Applied Animal Behaviour Science 145 (2013) 44–50

Contents lists available at SciVerse ScienceDirect

Applied Animal Behaviour Science

journal homepage: www.elsevier.com/locate/applanim

In search of the behavioural correlates of optical flow patterns in the automated assessment of broiler chicken welfare

Marian Stamp Dawkins[a,*], Russell Cain[a], Kathryn Merelie[a], Stephen J. Roberts[b]

[a] University of Oxford, Department of Zoology, South Parks Road, Oxford OX1 3PS, UK
[b] University of Oxford, Department of Engineering Science, Parks Road, Oxford OX1 3PJ, UK

ARTICLE INFO

Article history:
Accepted 3 February 2013
Available online 6 March 2013

Keywords:
Broiler chicken welfare
Hockburn
Pododermatitis
Gait
Optical flow
Behaviour

ABSTRACT

Assessment of chicken welfare using camera surveillance of behaviour has great potential as a supplement to good stockmanship and as an aid to improving flock management. Suitable cameras are now readily available and the automated analysis of the lengthy video sequences from the cameras can be accomplished from statistical descriptors of the 'optical flow' patterns produced by flock movements. However, although optical flow measures have been shown to correlate with welfare outputs such as mortality, hockburn, pododermatitis and gait score, it is not yet clear how the optical flow algorithms achieve this – i.e. what variation in behaviour of individuals the cameras are picking up.

The aim of this paper is to clarify the relationship between optical flow, behaviour and welfare by correlating optical flow (mean, variance, skew and kurtosis) taken from 15 min video sequences of commercial broilers at 25 days of age with bird behaviour recorded from the same sequences and with welfare measures from the same flocks ($n = 24$). There were no significant between-flock correlations (r^2) between mean optical flow and % birds walking, % sitting/lying, walking speed or an estimate of the numbers of birds walking continuously for 10 s. or longer ($p > 0.02$, 2-tailed). Mean % birds walking was, however, significantly and negatively correlated with hock burn ($r^2 = -0.44$ $p < 0.05$). Skew and kurtosis of optical flow showed no correlation with % birds walking, % birds sitting/lying or with walking speed ($p > 0.02$) but were significantly and positively correlated with the number of birds walking continuously for at least 10 s (for skew, $r^2 = 0.51$, $p < 0.01$; for kurtosis, $r^2 = 0.46$, $p < 0.05$).

We conclude that there is no simple connection between optical flow and behaviour or between the behaviour recorded here and mortality, hockburn, pododermatis and gait score. However, reduced numbers of birds walking continuously for 10 s or more appear to be responsible for the increased kurtosis of flow in flocks with higher (less good) gait scores. Optical flow measures correlate more strongly these welfare outcomes than any single behavioural measure.

1. Introduction

Continuous, automated monitoring of commercial broiler chicken (*Gallus gallus*) flocks is potentially a major way of improving both welfare and production, not as a substitute for good stockmanship, but as an objective supplement to current methods that are often applied post-mortem (Allain et al., 2009) or are very labour intensive (e.g. gait scoring (Kestin et al., 1992)). With the many thousands of chickens found in modern broiler houses, remote sensing with cameras is a promising route for continuous monitoring on commercial farms. But while the required camera equipment is now inexpensive and readily available, there

* Corresponding author: Tel.: +44 01865 271215; fax: +44 01865 310447.
E-mail address: marian.dawkins@zoo.ox.ac.uk (M.S. Dawkins).

0168-1591/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.applanim.2013.02.001

are still major difficulties in analysing and making sense of the vast quantities of video data such cameras produce. Unless this analysis can be fully automated to give practical health and welfare information of use to producers, the full potential of camera data as a monitoring tool will remain untapped.

One solution to the problem of automating data analysis is to use the patterns of 'optical flow' (Sonka et al., 1999) created by the natural movement of flocks of chickens as they move around a house. Optical flow analysis works by detecting the rate of change of brightness in different parts of a moving visual image. An advantage of this method is that it is computationally very simple, making it ideal for continuous automated monitoring of large groups of commercial layers (Lee et al., 2011) or broiler (meat) chickens (Aydin et al., 2010; Dawkins et al., 2009, 2012; Kristensen and Cornou, 2011). More importantly, statistical measures of optical flow, particularly mean, skew and kurtosis of movement distributions, have been shown to yield highly informative correlations with key welfare measures in broilers such as % mortality, gait score and hockburn (Dawkins et al., 2012; Roberts et al., 2012). However, it is so far not clear exactly how these correlations arise – that is, how optical flow patterns are causally related to the behaviour and welfare of individual birds. The main aim of this paper is therefore to establish how differences between broiler flocks in their optical flow characteristics are related to differences in bird behaviour. A second aim is to see whether differences in behaviour can in turn be correlated with the four measures of welfare – mortality, gait, hockburn and pododermatitis- that have already been shown to correlate with optical flow (Dawkins et al., 2012; Roberts et al., 2012), thus clarifying the causal connections between welfare, behaviour and optical flow.

We tested two hypotheses. The first hypothesis was that variations in mean optical flow are primarily due to variation in the proportion of birds sitting, standing or walking. Commercial broiler chickens may spend 70%–80% of their time lying or sitting (Bizeray et al., 2002; Murphy and Preston, 1988), the exact proportion depending on age (Newberry et al., 1988; Weeks et al., 2000) and other factors such as light intensity (Alvino et al., 2009). Birds with worse walking ability (higher gait scores) also sit down more quickly after a disturbance than birds that walk well (Berg and Sanotra, 2003). Thus, this hypothesis predicts that increased optical flow will be correlated positively with the % of birds walking and negatively with the % of birds sitting or not moving.

The second hypothesis was that variation in optical flow patterns is primarily due to variation in walking speed of individual birds. Birds with poor gaits walk more slowly than birds with better gaits (Dawkins et al., 2009; Caplen et al., 2012) and so a flock with a high % of birds with poorer gaits would be expected to have an overall lower mean rate of movement than a healthy flock. Such flocks would also be less uniform (made up of birds with a wider range of gait scores e.g. 0, 1, 2, 3) than flocks composed entirely of birds that walked without difficulty (0, 1). The resulting increase in positive skew (more slow movers) and kurtosis (more birds moving in an extreme way) leads to the prediction that the mean optical flow rate will be positively correlated with the mean speed of walking of individual birds and that both skew and kurtosis will be correlated with mean walking speed.

The two hypotheses are not mutually exclusive and differ primarily in whether optical flow measures correlate more closely with the numbers of birds sitting/walking or with speed of walking of individual birds. To distinguish between the two hypotheses, we compared the behaviour of individual chickens as observed from video sequences with the optical flow results from the same video sequences. To clarify the connection between welfare, behaviour and optical flow, we also correlated bird behaviour with four measures of welfare: mortality, gait score (lameness), hockburn and pododermatitis.

2. Materials and methods

2.1. Animals

The video sequences used for this study were obtained from 24 commercial broiler flocks from a single site in the UK. The chickens were of mixed sexes and of one of two commercial broiler breeds. They were placed in the houses as day-olds (33,000–35,000/house) and grown to 35 days old with a target final stocking density of 38 kg/m^2. Each house was 1670 m^2 and contained 488 feed pans and 1735 water nipples. Lighting, feeding, temperature and other husbandry regimes were in accordance with practice recommended by the breeder companies (Cobb, 2008; Aviagen, 2009). Further details are given in Dawkins et al. (2012).

2.2. Camera equipment

Two pairs of cameras (Logitech International S.A. Plc., Romanel-sur-Morges, Switzerland) were installed at a height of 200 cm (±10 cm) in each house, each pair connected to a small form-factor (115 mm × 101 mm × 27 mm) industrial PC (Fit-PC2, Anders Electronics Plc., London, UK) enclosed in a protective waterproof casing and connected to a domestic power supply. The computers were programmed to record and analyze a 15 min section of video from each of their two cameras every 45 min between 0800 h and 2000 h. The house lights were always on when the cameras came on at 0800 h but in some houses the lights went off at around 1930 (the precise time varied between houses and was not under our control) so that the actual data used was collected between 0800 and 1930. We did not analyze the behaviour of birds after the lights went out. The equipment was left running from day 1 to day 35, when the birds were cleared.

2.3. Production and welfare data

The production company supplied the following information after the end of the flock: total mortality (% of flock dead before slaughter); total culls (% total mortality due to culling); daily mortality and culls (recorded on a daily basis by the farm manager); growth rate (average daily bird growth weight calculated from daily recording with automatic weighers in each house and additional weekly weighings by hand; hock burn (% of birds with any permanent discoloration to the hocks, assessed at the slaughter plant post mortem and after cleaning and defeathering); pododermatitis (% of birds with any lesion to foot pad, assessed at the slaughter plant post mortem and after cleaning and defeathering).

Gait scores were collected by the farm manager who had been trained to use the 6-point Bristol Gait Score (Kestin et al., 1992) and gait scored 60 birds/house on day 28. The results were expressed as a mean gait score for that flock. As a validation of this data, a second observer used a 3-point score (Dawkins et al., 2004; Webster et al., 2008) and gait scored a total of 100 individuals on days 32–34. On the first half of the data, the two scores were significantly positively correlated (Spearman rank correlation: $r_s = 0.71$, $N = 12$, $p < 0.01$), which was taken as validation of the observer.

2.4. Behaviour analysis from video

From the large optical flow data set (08.00–20.00 h video from 4 cameras from 24 flocks throughout their lives), we chose to analyze in detail the behavioural data from one 15 min section every 45 min from one camera from each flock at day 25, giving 16 sections/flock. Day 25 was chosen as a day close to gait scoring but when no flocks were being disturbed by gait scoring itself. Using birds of the same age minimized the potentially confounding effects of artefacts such as changing bird size.

2.5. Proportion of sitting and walking birds

To assess the proportion of birds engaged in different behaviours, we used scan sampling (Martin and Bateson, 2007), taking one scan sample from each 15 min section throughout the day. The video was played through a computer and the scan sample was taken two minutes after the beginning of each section to avoid artefacts due to camera switching at the beginning of a section. For each scan sample, the video was stopped and a transparent acetate sheet was placed over the computer screen. Each chicken appearing on the video was circled in a different colour depending on its behaviour. The following behaviours were scored: (1) sitting, using the terminology of Alvino et al. (2009) rather than that of Bizeray et al. (2002) who use the term ‘lying’; (2) ‘Walking’ defined as a bird fully standing up and taking steps and was distinguished from instances when a chicken moved without fully standing up – for example, if a bird shuffled along on its hocks rather than walking on its feet; (3) ‘Other’, which included such shuffling and standing without walking along with other instances when the behaviour was unclear, for example, if the bird were in the act of standing up or sitting down or engaged in behaviour that was not recorded separately, such as dustbathing. The overhead cameras made it easy to see if a bird walking or sitting but difficult to distinguish other behaviour, which is why the ‘other’ category is so diverse. The number of birds circled in each colour was then counted to give both a total number and a % of birds engaged in each behaviour. Birds at the edge of the video frame were excluded if it was not clear what they were doing. Ambiguity about whether a bird was walking or standing were resolved by moving the video on by one or two frames.

For each flock, the day’s 16 scan samples were averaged to give a single daily mean for each behaviour, so that $n = 24$, with the flock being the unit of analysis.

2.6. Measurement of walking speed

For each of the 24 flocks, the same sections of video described above were reanalyzed to measure the walking speed of 50 birds/flock. For each 15 min section, three to five walking birds were identified, so that the 50 walking incidents were spread throughout the day. ‘Walking’ for this analysis was defined as a bird walking without sitting down for at least 10 s (Note that this is different from the definition of walking used in the previous instantaneous scan sampling). 10 s was chosen because it gave the most direct comparison to the ‘10 steps’ used in gait scoring live birds (Kestin et al., 1992) even though the birds’ legs were not always visible on the video. Birds walking for at least 10 s also often had a distinctive oval shape (as opposed to the round shape of a sitting bird or one that shuffled for a couple of steps). If a bird stopped (without sitting) and then started walking again within 2–3 s, this was still counted as a walking bout, provided that the bird was moving at both the beginning and end of the 10 s period and had not sat down. To measure the speed of walking during the 10 s, an acetate sheet was placed against the computer screen on which the video was shown and a marker pen used to draw around the outline of the bird as it moved through the 10 s every two seconds. The path the bird took was measured with a ruler and a note made of the apparent size of the bird with the same ruler, so that all measurements of walking speed could be standardized as distance/body length. If the bird moved across the screen in such a way that its apparent body size changed, the median body size of all outlines was used. The 50 walking speeds/flock were converted to single measures per flock (mean, sd, coefficient of variation, range), with $n = 24$, the number of flocks.

2.7. Latency to identify a bird walking for at least 10 s

The same video blocks/flock as described above were analyzed a third time to measure the time from the beginning of each block to the first occurrence of a bird walking for at least 10 s. All the latencies for the day were then converted into a single mean latency for each flock ($n = 24$).

2.8. Optical flow analysis

The optical flow analysis involved detecting the rate of change of brightness in each area of an image frame through time (Sonka et al., 1999). Each image frame in the video was divided into 1200 ($= 40 \times 30$) 8-by-8 pixel blocks and the rate of change of image brightness was calculated for each block. The mean optical flow was calculated as the average change in image brightness across the whole frame over the 15 min section.

Table 1
Correlations (Pearson) between optical flow measures and the mean % of birds engaged in different behaviours on day 25 for 24 flocks.

Behaviour	Mean optical flow	Variance optical flow	Skew optical flow	Kurtosis optical flow
% Sitting (mean = 85.7% sd = 5.1 range: 77.7–94.0)	$r^2 = 0.15$	$r^2 = 0.16$	$r^2 = -0.06$	$r^2 = -0.04$
% Walking (mean = 7.2% sd = 4.3 range: 2.08–14.86)	$r^2 = -0.05$	$r^2 = -0.46^*$	$r^2 = -0.27$	$r^2 = -0.32$
% Other (mean = 7.0% sd = 3.3 range:2.6–15.8)	$r^2 = -0.20$	$r^2 = 0.33$	$r^2 = 0.45^*$	$r^2 = 0.48^§$

* $p < 0.05$.
§ $p < 0.02$ 2-tailed.

The computer automatically delivered four optical flow measures (mean, variance, skew and kurtosis) extracted from each sequence of 3600 image frames, representing a 15 min sequence of real time. Further details are given in Dawkins et al. (2009) and Lee et al. (2011). For the comparisons between flocks, values for all the 15 min sequences throughout the day were averaged to give a single datum for each of the four optical flow measures for each flock ($n = 24$).

2.9. Statistical analysis

A Pearson correlation was used to test for associations. In each case, two tailed tests were used.

3. Results

3.1. Percentage of birds sitting, standing and walking

The predicted negative correlation between % birds sitting and mean optical flow was not found nor was the predicted positive correlation between % birds walking and optical flow. The correlations between the daily mean % of birds sitting and walking and the daily mean, skew and kurtosis of optical flow are shown in Table 1. The numbers of birds in each frame varied considerably (60–200+). However, the results were similar whether the percentage of birds sitting, standing and walking or the absolute numbers were used (Table 2). In both cases, the category of behaviour designated as ‘other’ was significantly and positively correlated with both skew and kurtosis.

3.2. Walking speed

The correlations between walking speed and optical flow measures are shown in Table 3. The predicted correlations between skew and kurtosis of optical flow with the range of walking speeds were not observed.

3.3. Number of birds walking for at least 10 s

The time from the start of a 15 min video section to identifying a bird walking for at least 10 s (latency) was used as a proxy measure of the numbers of birds walking for at least 10 s in that section. The correlation between the mean latency and the various optical flow measures are shown in Table 4. There was no correlation between this latency and mean optical flow. There were, however, negative correlations between this latency and both the skew and kurtosis of flow: the higher the skew and kurtosis, the smaller the number of birds walking for 10 s or more.

3.4. Welfare and production data

The correlations between the behaviour measures and production measures are shown in Table 5. All four measures of reduced welfare (higher % mortality, higher (worse) gait scores, higher incidence of hock burn and pododermatitits) were positively associated with a higher % of birds sitting and negatively associated with a higher % of birds walking for more than 10 s, but only the correlation between % birds walking and % with hockburn reached statistical significance.

4. Discussion

4.1. Behaviour and optical flow

Neither of the two hypotheses we tested about how optical flow in broiler chicken flocks is causally related to the behaviour of individual birds was upheld. The mean optical flow was not significantly correlated with either the proportion or the absolute numbers of birds sitting

Table 2
Correlations (Pearson) between optical flow measures and the mean absolute number of birds engaged in different behaviours for day 25 for 24 flocks.

Behaviour	Mean optical flow	Variance optical flow	Skew optical flow	Kurtosis optical flow
SIt	−0.03	−0.03	0.06	0.01
Walk	−0.16	−0.44*	−0.13	−0.20
Other	−0.26	0.25	0.46*	0.43*

* $p < 0.05$, 2-tailed.

Table 3
Correlations (Pearson) between optical flow measures and mean speed of walking in birds walking for at least 10 s.

Walking speed (body lengths/second)	Mean optical flow	Variance optical flow	Skew optical flow	Kurtosis optical flow
Mean (0.4 sd = 0.1)	$r^2 = 0.22$	$r^2 = 0.47^*$	$r^2 = 0.20$	$r^2 = 0.22$

* $p < 0.05$, 2 tailed.

Table 4
Correlations between optical flow measures and the latency from the beginning of a 15 min block to the occurrence of the first bird walking for at least 10 s. For each flock, the latencies in successive 15 min blocks were averaged over the day to give a single mean.

Time to first 10 s + walker	Mean optical flow	Variance optical flow	Skew optical flow	Kurtosis optical flow
Mean = 57.7 s sd = 33.6 Range:6.9–125.8	$r^2 = -0.11$	$r^2 = -0.47^*$	$r^2 = 0.51^{**}$	$r^2 = 0.46^*$

* $p < 0.05$, 2-tailed.
** $p < 0.01$, 2 tailed.

down or walking (Tables 1 and 2) nor to the speed of walking as measured in birds walking for longer than 10 s (Table 3). This means that simple explanations that a higher mean flow can be explained by a greater % of birds walking or by birds walking faster are clearly inadequate.

On the other hand, variation in optical flow, as measured by variance, skew and kurtosis in the distribution of flow are often more closely correlated with what the birds are doing than just the mean optical flow (Tables 1–3). This suggests that what characterizes flocks with reduced welfare is that they are more variable in their behaviour than healthy flocks. For example, in flocks where most of the birds walk without difficulty, they will be recorded as having a narrow range of gait scores (0, 1 or 2 (Kestin et al., 1992)). But even in less healthy flocks, not all the birds will have poor gaits. There will still be some that are scored as 0, 1 or 2 but there will also be birds scored as higher than 2. There will thus be a wider spread of scores as well as a higher (worse) mean. Our current working hypothesis is that this wider spread, as evidenced particularly by the skew and kurtosis in some flocks, is due to the wider variety of movement seen in less healthy flocks. Healthy birds move uniformly in the same healthy ways. Less healthy ones show greater variety.

This revised (uniformity is healthy) hypothesis also finds support from the unexpected correlations that were found between optical flow and 'other' behaviour. 'Other' behaviour constituted the minority (7%) of behaviours but had significant positive correlations with and skew and kurtosis (Tables 1 and 2). This category was very diverse (it included dustbathing, birds in the process of standing up or sitting down and birds shuffling on their hocks rather than walking) As our main focus in this study was on the correlations between optical flow and the two commonest behaviours – active walking and sitting – we did not distinguish between the different categories of 'other' behaviour, but it would clearly repay more detailed investigation in future.

Further support for the uniformity is healthy hypothesis also comes from the result that the latency to identify a bird walking for at least 10 s within a 15 min block was correlated with both the skew and kurtosis of optical flow (Table 4). The longer this latency (the lower the probability of encountering a bird walking for at least 10 s), the higher the (left) skew to the flow distribution, reflecting the greater number of birds moving below the mean value and the higher the kurtosis. This suggests that birds that keep walking for at least 10 s are being detected as oddities in the optical flow output of less healthy flocks where it is unusual for birds to walk for 10 s without sitting down. In healthier flocks, where walking for much more than 10 s is the norm, such long distance walkers do not stand out from the rest of the flock and there is consequently a low kurtosis in the healthiest flocks. Almost paradoxically, then, it seems that it may be the smaller number of healthy (>10 s) walkers that are still found in less healthy flocks that are contributing to the higher kurtosis found in less healthy flocks. When healthy, normal walking becomes unusual within a flock, that is

Table 5
Correlations (Pearson) between behaviour and mortality, gait, hockburn and pododermatitis.

	% Lying	% Walking	% Other	Walking speed	No. birds walking >10 s.
Mortality	0.05	−0.14	0.10	−0.03	−0.23
Gait	0.06	−0.27	−0.27	0.14	−0.21
Hock	0.27	−0.44*	0.16	0.23	−0.17
Podo	0.06	−0.27	0.26	0.03	−0.07

*** $p < 0.01$, 2-tailed.
* $p < 0.02$, 2-tailed.

a sign that the welfare of the flock as a whole may be reduced.

4.2. Behaviour, welfare and production

We have previously shown that optical flow, particularly a combination of mean, variance, skew and kurtosis cumulated over time is correlated with gait, hockburn and mortality (Dawkins et al., 2009, 2012; Roberts et al., 2012). We had therefore expected that behaviour such as the percentage of birds walking or sitting down might also be correlated with measure of bird welfare such as the incidence of hockburn or poor gaits. However, just as we failed to detect simple behavioural explanations for between flock variation in optical flow, so we equally failed to find correlations between behaviour and measures of bird health and welfare. The behavioural measures we used (% birds sitting, % birds walking, speed of walking and number of birds walking for more than 10 s) were not correlated with mortality, lameness, hockburn or pododermatitis (Table 5). Only the percentage of birds with hockburn showed a significant negative correlation with the percentage of birds walking (Table 5).

As with the interpretation of optical flow, the connection between what the birds do and their health and welfare is not simple. Pododermatitis and hockburn, for example, have multiple causes and are sometimes, but not always correlated at either flock or individual level (Allain et al., 2009; Haslam et al., 2007; Meluzzi et al., 2008; Shepherd and Fairchild, 2010;). The causes of both are multifactorial (Hepworth et al., 2010, 2011; de Jong et al., 2012; Shepherd and Fairchild, 2010) and although litter moisture is often cited as a major factor (Haslam et al., 2007; Mayne et al., 2007; Shepherd and Fairchild, 2010), it is not the only one. Genetics (Ask, 2010; Kapell et al., 2012), litter composition (Eichner et al., 2007; Nagaraj et al., 2007) and how much time the legs and feet of the birds are actually in contact with wet litter will all play a part (Hermans et al., 2006).

Lameness, high mortality and other signs of poor welfare also have multiple causes and different manifestations (Bradshaw et al., 2002; Knowles et al., 2008). The lack of clear cut correlations with single behaviours results reported in this paper therefore reinforces, rather than detracts from, the plausibility of optical flow in the assessment of welfare. Optical flow, particularly where the analysis is done using a combined statistical measure (Roberts et al., 2012) appears to do more than just pick out particular behaviours such as walking or sitting. Even though we do not yet understand exactly what behaviour it is detecting, optical flow appears to be effective at detecting complex multifactorial welfare outcomes and more so than our attempts to relate welfare outcomes to single behaviours.

5. Conclusions

Commercial flocks of broiler chickens differ in the characteristics of their patterns of optical flow produced by the movements of the birds (Dawkins et al., 2009, 2012; Roberts et al., 2012) but it is still not clear how these patterns are generated at the behavioural level. In this paper we have shown that the most obvious hypothesis – that flocks with a higher mean level of optical flow are those where more birds are walking around and fewer are sitting – is not supported by the evidence. Nor is mean optical flow rate correlated with the average speed with which individual birds walk, at least for those that are on their feet for at least 10 s.

We conclude that the most likely explanation for the observed correlations between optical flow and welfare measures (hockburn, pododermatitis, mortality and walking ability) is that optical flow is sensitive to the uniformity or lack of it in flock behaviour, as evidenced by the variance, skew and kurtosis of the movement distribution. If all birds in a flock are showing a similar range of behaviour – for example, all are walking evenly and well – that flock will have a lower skew and kurtosis than a flock in which some individuals walk well and others less well. A small number of healthy walkers in a flock that contains many birds that walk less well will stand out 'like sore thumbs' and be detected as outliers (high kurtosis) in comparison to the others. A combination of mean, variance, skew and kurtosis of optical flow through the whole history of a flock is more informative about flock welfare (Roberts et al., 2012) than any single behavioural measure so far.

Acknowledgement

We are very grateful to the BBSRC for funding this work.

References

Allain, V., Mirabito, L., Arnould, C., Colas, M., Le Bouquin, S., Lupo, C., Michel, V., 2009. Skin lesions in broiler chickens measured at the slaughterhouse: relationships between lesions and between their prevalence and rearing factors. Br. Poult. Sci. 50, 407–417.

Alvino, G.M., Archer, G.S., Mench, J.A., 2009. Behavioural time budgets of broiler chickens reared in varying light intensities. Appl. Anim. Behav. Sci. 118, 54–61.

Ask, B., 2010. Genetic variation of contact dermatitis in broilers. Poult. Sci. 89, 866–875.

Aviagen, 2009. Ross Broiler Management Manual. Aviagen, Newbridge http://www.aviagen.com

Aydin, A., Cangar, O., Ozcan, S.E., Bahr, C.a., Berckmans, D., 2010. Application of a fully automated analysis tool to assess the activity of broiler chickens with different gait scores. Comput. Electron. Agric. 73, 194–199.

Berg, C., Sanotra, G.S., 2003. Can a modified latency-to-lie be used to validate gait-scoring results in commercial broiler flocks? Anim. Welfare 12, 655–659.

Bizeray, D., Estevez, I., Leterrier, C., Faure, J.M., 2002. Effects of increasing environmental complexity on the physical activity of broiler chickens. Appl. Anim. Behav. Sci. 79, 27–41.

Bradshaw, R.H., Kirkden, R.D., Broom, D.M., 2002. A review of the aetiology and pathology of leg weakness in broilers in relation to welfare. Avian Poult. Biol. Rev. 13, 45–103.

Caplen, G., Hothersall, B., Murrell, C., Nicol, C.J., Waterman-Pearson, A.E., Weeks, C.A., Colbourne, G.R., 2012. Kinematic analysis quantifies gait abnormalities associated with lameness in broiler chickens and identifies evolutionary gait differences. PLoS One 7 (7) [1932–6203].

Cobb, 2008. Broiler Management Guide. Cobb-Vantress, Siloam Springs, Arkansas http://www.Cobb-vantress.com/contactus/brochures/Broiler_Mgmt_Guide_2008.pdf

Dawkins, M.S., Donnelly, C.A., Jones, T.A., 2004. Chicken welfare is influenced more by housing conditions than stocking density. Nature 427, 342–344.

Dawkins, M.S., Lee, H.-J., Waitt, C., Roberts, S.J., 2009. Optical flow patterns in broiler chicken flocks as automated measures of behaviour and gait. Appl. Anim. Behav. Sci. 119, 203–209.

Dawkins, M.S., Cain, R., Roberts, S.J., 2012. Optical flow, flock behaviour and chicken welfare. Anim. Behav. 84, 219–223.

Eichner, G., Vieira, S.L., Torres, C.A., Coneglian, J.L.B., Freitas, D.M., Oyarzabal, O.A., 2007. Litter moisture and foot pad dermatitis as affected by diets formulated on an all-vegetable basis or having the inclusion of poultry by-product. J. Appl. Poult. Sci. 16, 344–350.

Haslam, S.M., Knowles, T.G., Brown, S.N., Wilkins, L.J., Kestin, S.C., Warris, P.D., Nicol, C.J., 2007. Factors affecting the prevalence of foot pad dermatitits, hock burn and breast burn in broiler chicken. Br. Poult. Sci. 47, 13–18.

Hepworth, P.J., Nefedov, A.V., Muchnik, I.B., Morgan, K.L., 2010. Early warning indicators for hock burn in broiler flocks. Avian Path. 39, 405–409.

Hepworth, P.J., Nefedov, A.V., Muchnik, I.B., Morgan, K.L., 2011. Hock burn: an indicator of broiler flock health. Vet. Rec., 168.

Hermans, P.G., Fradkin, D., Muchnik, I.B., Morgan, K.L., 2006. Prevalence of wet litter and the associated risk factors in broiler flocks in the United Kingdom. Vet. Rec. 158, 615–622.

Jong, I.C. de, Harn, J. van, Gunnink, H., Hindle, V.A., Lourens, A., 2012. Footpad dermatitis in Dutch broiler flocks: prevalence and factors of influence. Poult. Sci. 91, 1564–1574.

Kapell, D.N.R.G., Hill, W.G., Neeteson, A.-M., McAdam, J., Koerhuis, A.N.M., Avendano, S., 2012. Genetic parameters of foot-pad dermatitis and body weight in purebred broiler lines in 2 contrasting environments. Poult. Sci. 91, 565–574.

Kestin, S.C., Knowles, T.G., Tinch, A.E., Gregory, N.G., 1992. Prevalence of leg weakness in broiler chickens and its relationship to genotype. Vet. Rec. 131, 190–194.

Knowles, T.G., Kestin, S.C., Haslam, S.M., Brown, S.N., Green, L.E., Butterworth, A., Pope, S.J., Pfeiffer, D., Nicol, C.J., 2008. Leg disorders in chickens: prevalence, risk factors and prevention. Plos One, 3.

Kristensen, H.H., Cornou, C., 2011. Automatic detection of deviations in activity levels in groups of broiler chickens – a pilot study. Biosyst. Eng. 109, 369–376.

Lee, H.-J., Roberts, S.J., Drake, K.A., Dawkins, M.S., 2011. Prediction of feather damage in laying hens using optical flows and Markov models. J. R. Soc. Interface 8, 489–499.

Martin, P., Bateson, P., 2007. Measuring Behaviour. Cambridge University Press, Cambridge.

Mayne, R.K., Else, R.W., Hocking, P.M., 2007. High litter moisture alone is sufficient to cause footpad dermatitis in growing turkeys. Br. Poult. Sci. 48, 538–545.

Meluzzi, A., Fabbri, C., Folegatti, E., Sirri, F., 2008. Survey of chicken rearing conditions in Italy: effects of litter quality and stocking density on productivity, foot dermatitis and carcase injuries. Br. Poult. Sci. 49, 257–264.

Murphy, L.B., Preston, A.P., 1988. Time-budgeting in meat chickens grown commercially. Br. Poult. Sci. 29, 671–680.

Nagaraj, M., Wilson, C.A.P., Hess, J.B., Bilgill, S.F., 2007. Effect of high-protein and all-vegetable diets on the incidence and severity of pododermatitis in broiler chickens. J. Appl. Poult. Sci. 18, 394–312.

Newberry, R.C., Hunt, J.R., Gardier, E.E., 1988. Influence of light on behaviour and performance of broiler chickens. Poult. Sci. 87, 1020–1026.

Roberts, S.J., Cain, R., Dawkins, M.S., 2012. Prediction of welfare outcomes from broiler chickens using Bayesian regression on continuous optical flow data. R. Soc. J. Interface 9, 3436–3443.

Shepherd, E.M., Fairchild, B.D., 2010. Footpad dermatitis in poultry. Poult. Sci. 89, 2043–2051.

Sonka, M., Hlavac, V., Boyle, R., 1999. Image Processing Analysis and Machine Vision, second edn. PWS Publishing, London.

Webster, A.B., Fairchild, B.D., Cummings, T.S., Sayer, P.A., 2008. Validation of a three-point gait-scoring systems for field assessment of walking ability of commercial broilers. J. Appl. Poult. Res. 17, 529–539.

Weeks, C.A., Danbury, T.D., Davies, H.C., Hunt, P., Kestin, S.C., 2000. The behaviour of broiler chickens and its modification by lameness. Appl. Anim. Behav. Sci. 67, 111–125.