherstone et al. (1997) detail the genetic evaluation of lifespan. The phenotypic lifespan trait is the actual lifespan of the cow, or if she is still alive, her predicted lifespan. Sire EBV for type traits were taken from the output of the analysis described above and their corresponding reliabilities were estimated from the standard errors of the sire solutions as follows:

$$RL_i = 1.0 - (SE_i^2 / \sigma_{a(i)}^2),$$

where RL_i = sire reliability for trait i ; SE_i = standard error of sire EBV for trait i ; and $\sigma_{a(i)}^2$ = additive genetic variance for trait i .

Sire EBV and reliabilities for milk, fat, CI, NR56, and longevity were taken from the UK national evaluation records of May 2007. Sires with missing EBV for any of the traits of interest were eliminated. Minimum reliability for type traits used in estimating the corre-

lations was 0.30, resulting in a minimum reliability for production traits, CI, NR56, and lifespan of 0.50, 0.34, 0.35, and 0.32, respectively. Correlations were based on 973 sires.

Estimation of Approximate Genetic Correlations Between DD and Lifespan, Production, and Fertility Traits

As described above, sire EBV were correlated to obtain approximate genetic correlations between DD and LS, milk, fat, CI, and NR56. Again, sire EBV for DD were taken from sire solutions and their reliabilities calculated from the standard errors of the solutions. The low heritability of DD resulted in many bulls having EBV of low reliability. Therefore, the minimum reliability requirement for DD was reduced from 0.30 to 0.10 which resulted in a lower limit of 0.28 (LS), 0.41 (production traits), and 0.27 (fertility traits), respectively. Correlations were based on 2,461 sires.

All correlations estimated from EBV were adjusted for their reliabilities by the method of Calo et al. (1973):

$$\hat{r}_{g1,2} = \frac{\sqrt{\{\sum RL_1\} \times \{\sum RL_2\}}}{\sum \{RL_1 \times RL_2\}} \times r_{1,2},$$

where RL_1 and RL_2 = reliabilities of traits 1 and 2; $\hat{r}_{g1,2}$ = approximate genetic correlation between traits 1 and 2; and $r_{1,2}$ = correlation between EBV for traits 1 and 2.

The standard errors of correlations were estimated using the formula below:

$$SE = \sqrt{\frac{1 - \hat{r}_{g1,2}^2}{n - 2}},$$

where n = number of sires with records (Sokal and Rohlf, 1995).

To investigate whether genetic associations between type and fertility were mediated through production, approximate genetic correlations between these traits were adjusted for milk yield. Similarly, the correlations between DD and fertility traits were adjusted for milk yield. The partial correlation coefficients were estimated using the following formula (Sokal and Rohlf, 1995):

$$\hat{r}_{1,2,3}^{\circ} = \frac{\hat{r}_{g1,2} - \hat{r}_{g1,3}\hat{r}_{g2,3}}{\sqrt{\{1 - \hat{r}_{g1,3}^2\}\{1 - \hat{r}_{g2,3}^2\}}},$$

where $\hat{r}_{1,2,3}^{\circ}$ = partial correlation coefficient among DD, CI, and NR56 adjusted for milk yield; $\hat{r}_{g1,3}$ and $\hat{r}_{g2,3}$ = approximate genetic correlations of trait 1 (DD) with milk yield and trait 2 (CI and NR56) with milk yield.

The partial correlations were tested for significance with a *t*-statistic as shown below (Sokal and Rohlf, 1995):

$$t = \hat{r}_{1,2,3}^{\circ} \sqrt{\frac{n-2-m}{1 - \hat{r}_{1,2,3}^{\circ 2}}},$$

where *m* = number of variables kept constant, which is 1 in our case—milk yield.

Standard errors for the partial correlations were estimated in the same way as standard errors of ordinary correlations.

RESULTS

Descriptive Analysis

The data set consisted of 15,000 herd-year-visit effects, and the proportion of heifers recorded as having

DD was 12.1%. The mean incidences of cows with DD per housing type, irrespective of housing period were 0.14, 0.11, 0.08, and 0.14 for cubicles, straw yards, pasture, and slatted or loafing yards, respectively. The mean proportion of cows affected by DD in each housing system relative to the amount of time spent (months) in the system is given in Table 3. The incidence of DD was greater in both cubicles and slatted or loafing yards compared with the other housing systems and increased with housing time in cubicles and straw yards (Figure 1). Cows showed reduced signs of DD as they spent more time on grass and were less susceptible to DD than cows housed in other systems.

In general, age of cow at inspection, stage of lactation at inspection, and month of calving removed a significant amount of variation in DD and the type traits (*P* < 0.05), whereas the proportion of Holstein genes was not significant.

Housing Situation and Flooring Effect

Housing situation and flooring condition removed significant amounts of variation in DD. Predicted effect of housing situation (relative to pasture for all months) and flooring condition (relative to flooring condition 5) on the incidence of DD is given in Table 4. Cows housed in cubicles had significantly (*P* < 0.05) increased DD lesions as the housing period increased compared with cows spending similar periods on pasture. This result is consistent with the mean incidence of DD within

Table 3. Mean proportion of cows affected by digital dermatitis in different housing systems relative to months in housing and flooring conditions

Housing system	Housing period (mo)	Proportion of cows affected	Number of cows evaluated	Flooring condition ¹	Proportion of cows affected	Number of cows evaluated
Cubicles	1	0.075	19,068	1	0.059	16,411
	2	0.11	2,673	2	0.12	2,723
	3	0.18	3,973	3	0.14	9,047
	4	0.18	9,381	4	0.16	19,930
	5	0.16	19,451	5	0.12	45,230
	6	0.20	6,292			
Straw yards	1	0.074	700			
	2	0.075	385			
	3	0.070	317			
	4	0.079	649			
	5	0.11	962			
	6	0.19	872			
Pasture	1	0.13	10,163			
	2	0.082	2,879			
	3	0.054	2,767			
	4	0.059	4,641			
	5	0.039	5,375			
	6	0.024	2,076			
Slatted or loafing yards		0.14	767			

¹Flooring condition: 1 = slippery, dirty surfaces with holes in concrete; 2 = even concrete, but slippery underfoot; 3 = uneven/sloping concrete; 4 = level concrete; 5 = perfect nonslippery, clean, and level surfaces.

each housing period (Table 3). Cows kept in straw yards showed significantly ($P < 0.05$) greater signs of DD compared with those on pasture when housed for at least 6 mo. The results generally show that cows on pasture were less susceptible to DD than cows in other housing systems.

Poor flooring condition (floor 1) was associated with a reduced incidence of DD whereas flooring condition 4 was associated with a greater incidence of DD compared with the ideal flooring condition. There was no significant difference in DD between cows classified on flooring types 2 and 3 and those on 5.

Heritabilities and Correlations Between DD and Type Traits

Estimates of heritabilities of DD and genetic correlations between DD and type traits, together with their standard errors, are given in Table 5. The genetic variance of DD was significantly greater than zero and the estimate of heritability was 0.011 (± 0.003). After transformation to the underlying scale, the heritability of DD increased to 0.029 (± 0.007).

Bone quality, LOCO, and L&F had moderate to high genetic correlations with DD. The estimates were -0.21 , -0.67 , and -0.63 , respectively, suggesting that cows with no DD were genetically superior for flat and refined bone quality, sound locomotion, and better legs and feet. The genetic correlations between DD and RLS and FA were low in size and did not differ significantly from zero.

Figure 1. Combined effect of housing system and housing period on digital dermatitis (DD) incidence. Black, white, and gray bars = incidence of DD in cubicles, straw yards, and pasture, respectively.

The phenotypic correlations between DD and the type traits were lower than their corresponding genetic estimates and were all significantly ($P < 0.05$) different from zero. Only RLS had a positive phenotypic association with DD. The result suggests that, phenotypically, cows with no signs of DD have higher linear type scores and better legs and feet. When transformed from the 0/1 scale to the underlying continuous scale, the phenotypic correlations also increased (Table 5).

Table 4. Predicted influence with standard error (SE) of housing situation (relative to pasture) and flooring condition¹ (relative to floor 1) on the incidence of digital dermatitis

Housing situation	Housing period (mo)	Predicted value	SE
Cubicles	1	−0.027*	0.010
	2	0.048*	0.021
	3	0.107*	0.019
	4	0.121*	0.014
	5	0.119*	0.012
	6	0.174*	0.012
Straw yard	1	−0.030 ^{NS}	0.031
	2	0.027 ^{NS}	0.046
	3	0.032 ^{NS}	0.046
	4	0.038 ^{NS}	0.034
	5	0.048 ^{NS}	0.028
	6	0.11*	0.033
Slatted or loafing yard		−0.01 ^{NS}	0.029
Flooring condition			
	1 vs. 5	−0.048*	0.009
	2 vs. 5	0.011 ^{NS}	0.014
	3 vs. 5	0.008 ^{NS}	0.009
	4 vs. 5	0.032*	0.007

¹Flooring condition: 1 = slippery, dirty surfaces with holes in concrete; 2 = even concrete, but slippery underfoot; 3 = uneven/sloping concrete; 4 = level concrete; 5 = perfect nonslippery, clean, and level surfaces.

* $P < 0.05$.

Table 5. Heritability (h^2) of DD and genetic (r_g) and phenotypic (r_p) correlations of DD with type traits plus their standard errors (SE)

Trait ¹	h^2	SE (h^2)	r_g	SE (r_g)	r_p	SE (r_p)	$r_{p^*}^2$	SE (r_{p^*})
DD	0.011 (0/1 scale) 0.029 (normal)	0.003 0.007						
LOCO	—	—	−0.67*	0.08	−0.31*	0.003	−0.50*	0.005
RLS	—	—	0.15 ^{NS}	0.11	0.08*	0.004	0.12*	0.007
FA	—	—	0.03 ^{NS}	0.11	−0.01*	0.004	−0.02*	0.007
L&F	—	—	−0.63*	0.08	−0.22*	0.003	−0.36*	0.005
BONEQ	—	—	−0.21*	0.10	−0.06*	0.004	−0.09*	0.007

¹DD = digital dermatitis; LOCO = locomotion score; RLS = rear legs, side view; FA = foot angle; L&F = leg and feet composite; BONEQ = bone quality.

² r_{p^*} = transformed phenotypic correlations.

* $P < 0.05$.

Approximate Genetic Correlations Among Type Traits, LS, Milk, Fat, CI, and NR56

Table 6 gives the approximate genetic correlations of the type traits with LS, production, and fertility, together with standard errors. The correlations between type traits and LS were all significantly different from zero. Lifespan had high approximate genetic correlations with BONEQ (0.50), LOCO (0.66), and L&F (0.69), suggesting that flat and refined bones, good locomotion, and better legs and feet are associated with increased longevity. Foot angle was moderately correlated with LS; evidence that cows with a steeper foot angle had increased longevity. The correlation between RLS and LS (−0.32) was negative, indicating that sickled rear legs as judged from the side are associated with reduced lifespan.

The approximate genetic correlations of type traits with milk were all low but significantly different ($P < 0.05$) from zero apart from LOCO. Only the correlation between milk and RLS was positive. The correlations show that daughters of sires with steep FA, good L&F, and refined bones had reduced milk yield. Correlations of type traits with fat were also low but moderate for

LOCO (0.22). They were significantly different from zero except the estimates for FA and BONEQ. Based on the genetic correlations, cows with good locomotion and better L&F score will give greater fat yield. Rear legs, side view had a negative correlation with fat, which shows that sickled legs are associated with decreased fat yield.

Generally, the approximate genetic correlations of type traits with NR56 were low, except for that between BONEQ and NR56 (0.36) but significantly different from zero. The correlations indicate that straighter RLS, steeper FA, better L&F, and flatter, more refined bone quality are associated with better conception rate. Correlations with CI were less intuitive but these correlations are subject to management influences. The partial correlations between type and fertility traits adjusted for milk yield are presented in Table 7. The partial correlation coefficients were all significant except between L&F and NR56, indicating that only the association between L&F and NR56 is mediated through milk yield.

Lifespan showed a moderate genetic association with milk yield (−0.24), being consistent with previous reports that high milk yield is associated with a shorter

Table 6. Approximate genetic correlations $\pm$ SE among type traits, LS, production and fertility traits, and DD

Trait ²	Trait ¹				
	LS	Milk	Fat	CI	NR56
LOCO	0.66 $\pm$ 0.02	−0.04 $\pm$ 0.03	0.22 $\pm$ 0.03	0.04 $\pm$ 0.03	0.02 $\pm$ 0.03
RLS	−0.32 $\pm$ 0.03	0.06 $\pm$ 0.03	−0.08 $\pm$ 0.03	−0.09 $\pm$ 0.03	−0.11 $\pm$ 0.03
FA	0.27 $\pm$ 0.03	−0.07 $\pm$ 0.03	0.04 $\pm$ 0.03	0.19 $\pm$ 0.03	0.14 $\pm$ 0.03
L&F	0.69 $\pm$ 0.02	−0.11 $\pm$ 0.03	0.12 $\pm$ 0.03	0.06 $\pm$ 0.03	0.07 $\pm$ 0.03
BONEQ	0.50 $\pm$ 0.03	−0.12 $\pm$ 0.03	−0.01 $\pm$ 0.03	0.07 $\pm$ 0.03	0.36 $\pm$ 0.03
LS		−0.24 $\pm$ 0.03	0.05 $\pm$ 0.03	−0.49 $\pm$ 0.03	0.39 $\pm$ 0.03
Milk			0.43 $\pm$ 0.02	0.27 $\pm$ 0.02	−0.44 $\pm$ 0.04
Fat				0.27 $\pm$ 0.03	−0.22 $\pm$ 0.03
CI					−0.34 $\pm$ 0.03
DD	−0.16 $\pm$ 0.02	−0.31 $\pm$ 0.02	−0.43 $\pm$ 0.02	−0.07 $\pm$ 0.02	0.48 $\pm$ 0.02

¹LS = lifespan; CI = calving interval; NR56 = nonreturn after 56 d; DD = digital dermatitis.

²LOCO = locomotion score; RLS = rear legs, side view; FA = foot angle; L&F = legs and feet composite; BONEQ = bone quality.

lifespan. This was not the case for fat yield because the correlation was not significantly different from zero. Also, LS had a moderate genetic association with CI (−0.49) and NR56 (0.39), suggesting that a longer CI is linked to a reduction in LS, whereas successful conception is associated with increased longevity.

Milk and fat yield had moderate genetic associations with CI, and the correlations were similar (0.27) and significantly different from zero implying that longer CI is associated with increased milk and fat production. Milk, fat, and CI were negatively correlated with NR56, suggesting that high milk or fat yield or longer CI is linked with a lower conception rate.

Approximate Genetic Correlations of DD with LS, Milk, Fat, CI, and NR56

Approximate genetic correlations of DD with LS, milk, and fat were negative and moderate suggesting that the presence of DD is associated with reduced longevity and decreased milk and fat yield. Thus, breeding for resistance to DD should improve both production and longevity.

The association between DD and CI (−0.07) was low and negative, indicating that cows affected by DD had slightly shorter CI than cows with no evidence of DD. From the partial correlation between DD and CI (0.015), it was seen that the shorter CI is mediated through the reduced milk yield of affected cows, because the association was not significantly different from zero. In addition, DD and NR56 were moderately correlated (0.48), indicating an association between DD and greater conception rates. The partial correlation coefficient (0.40) between DD and NR56 (Table 7) was still significant, suggesting the correlation is not mediated through milk yield.

DISCUSSION

To allow estimation of housing and flooring, herd-year-visit was fitted as a random effect. Herd-year-

visit comprises many components including time of visit, farm size, grass quality, and field officer biases. The assumption of independent herd-year-visit effects is, to some extent, infringed by the presence of field officer biases. This could be dealt with by including field officer as an additional fixed effect in the model; however, for simplicity we chose not to do this, as we believe these biases are of little importance.

Association Between Housing System, Flooring Condition, and DD

Results of this analysis show that housing dairy cows in cubicle houses predisposes them to DD infection, and DD increases as housing periods increase. High incidence of DD has been reported for cows kept in cubicles (Frankena et al., 1991; Somers et al., 2005). Faye and Lescourret (1989) also showed that claw health was worse in indoor cubicle housing than during pasturing. Cubicle houses are characterized by abrasive solid concrete, which causes wear and tear of the cow hooves, thus exposing the inner claws to microorganisms causing infectious diseases such as DD and other injuries. Results from the current study also showed that straw yards predispose cows to DD when housed for extended periods. Straw yards are softer environments than cubicles, and with good management such as daily removal of bedding (which prevents wetness and pathogen build-up), cows should be less vulnerable to DD. There was no significant difference in DD between cows in slatted or loafing yards and those on pasture. However, because the amount of time spent by cows in this system was not accounted for in our analysis, we cannot ascertain whether slatted/loafing yards are compatible with pasture in terms of reduced incidence of DD with longer housing periods. Moreover, a small number of animals were recorded in this system compared with the number of animals at pasture.

Cows with full access to pasture have been found to have a reduced incidence of DD (Wells et al., 1999; Somers et al., 2003, 2005). Our findings corroborate these reports. Figure 1 clearly indicates that cows become less vulnerable to DD as they spend more time on pasture. The high incidence of DD experienced by cows on pasture in the first month may be a result of the housing type where cows were housed in the previous month. The association between flooring condition and incidence of DD was counterintuitive. The lower incidence of DD in dirty, slippery floor conditions compared with the other flooring conditions could be due to difficulty in identifying lesions on dirty feet. As a result, many of the DD cases might go undetected by field officers. Wells et al. (1999) reported a lower incidence

Table 7. Approximate genetic correlations $\pm$ SE between type, DD, and fertility traits¹ at constant milk yield

Trait ²	CI	NR
LOCO	—	—
RLS	−0.11 $\pm$ 0.03	−0.09 $\pm$ 0.03
FA	0.22 $\pm$ 0.03	0.12 $\pm$ 0.03
L&F	0.09 $\pm$ 0.03	0.02 $\pm$ 0.03
BONEQ	0.11 $\pm$ 0.03	0.34 $\pm$ 0.03
DD	0.015 $\pm$ 0.02	0.40 $\pm$ 0.02

¹CI = calving interval; NR56 = nonreturn after 56 d.

²LOCO = locomotion score; RLS = rear legs, side view; FA = foot angle; L&F = leg and feet composite; BONEQ = bone quality; DD = digital dermatitis.

of DD on dirt, pasture, or smooth concrete compared with grooved concrete.

Estimates of Genetic Parameters

Heritability. The heritability estimates for DD in this study were lower than previous reports in literature. Using a sire model, van der Waaij et al. (2005) reported an estimate of 0.10 (linear and threshold) for DD in Dutch Holstein-Friesians whereas Koenig et al. (2005) obtained an estimate of 0.073 from a linear logistic mixed model. The disparity in these heritability estimates could be attributed to the differences in the number of records as well as the models used in data analysis. Although our estimates of heritability were low, they were significantly different ($P < 0.05$) from zero, implying that DD is heritable, and genetic improvement for resistance to DD is possible through selection.

Genetic Correlations. The association between DD and LOCO (−0.67) is similar to the estimate of van der Waaij et al. (2005). The genetic relationships between DD and LOCO and L&F were of similar magnitude in our study and this is not surprising, because both traits have been reported to be highly genetically and phenotypically correlated (van der Waaij et al., 2005; Onyiro and Brotherstone, 2008). The correlations among DD and type traits relating to legs and feet suggest better legs and feet if cows are bred for increased resistance to DD. Conversely, selection for improved type traits would lead to increased resistance to DD. Nonsignificant associations among DD, FA, and RLS were noted by van der Waaij et al. (2005).

Approximate Genetic Correlations

Correlations among Type, LS, Production, and Fertility Traits. The strong association between the type traits and LS could be linked to the fact that improved conformation particularly related to legs and feet will make cows less vulnerable to locomotive disorders. This is consistent with the correlations between DD and type traits (Table 5). Dekkers et al. (1994) reported moderate genetic association among BONEQ, L&F, set of rear legs on a desirability scale and functional herd life.

The relationships between FA, RLS, L&F, and BONEQ suggest that lower FA, more sickled rear legs, poorer L&F score, and coarser bones are associated with increased milk production. Perez-Cabal et al. (2006) also found that sickled rear legs were associated with increased milk yield. However, they detected a positive association between better legs and feet and greater production, whereas we found that poorer legs and feet score was associated with greater milk yield.

In this analysis, we found no significant association between LOCO and milk yield.

In general, the relationships between type and CI are quite surprising but could be due to management effects. Pryce et al. (2000) obtained a negative correlation of FA with CI (−0.20), but positive with RLS (0.19). Because fertility remains an economically important trait in the breeding goals of farmers, and selection for productive life is expected to result in improved health and fertility, the associations between type and fertility traits warrant further research.

Correlations Among LS, Production, and Fertility Traits. The unfavorable approximate genetic correlation between LS and milk yield is an indication that daughters of sires with high EBV for milk yield will have reduced longevity. The correlations among LS, CI and NR56 were favorable (−0.49 and 0.39, respectively). Cows having shorter CI and successful conception will stay longer in the herd. The antagonistic relationship between CI and NR56 (−0.34) means that a longer CI is associated with a reduced pregnancy rate.

The association between milk, fat, and fertility traits suggests that high-yielding cows will have longer CI and impaired conception leading to reduced reproductive fitness. Poor fertility and health along with low production have been identified as reasons for involuntary culling (Esslemont and Kossaibati, 1997). Many studies have reported similar genetic relationships between production and fertility traits. Wall et al. (2003) reported antagonistic correlations between milk yield and CI (0.27) and NR56 (−0.45). Brotherstone et al. (2002) estimated unfavorable genetic correlations between combined 305-d fat and protein and CI (0.40) and NR56 (−0.29). These findings support the inclusion of fitness related traits with production in national selection indices (Miglior et al., 2005).

Correlations Among DD, LS, and Production. Correlation of the EBV adjusted for their reliabilities among DD, LS, and milk and fat (−0.16, −0.31, −0.43, respectively), suggest that increased incidence of DD is associated with reduced LS and decreased milk and fat production. Contrary to our estimate, Koenig et al. (2005) obtained a positive correlation between DD and milk yield in the first stage of lactation (0.24) but the analysis involved a small data set.

As the presence of DD was identified by field officers rather than veterinarians and was scored only once in first lactation, the incidence of the disease as estimated from our data may be biased downwards. However, recording the presence of DD on the national population (around 60,000 heifers per year are type classified in the UK) should give sufficient information to predict sire breeding values for DD of reasonable reliability. Results from our analyses indicate that breeding for in-

creased resistance to DD is associated with an increase in both longevity and production. Thus, DD should be considered a useful disease trait to be recorded and included in a national selection index for increased productive life.

CONCLUSIONS

Cows at pasture had reduced incidence of DD compared with cows in other housing systems. Also, cows with flatter and more refined bones, higher locomotion score, and better leg and feet composite had reduced incidence of DD. Digital dermatitis showed heritable variation among cows and was moderately associated with lifespan and production. Therefore, its inclusion in a selection index will be useful to improve the resistance of cows to the disorder and increase lifespan. The genetic correlations between type traits related to legs and feet and lifespan ranged from moderate to high, whereas, in general, these type traits had low associations with production and fertility.

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