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Assessment of the effect of housing on feather damage in laying hens using IR thermography

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Plumage damage represents one of the animal-based measures of laying hens welfare. Damage occurs predominantly due to age, environment and damaging pecking. IR thermography, due to its non-invasiveness, objectivity and repeatability is a promising alternative to feather damage scoring systems such as the system included in the Welfare Quality® assessment protocol for poultry. The aim of this study was to apply IR thermography for the assessment of feather damage in laying hens kept in two housing systems and to compare the results with feather scoring. At the start of the experiment, 16-week-old laying hens ($n = 30$*) were divided into two treatments such as deep litter pen and enriched cage. During 4 months, feather damage was assessed regularly in 2-week intervals. One more single assessment was done nine and a half months after the start of the experiment. The feather damage on four body regions was assessed by scoring and IR thermography: head and neck, back and rump, belly, and underneck and breast. Two variables obtained by IR thermography were used: the difference between the body surface temperature and ambient temperature (*ΔT_B*) and the proportion of featherless areas, which were defined as areas with a temperature >33.5°C. Data were analyzed using a GLM model. The effects of housing, time, region and their interactions on feather damage, measured by the feather scoring and by both IR thermography measures, were all significant (*$P < 0.001$*). The *ΔT_B* in all assessed regions correlated positively with the feather score. Feather scoring revealed higher damage in enriched cages compared with deep litter pens starting from week 6 of the experiment on the belly and back and rump regions, whereas *ΔT_B* from week 6 in the belly and from week 8 on the back and rump region. The proportion of featherless areas in the belly region differed significantly between the housings from week 8 of the experiment and on the back and rump region from week 12. The IR thermography assessment of the feather damage revealed differences between hens kept in different housing systems in agreement with the feather scoring. In conclusion, it was demonstrated that the IR thermography is a useful tool for the assessment of poultry feather cover quality that is not biased by the subjective component and provides higher precision than feather damage scoring.*

Keywords: feather scoring, welfare, poultry housing, IR thermography, laying hens

Implications

Plumage conditions reflect the actual health status of hens, as well as the outcome of their interaction with the housing environment and other birds. Feather cover quality is generally accepted as one of the animal-based welfare indicators. There is a continuous need to develop standardized methods of assessing animal welfare that are feasible for on-farm use. The IR thermography (IRT) represents one such tool. This study describes the experience with the assessment of plumage conditions in different housings using traditional feather scoring (FS) and IRT.

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Introduction

Laying hens may lose a considerable proportion of their feathers because of feather pecking (Savory, 1995) or abrasion and molting (Glatz, 2001). There is an increase in convective heat loss from birds with poor feather cover and thus an increase in heat production, feed consumption and decrease in egg production (Nichelmann *et al*., 1986; Mills *et al*., 1988). Although plumage damage is an indirect measure of feather pecking, it is easier to assess than the behavior itself (Nicol *et al*., 2013). The quality of plumage may provide valuable information about the welfare status of laying hens in various housing systems. For example, significant differences in plumage condition have been shown in various cage systems by Tauson (1984), who compared several conventional battery cage systems and found that cages with solid side partitions caused less feather abrasion compared with cage systems with wire mesh partitions. In cages, feather damage develops due to both abrasion and feather pecking, whereas in floor-kept birds, it is mostly caused by feather pecking (Tauson, 1984). Taylor and Hurnik (1994) reported that caged hens had poorer feather cover and 39% of caged birds had denuded areas >5 cm^2, whereas 68% of aviary hens had complete plumage. Mollenhorst *et al*. (2005) compared feather condition scores on 10 farms with battery cages and 10 farms with deep litter systems. The total feather condition score did not differ between housing systems. Analysis per body part, however, indicated that the wing and breast were more damaged in a battery cage system, and the head and underneck were more damaged in a deep litter system. Sherwin *et al*. (2010) compared feather damage and other parameters in conventional cages, furnished cages, barn (indoor single-tier aviary) and free-range systems. Their study found that the prevalence of severe feather pecks received was highest in barn hens corresponding with barn hens with the highest feather damage score.

The commonly used method of feather cover assessment is FS, a visual evaluation of plumage on different parts of the body (Tauson *et al*., 1984; Bilčík and Keeling, 1999; Welfare Quality®, 2009). Although this method is easy to use, it is relatively subjective, semi-quantitative and less repeatable. Two FS scorers may provide significantly different scores for the same bird despite both of the observers being trained under the same scheme (Tauson *et al*., 1984). Another method used for feather damage evaluation is IRT. The principle of the IRT method is the direct measurement of heat loss in the IR spectrum resulting from poor feather cover. Cook *et al*. (2006) compared feather cover assessment by IRT and FS and concluded that the data derived from IRT provided a continuous variable that more accurately reflects either actual feather cover or areas of bare skin than the FS. Zhao *et al*. (2013) also claimed that IRT is a promising tool providing more objective and quantitative evaluation of feather conditions of laying hens than FS. IRT was not only used for the assessment of feather cover in laying hens but also in broiler chickens. It was shown that featherless body regions reflected a higher surface temperature compared with feathered regions and the featherless areas responded faster to changes in air temperature (Nääs *et al*., 2010).

The aim of our study was to validate the assessment of the feather cover quality of laying hens using IRT methods by evaluating plumage of hens kept under two housing conditions and compare the results with FS.

Material and methods

Animals

Dekalb White laying hens with trimmed beaks were obtained from a commercial supplier, where they had been kept in enriched cages at the age of 16 weeks. Half of the animals ($n = 15$) were housed in enriched cages and the other half ($n = 15$) were housed in deep litter pens. Enriched cages (STS Hostivice, Hostivice, Czech Republic) provided at least 750 cm^2 space/hen and were equipped with a nesting area, dust bathing area, perches, feed trough, nipple drinkers and a claw-shortening device. Deep litter pens provided 1500 cm^2 of floor space/hen covered with ~10 cm layer of wood shavings. Pens were fitted with the feed trough, nipple drinkers, metal nest box mounted on the wall (one of the pen walls was solid) and two perches installed at different levels. Plastic mesh walls had a bottom part that was covered by a black mat to prevent contact between animals from different pens. In all groups, water and food were provided *ad libitum* and the hens were kept under the 14 h light–10 h dark cycle (fluorescent tube, 15 lux).

Experimental design

Feather assessment was performed regularly in 2-week intervals for 4 months after the start of the experiment (weeks 2, 4, 6, 8, 10, 12, 14 and 16 of the experiment) and one more single assessment nine and a half months after the start of the experiment (week 38 of the experiment). Each bird was scored using the FS system based on the Welfare Quality protocol (Welfare Quality®, 2009). Four body regions such as belly (B), back and rump (BR), head and neck (HN), and underneck and breast (UB) – were assessed (Figure 1). For each body region, a score was given on a three-point scale: 0 – no or slight wear, complete feather with only single feather missing; 1 – moderate wear, worn plumage or one or more featherless areas <5 cm in diameter; 2 – at least one featherless area ⩾ 5 cm in diameter at the largest extension.

Feather cover was also estimated from the thermal images obtained by the IR camera (FLIR E5; FLIR System AB, Täby, Sweden). The thermal images of the frontal side, dorsal side (animals were held upside down) and ventral side of each bird were captured from a fixed distance of 1 m. The animals were held in front of a white wall without any sun reflections. The camera was fixed on a tripod, and the emissivity was set to 0.95 (Cangar *et al*., 2008; Nääs *et al*., 2010). The actual room temperature was set on the basis of the thermo hygrometer (Klima Logger TFA 303015; TFA-Dostmann,

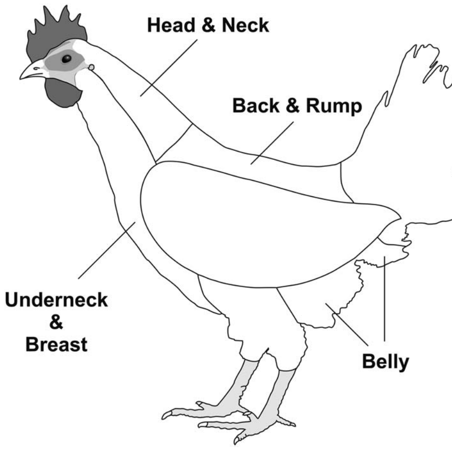

Figure 1 Body regions used in feather cover quality assessment of laying hens (adapted from Bilčík and Keeling, 1999).

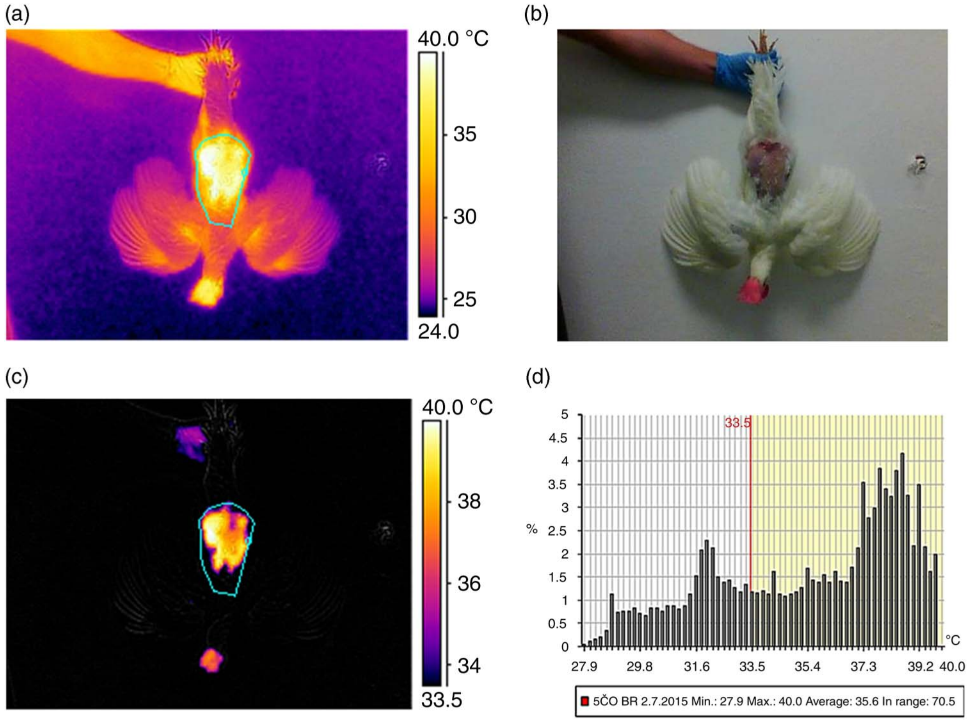

Figure 2 Example of the IR image of laying hen from the dorsal view with the delineated back and rump region (a); corresponding digital image (b); IR image with the featherless areas selected by the software (c); and the histogram of the selected region and the calculation of the percentage of featherless areas in this region (percentage of pixels with temperature higher than 33.5°C in the selected region) (d).

Wertheim, Germany). IR images were analyzed using the FLIR Report Professional software. The regions of interest were delineated from the thermal image (corresponding to the regions defined for the FS) and the IRT mean temperature values were independently measured for each region. On the basis of IRT data, two parameters were used in further analyses: the temperature difference (ΔT_B) and proportion of featherless areas (FL%). The ΔT_B represents the difference in temperatures of the body region surface and ambient temperature. It was calculated to correct for the effect of ambient temperature (Cangar *et al.*, 2008). The FL% was estimated as the number of pixels with the temperature above 33.5°C out of the total number of pixels in each of the selected regions (Figure 2).

Statistical methods

All of the statistical analyses were performed in SAS (version 9.04; SAS® University Edition, Cary, NC, USA). Data were analyzed using three-way repeated-measures ANOVA (Mixed procedure). Fixed effects included housing, body region, time spent in housing and all two- and three-way interactions. Time spent in housing was the repeated variable, with the individual hen nested in housing as the subject for the repeated statement. Tukey's *post hoc* test was used to detect any pairwise differences between the variables across treatments. ΔT_B and FL% parameters obtained by IRT were tested against the FS categories using two-way ANOVA. The Pearson's coefficient of correlation was used to estimate the strength of the association between various feather damage parameters (FS, ΔT_B and FL%).

Results

There was a significant effect of housing on the quality of feather cover, as measured by FS, as well as both parameters obtained from the IRT data – that is, ΔT_B and FL% (Table 1). In general, the hens housed in the enriched cages had worse feather cover than the hens kept in the deep litter pens. There was also a strong effect of time on plumage deterioration as reflected by both of the methods used (Table 1). The effect of body region was highly significant in cases of all three parameters (Table 1). However, the amount of damage to various body regions differed as estimated by FS, ΔT_B and FL %. All three parameters evaluated B as the most and HN as the least damaged region. Nevertheless, the B feather condition did not differ from the BR region as assessed by FS. However, while according to the ΔT_B, the second most damaged area was the UB and then the BR. An estimate of feather cover condition by the FL% indicated that BR damage did not differ from the UB damage, but they both differed from the B and HN area.

There was a significant effect of housing × time interaction on the FS, ΔT_B and FL%. The feather damage of the B and BR region were significantly higher in caged hens from week 6 of the experiment as assessed by the FS, and the B from week 6 and the BR from week 8 as assessed by the ΔT_B (Figures 3 and 4). Assessment of FL% areas by the IRT showed significant differences between the cage and deep litter environments in the B region from week 8 and in the BR from week 12 (Figure 5). The FS method indicated significant differences in feather cover between the housings

Table 1 *Effects of housing, duration of housing treatment (weeks) and body region on plumage condition in laying hens as assessed using the feather score (FS) and IR thermography (mean temperature difference (ΔTB) and mean featherless area (FL%))*

	Housing			Time in housing (weeks)										Body region						
	EC	DLP	*P*	2	4	6	8	10	12	14	16	38	*P*	HN	BR	B	UB	*P*	RMSE	*P*
FS	0.83^a	0.12^b	0.001	0.00^a	0.00^a	0.16^b	0.34^c	0.55^d	0.55^d	0.71^e	0.88^f	1.07^g	0.001	0.15^a	0.64^b	0.69^b	0.40^c	0.001	0.39	0.001
ΔT_B (°C)	5.70^a	4.07^b	0.001	4.54^a	3.76^b	2.28^c	3.81^b	4.61^a	5.81^d	5.85^d	5.24^e	8.06^f	0.001	3.10^a	4.71^b	6.21^c	5.52^d	0.001	1.58	0.001
FL% (%)	14.73^a	1.59^b	0.001	0.49^a	0.43^a	0.82^a	3.25^b	6.22^c	7.72^c	10.55^d	21.65^e	22.86^e	0.001	0.53^a	7.11^b	19.55^c	5.46^b	0.001	10.98	0.001

EC = enriched cages; DLP = deep litter pens; HN = head and neck; BR = back and rump; B = belly; UB = underneck and breast; RMSE = root mean square error that applies to the statistical model.
Values are least squares means.
[a,b,c,d,e,f,g]Within row and within factor (housing, time in housing, body region) with different superscript letters differ ($P < 0.05$).

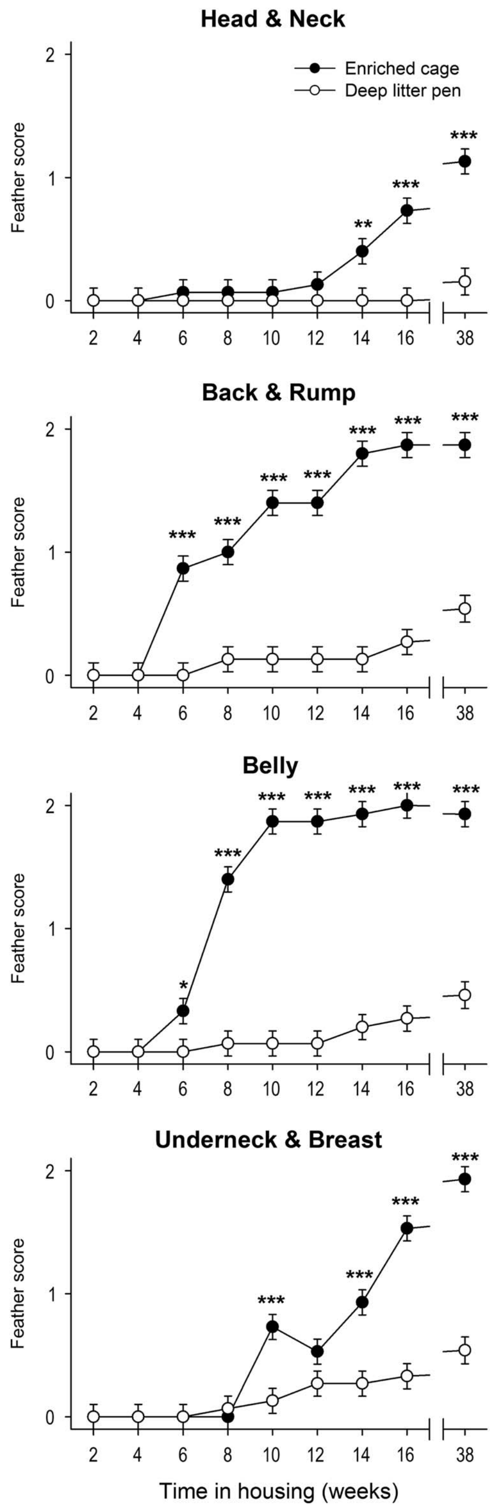

Figure 3 The assessment of the feather cover quality of laying hens in enriched cages and deep litter pens in four body regions using feather scoring. Points represent the least squares means ± SE. $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$.

in the HN region from week 14 until the end of the experiment and in the UB region from week 10 (except week 12, when only a trend was observed; Figure 3). Both IRT parameters showed minor damage and no significant

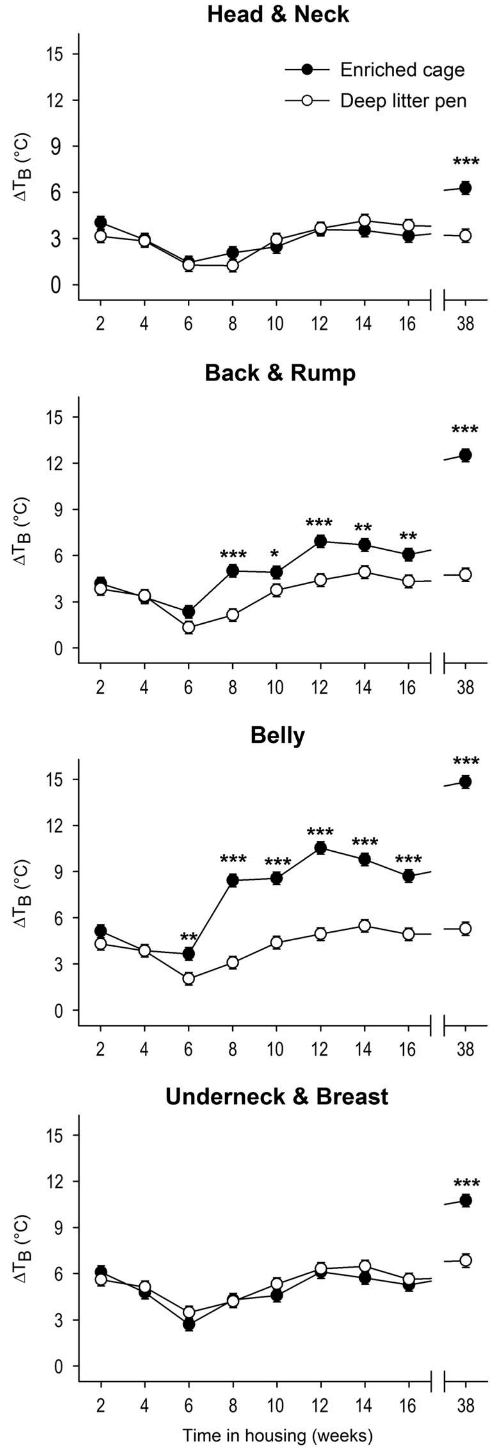

Figure 4 The assessment of the feather cover quality of laying hens in enriched cages and deep litter pens in four body regions using the temperature difference between measured surface temperature and ambient temperature (ΔT_B). Points represent the least squares means ± SE. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

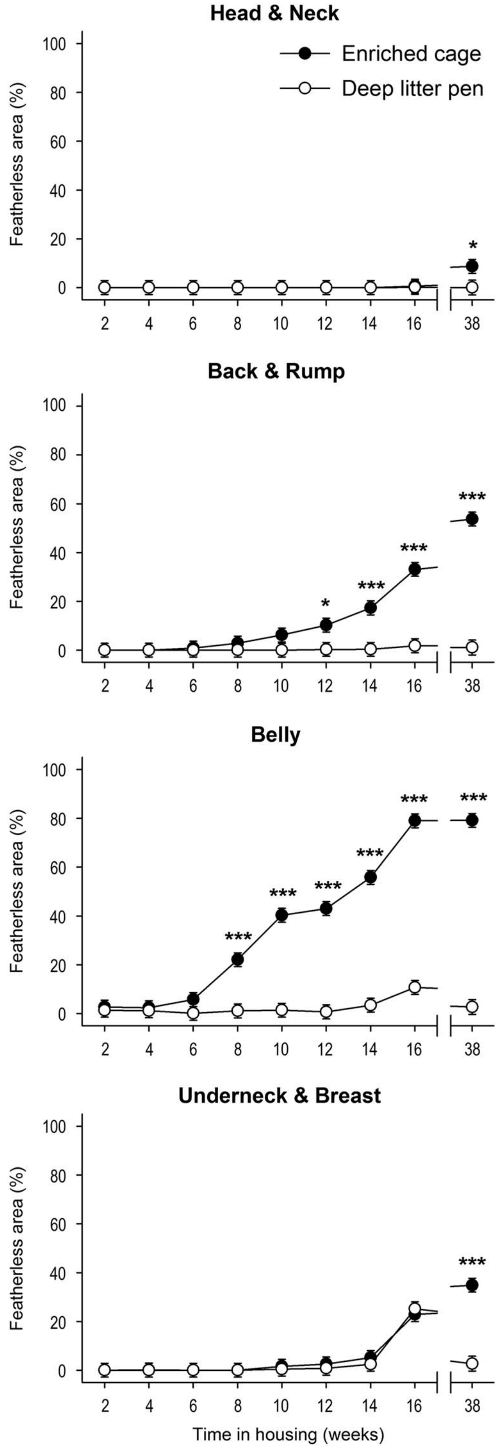

Figure 5 The assessment of the feather cover quality of laying hens in enriched cages and deep litter pens in four body regions using the percentage of featherless areas calculated from the thermal images. Points represent the least squares means ± SE. *$P < 0.05$, ***$P < 0.001$.

differences between groups in the HN and UB regions. Only the last assessment in week 38 of the experiment based on the ΔT_B and FL% showed the feather cover condition of the hens from enriched cages in the HN and UB region inferior to those of the deep litter kept hens (Figures 4 and 5).

The distinct FS categories resembled the specific mean ΔT_B. In case of the HN, BR and B there were clear differences between the mean ΔT_B corresponding to each of the FS categories. In case of the UB, the mean ΔT_B corresponding to the FS 0 did not differ from the FS 1, but they both differed from the FS 2. The ΔT_B in all assessed body regions

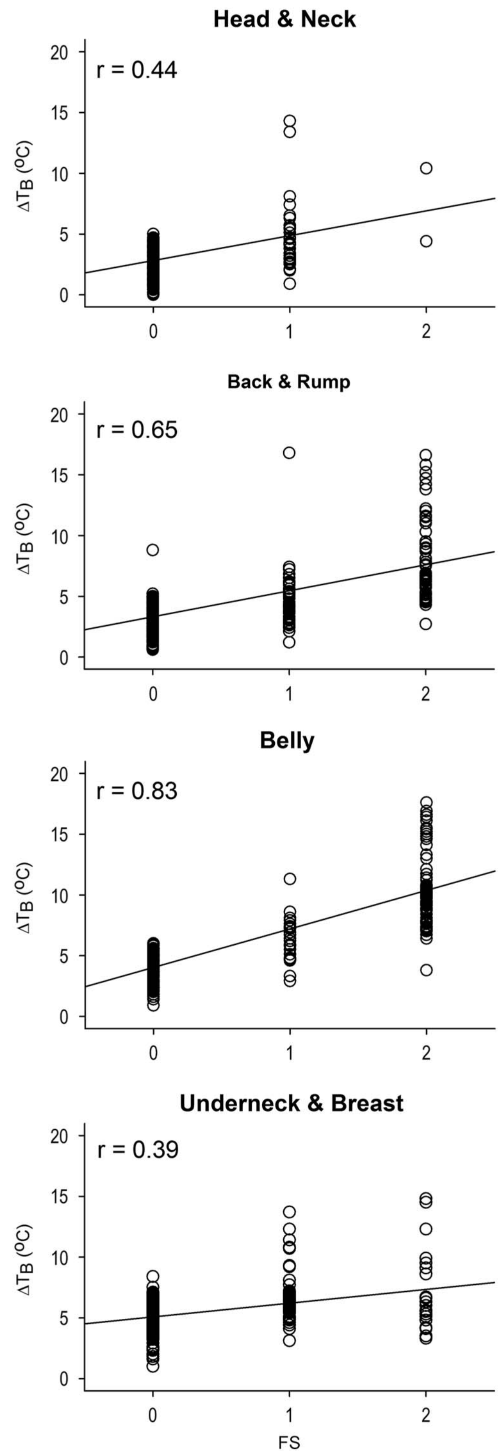

Figure 6 Association between the feather score (FS) and ambient temperature (ΔT_B). Each circle represents ΔT_B of an individual hen classified by the given feather damage score.

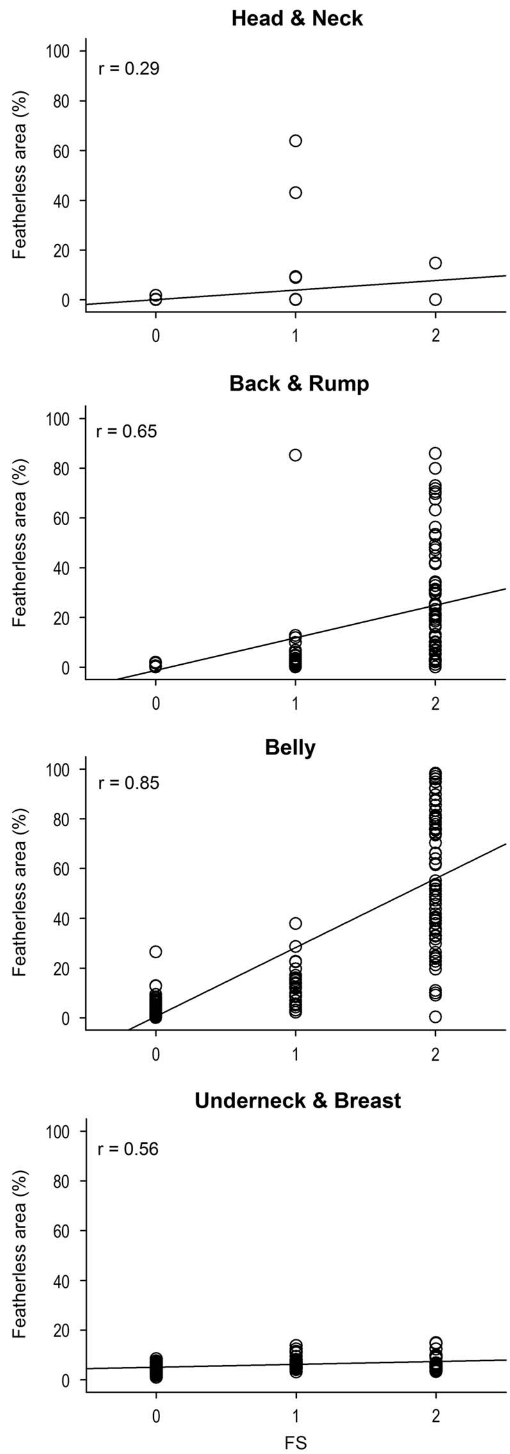

Figure 7 Association between feather score (FS) and the percentage of featherless areas. Each circle represents percentage of featherless areas of an individual hen classified by the given feather damage score.

was positively correlated with the FS (HN, $r = 0.44$; BR, $r = 0.65$; B, $r = 0.83$; UB, $r = 0.39$; $P < 0.001$ for all) (Figure 6). Again, there was lower correlation with the less damaged regions (HN and UB). The larger featherless areas in all body regions, as reflected by the FL%, were associated with a higher score. In this case, in the B and UB regions, there was a distinct proportion of featherless areas associated with each point of the FS scale, whereas in case of the HN and BR regions, FS 0 did not differ from FS 1. The FS and FL% were positively correlated (HN, $r = 0.29$; BR, $r = 0.65$; B, $r = 0.85$; UB, $r = 0.56$; $P < 0.001$ for all) (Figure 7).

Discussion

The results of our experiment demonstrated that IRT is an objective and feasible method for the feather cover assessment of laying hens kept in different housing systems. During the 1st month of the experiment, most of the hens had no or very little feather wear on all body regions. Low feather wear was caused by a short stay in a particular environment, as well as by the relatively low age of hens. Starting from week 6 of the experiment, rapid changes in the feather condition, particularly in the B and BR regions, were observed in hens kept in enriched cages. Quick progression of plumage deterioration in these regions was indicated by both the FS and ΔT_B. The development of feather damage in these regions showed a similar pattern; in both regions, rapid feather cover worsening was observed in enriched cages and it was significantly faster than in hens from the deep litter pens. The time course of feather damage, as well as the most affected regions, are consistent with Bilčík and Keeling (1999). Tauson *et al.* (1984) also described the B and BR as regions with early feather deterioration. Norgaard-Nielsen *et al.* (1993) found that the back of laying hens were the most frequently affected by feather pecking.

Data on feather damage to different body regions differed between authors, reflecting variation in the number of assessed regions and their delineation, in the scoring system or in the details of the IRT measurement, breeds or housing. Surface temperature changes in time are dependent on the number and quality of the feathers in different places, which act as an insulation layer (Cangar *et al.*, 2008). Zhao *et al.* (2013) assessed the feather cover of laying hens by IRT independently in regions with excellent feather and no feather cover. Laying hens with excellent feather cover had higher surface temperature on the head, breast, belly, and front neck and crop, indicating a thinner insulating layer, and lower surface temperature on the dorsal neck and back, indicating a thicker layer. Temperatures of different body parts with no feather cover were relatively close. In contrast, Cangar *et al.* (2008) using the IRT in broilers observed the lowest temperatures on the wings and breast, concluding that these are locations with the thickest feather cover. A potential explanation of the contradictory results (e.g. in case of breast) could be the difference between the laying hens and broilers.

Nevertheless, using the FS approach, Mills *et al.* (1988) found that the feather damage to different body regions in laying hens and broiler breeders at 52 weeks of age did not substantially differ. In both cases, the breast was the most damaged region, whereas the back was the least damaged region in laying hens and second least damaged region in broiler breeders. Using their specific FS system in a relatively small group of laying hens kept in experimental deep litter pens between 18 and 32 weeks of age, Bilčík and Keeling (1999) identified significantly worsened feathering on the back, rump and belly, that closely resembled our results with birds kept in similar experimental deep litter pens. Conversely, Mollenhorst *et al.* (2005) used the same FS method of Bilčík and Keeling (1999) in on-farm conditions. In laying hens kept on deep litter (median age 50 weeks, median flock size 4470 birds), the most damaged feathers were underneck, neck and tail. In battery cages (median age 41 weeks, median flock size 27 841 birds), the most damaged feathers were breast, tail and neck. The FL% parameter derived from the IRT measurement indicated significant differences between the housing groups in the B and BR regions from week 8 and week 12 of the experiment, respectively. The differences between FS and FL% were due to the FS, which includes all stages of feather damage, and the FL% parameter reflects only the completely defeathered areas. Thus, the ΔT_B is another parameter obtained from the IRT measurements that provides results analogous to FS because it reflects the heat loss caused by a wider range of feather damage (including scruffy and sporadically missing feathers) compared with FL%.

In contrast to the FS method, the IRT-based parameters indicated only minor plumage differences between the housing groups in the HN and UB regions. There are several potential explanations for this finding. The first explanation can be the varying position of the head during the capture of IRT thermal images. Some positions of the hen neck could hide the less feathered areas. The second potential cause of a lower association between the FS and IRT measures of feather damage may be an overestimation of feather damage in the HN and UB regions by the assessors. Lower consistency of scoring between different assessors is one of the general disadvantages of FS method (Tauson *et al.*, 1984; Forkman and Keeling, 2009). A slower decrease in the feather quality in the HN was not unexpected because the damage in this body region is usually described as a consequence of aggressive attacks aimed at the head (Savory, 1995) or upper part of the body (Keeling, 1995). However, there was very little aggressive behavior observed in any of our groups.

Differences in time when feather damage in different regions became apparent may be the consequence of the accessibility of the body part to feather pecking (Leonard *et al.*, 1995), which is also dependent on housing design. Abrasion of the plumage against cage walls may be a cause of lower feather quality in laying hens (Abrahamsson, 1996). The loss of feathers due to wear against the environment was rather small in deep litter pens, which most likely contributed to the slower progress of plumage deterioration in these animals. Nevertheless, according to Hughes and Michie (1982), even in cages, the most damage is caused by feather pecking by cage mates or hens from adjacent cages rather than by abrasion. In an environment where the animals are not able to perform the whole repertoire of their natural behavior (e.g. ground pecking or foraging behavior in cages with a wire mesh floor) may contribute to the occurrence of feather pecking and consecutive feather deterioration (Wood-Gush and Rowland, 1973). Nevertheless, birds with the possibility to behave more naturally might be negatively affected by their environment after a longer period of time (Nicol *et al.*, 2009). Plumage condition can also be negatively affected by age and egg production (Hughes, 1983; Tauson, 1984).

The surface temperature ranges obtained in this study (data not shown) were higher than those reported by Cook *et al*. (2006) and lower than those reported by Zhao *et al*. (2013). This variation presumably emerged from the differences in ambient temperature. The exposure to elevated ambient temperature increases blood flow to the skin, particularly to the non-feathered areas, as a result of vasodilatation (Wolfenson, 1986; Yahav *et al*., 1998). To eliminate the effect of environmental temperature during IRT, measurements should be performed under thermoneutral conditions (air temperature 21°C ± 1°C, relative humidity 40% ± 5%) after at least 30 min of adaptation (Tao and Xin, 2003). However, this is not possible under commercial conditions. Thus, to minimize the effect of ambient temperature on heat dissipation, we used the ΔT_B, which represents the difference of measured surface temperature and the temperature, the measure used by several authors (Cangar *et al*., 2008; Nääs *et al*., 2010).

Our data, similarly to those of Cook *et al*. (2006) and Zhao *et al*. (2013), showed a strong association between the IRT and FS. Our data showed that the correlation between the FS and ΔT_B in HN and UB regions was lower compared with other body regions, which was most likely caused by lower feather damage in these regions. Another source of differences between the FS and IRT parameters is the fact, that the relationship between temperature and the FS is quadratic (Cook *et al*., 2006; Cook and Schaefer, 2013). Cook *et al*. (2006) also found that the relationship between the mean image temperature obtained by the IRT and FS was dependent on the direction of the capture. They were statistically stronger for the dorsal and ventral views relative to the front view.

FS is an accepted animal-based indicator of the welfare of laying hens. We showed a highly significant positive relationship between the IRT (ΔT_B and FL%) and FS assessment of feather cover. Our findings support the feasibility of IRT assessment of feather cover quality in laying hens. An adoption of thermal imaging technology enables the reliable measurement of plumage quality and avoids the problems of FS method such as the reliability of data obtained by different assessors. However, the use of IRT in commercial conditions requires further standardization of the methodology to obtain consistent data.

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References

Abrahamsson P 1996. Furnished cages and aviaries for laying hens. Effects on production, health and use of facilities. Report No. 9157650829, Swedish University of Agricultural Sciences, Uppsala, Sweden, pp. 1–30.

Bilčík B and Keeling L 1999. Changes in feather condition in relation to feather pecking and aggressive behaviour in laying hens. British Poultry Science 40, 444–451.

Cangar Ö, Aerts J-M, Buyse J and Berckmans D 2008. Quantification of the spatial distribution of surface temperatures of broilers. Poultry Science 87, 2493–2499.

Cook N and Schaefer A 2013. Infrared thermography and disease surveillance. In Thermography: current status and advances in livestock animals and in veterinary medicine (ed. F Luzi, M Mitchell, L Nanni Costa and V Redaelli), pp. 79–92. Fundazione Iniziative Zooprofilattiche e Zootecniche – Brescia, Brescia, Italy.

Cook N, Smykot A, Holm D, Fasenko G and Church J 2006. Assessing feather cover of laying hens by infrared thermography. The Journal of Applied Poultry Research 15, 274–279.

Forkman B and Keeling L (eds) 2009. Assessment of animal welfare measures for layers and broilers. Report No. 1902647793, School of City and Regional Planning, Cardiff, Wales, p. 176.

Glatz P 2001. Effect of poor feather cover on feed intake and production of aged laying hens. Asian-Australasian Journal of Animal Sciences 14, 553–558.

Hughes B 1983. The effects of methionine deficiency and egg production on feather loss in caged layers. British Poultry Science 24, 549–553.

Hughes BO and Michie W 1982. Plumage loss in medium-bodied hybrid hens: the effect of beak trimming and cage design. British Poultry Science 23, 59–64.

Keeling L 1995. Feather pecking and cannibalism in layers. Poultry International 34, 46–50.

Leonard M, Horn A and Fairfull R 1995. Correlates and consequences of allopecking in White Leghorn chickens. Applied Animal Behaviour Science 43, 17–26.

Mills A, Faure J and Williams J 1988. Feather loss and egg production in broiler breeders and layers. Annales de Zootechnie 37, 133–142.

Mollenhorst H, Rodenburg T, Bokkers E, Koene P and De Boer I 2005. On-farm assessment of laying hen welfare: a comparison of one environment-based and two animal-based methods. Applied Animal Behaviour Science 90, 277–291.

Nääs IA, Romanini CEB, Neves DP, Nascimento GR and Vercellino RA 2010. Broiler surface temperature distribution of 42 day old chickens. Scientia Agricola 67, 497–502.

Nichelmann M, Baranyiova E, Goll R and Tzschentke B 1986. Influence of feather cover on heat balance in laying hens (*Gallus domesticus*). Journal of Thermal Biology 11, 121–126.

Nicol C, Bestman M, Gilani A, De Haas E, De Jong I, Lambton S, Wagenaar J, Weeks C and Rodenburg T 2013. The prevention and control of feather pecking: application to commercial systems. World's Poultry Science Journal 69, 775–788.

Nicol C, Caplen G, Edgar J and Browne W 2009. Associations between welfare indicators and environmental choice in laying hens. Animal Behaviour 78, 413–424.

Norgaard-Nielsen G, Vestergaard K and Simonsen H 1993. Effects of rearing experience and stimulus enrichment on feather damage in laying hens. Applied Animal Behaviour Science 38, 345–352.

Savory C 1995. Feather pecking and cannibalism. World's Poultry Science Journal 51, 215–219.

Sherwin C, Richards G and Nicol C 2010. Comparison of the welfare of layer hens in 4 housing systems in the UK. British Poultry Science 51, 488–499.

Tao X and Xin H 2003. Surface wetting and its optimization to cool broiler chickens. Transactions of the ASABE 46, 483–490.

Tauson R 1984. Plumage condition in SCWL laying hens kept in conventional cages of different designs. Acta Agriculturae Scandinavica 34, 221–230.

Tauson R, Ambrosen T and Elwinger K 1984. Evaluation of procedures for scoring the integument of laying hens – independent scoring of plumage condition. Acta Agriculturae Scandinavica 34, 400–408.

Taylor AA and Hurnik JF 1994. The effect of long-term housing in an aviary and battery cages on the physical condition of laying hens: body weight, feather condition, claw length, foot lesions, and tibia strength. Poultry Science 73, 268–273.

Welfare Quality® 2009. Welfare Quality® assessment protocol for poultry (broilers, laying hens). Welfare Quality® Consortium, Lelystad, The Netherlands.

Wolfenson D 1986. The effect of acclimatization on blood flow and its distribution in normothermic and hyperthermic domestic fowl. Comparative Biochemistry and Physiology Part A: Physiology 85, 739–742.

Wood-Gush D and Rowland C 1973. Allopreening in the domestic fowl. Revue du Comportement Animal 7, 83–91.

Yahav S, Luger D, Cahaner A, Dotan M, Rusal M and Hurwitz S 1998. Thermoregulation in naked neck chickens subjected to different ambient temperatures. British Poultry Science 39, 133–138.

Zhao Y, Xin H and Dong B 2013. Use of infrared thermography to assess laying-hen feather coverage. Poultry Science 92, 295–302.