THE EFFECT OF MORPHOLOGY ON WALKING ABILITY IN THE MODERN BROILER: A GAIT ANALYSIS STUDY

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Abstract

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*This study tests the hypothesis that growth rate and bodyweight affect walking ability in broilers by comparing objective measurements of the spatial and temporal gait parameters of several groups of birds. Two strains of birds were used (relaxed and selected), raised on two feeding regimes (*ad-libitum *and restricted), and culled at the same final bodyweight (commercial cull weight of 2.4 kg). The* ad-libitum-*fed selected birds walked more slowly, with lower cadences, and took shorter steps. The steps were wider, and the toes were pointed outwards, resulting in a wider walking base. They kept their feet in contact with the ground for longer periods, having longer percentage stance times, shorter percentage swing times and increased double-contact times compared to the relaxed birds. These changes serve to increase stability during walking and are a likely consequence of the morphological changes in the selected broiler — in particular, the rapid growth of breast muscle moving the centre of gravity forward, and the relatively short legs compared to their bodyweight (see Corr et al, pp 145–157, this issue). This altered gait would be very inefficient and would rapidly tire the birds, and could help to explain the low level of activity seen in the modern broiler.*

Keywords: *animal welfare, gait, lameness, morphology, musculoskeletal, poultry*

Introduction

Lameness is a major problem in the poultry industry (Sainsbury 1999; Bennett *et al* 1999; McGeown *et al* 1999), and the incidence of leg problems has been shown to correlate highly with liveweight/growth-rate (Vestergaard & Sanotra 1999; Kestin *et al* 2001). There is much debate as to whether pain is a significant causal factor of abnormal gait (Kestin *et al* 1992; Hocking 1994; Gentle & Corr 1995; Pickup *et al* 1997). Whereas some studies have shown an increase in activity following the administration of analgesia (McGeown 1999), others have not (Hocking 1994).

Some research has shown that along with the rapid growth rate to high bodyweight, the modern broiler has been selected to produce more breast (pectoral) muscle, resulting in a change in conformation (Lilburn 1994; Webster 1994; Corr *et al*, pp 145–157, this issue). Both of these factors can affect locomotion: the rapidly increasing bodyweight will place greater demands on the immature skeleton, and the change in shape can alter the forces produced during walking. The abnormal gait seen in modern broilers could therefore be the

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result of pain, of biomechanical problems associated with different types of conformation, or of both.

The hypothesis that the increased growth rate and bodyweight of modern poultry have a detrimental effect on locomotor ability has been difficult to prove conclusively. Many studies have shown an increase in leg problems in rapidly growing birds (Nestor *et al* 1985; Nestor *et al* 1987; Leterrier & Nys 1992), whereas others have found no difference in incidence based on growth rate or feeding regime (Haye & Simons 1978; Cook *et al* 1984; Duff & Hocking 1986). However, it is generally accepted that slowing the rate of weight gain in the early stages appears to allow for more skeletal growth as opposed to muscular development, and that this should improve walking ability (Hester *et al* 1990; Hester 1994; Lilburn 1994; Kestin *et al* 2001). Many studies use the subjective method of gait assessment described by Kestin *et al* (1992), and the commonly used descriptor "leg weakness" is in itself rather vague. Whereas in the previous paper (Corr *et al*, pp 145–157, this issue) we considered the effect of morphology on the musculoskeletal system of broilers, in this paper we test the hypothesis that growth rate and bodyweight affect walking ability by comparing objective measurements of the spatial and temporal gait parameters of the birds. Two strains of birds were used ('relaxed' [ie random-bred] and selected), raised on two feeding regimes (*ad-libitum* and restricted), and culled at the commercial cull bodyweight of 2.4 kg.

Materials and methods

Equipment

Gait assessment was carried out using a purpose-built pedobarograph, which is described in detail in previous work by Corr *et al* (1998) and is illustrated in Figure 1. The recording surface was a glass plate (540 × 400 × 6 mm) built into a runway (200 cm long, 40 cm wide, and 42 cm high at the sides). Both the runway and the glass plate were covered with a layer of polythene-backed protective sheeting (Benchkote, Whatman International Ltd) to provide a homogenous surface for the birds to walk upon. As the birds walked across the recording surface, their footprints were video-recorded from underneath using a closed-circuit television camera (Panasonic WV-BP3101B). The video was recorded on an S-VHS recorder (Panasonic AG-7355), and the images transferred to a Powermac 8100/110 computer using a Scion LG-3 frame-grabber card and analysed using Scion Image (version 1.57) software (Scion Corporation, Maryland, USA).

Birds and treatments

The birds, treatments and feeding regimes used in this study are described in detail in a previous study (see Corr *et al*, pp 145–157, this issue). In this study, various gait parameters were measured and compared between the groups:

1) Thirteen female Ross 308 strain 'selected' broilers, fed *ad libitum*, and culled at six weeks (Sel-Al).
2) Ten female Ross 'relaxed' strain broilers, fed *ad libitum*, and culled at 12 weeks (Rxd-Al).
3) Ten female Ross 308 strain 'selected' broilers, restricted-fed, and culled at 13 weeks (Sel-Rd).
4) Nine female Ross 'relaxed' strain broilers, restricted-fed, and culled at 23 weeks (Rxd-Rd).

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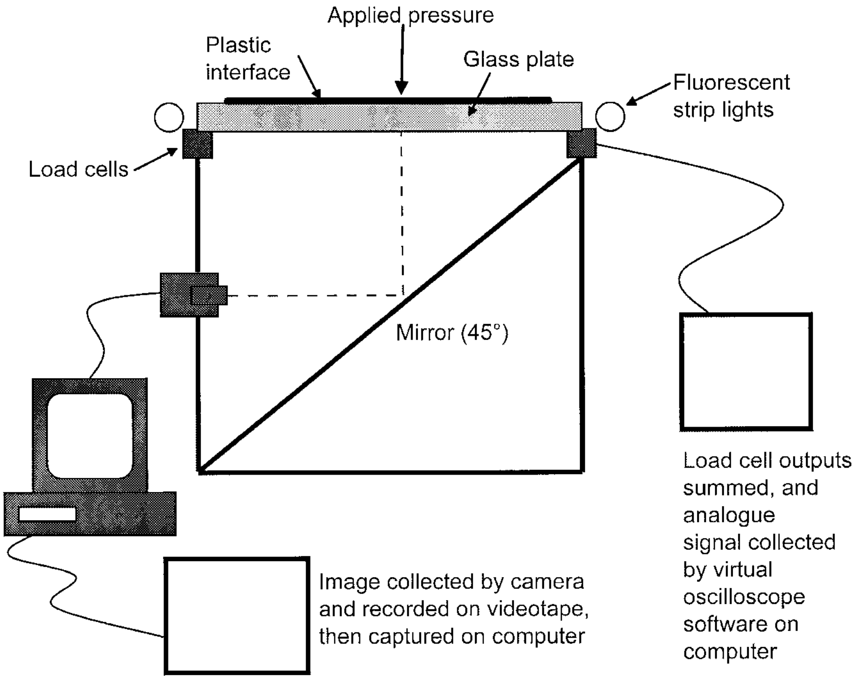

Figure 1 **Diagrammatic illustration of the pedobarograph recording surface and associated equipment.**

Testing protocol

The birds were familiarised with the runway from the age of one week old, and were motivated to walk along the runway by placing one bird at a time at the opposite end to their companions. Once per week, all the birds were weighed and several morphometric measurements were made (bodyweight, girth, leg length and tarsometatarsal diameter, as described in Corr *et al*, pp 145–157, this issue). On the following day they were assessed on the pedobarograph. Several different gait parameters were evaluated. Speed (m sec^{-1}) was calculated by dividing the distance the bird moved across the plate by the time interval between the first and the last point of foot contact. Cadence (steps min^{-1}), or step frequency, is a measure of the number of steps taken in a given time. The other gait parameters are illustrated in Figures 2 and 3.

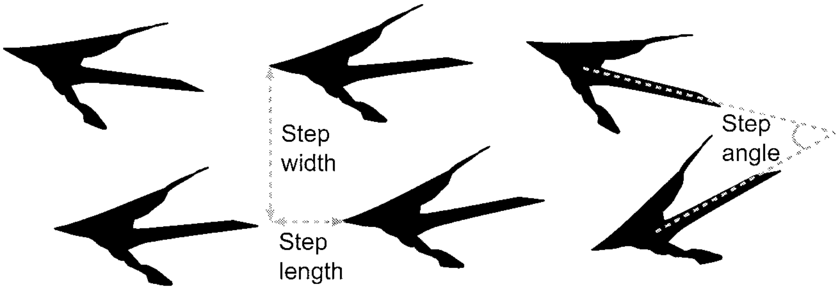

Figure 2 **Spatial gait parameters.**

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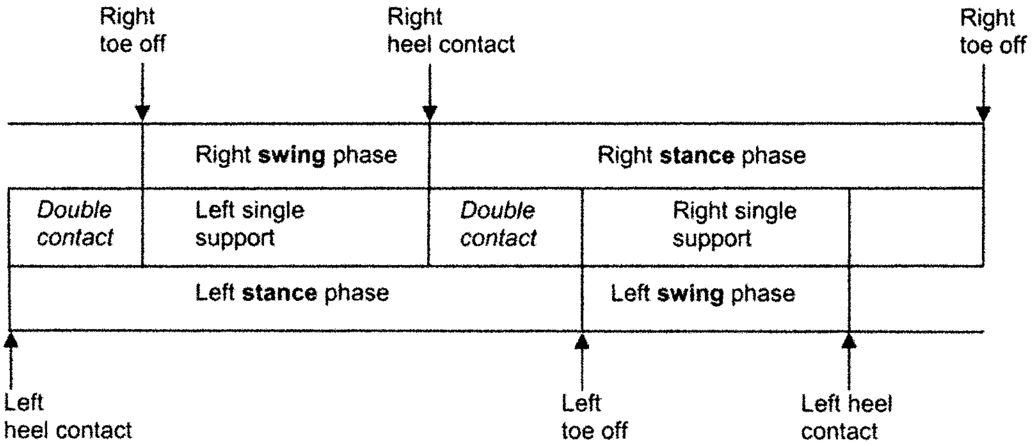

Figure 3 **Bipedal gait cycle (adapted from Whittle 1991).**

Data analysis

Statistical analysis was performed on the data from the first six weeks, the period of most rapid growth, which represents the commercial life span of the modern broiler. The cull data were also analysed in detail. As the groups were unbalanced, the group means and medians were generated using the residual maximum likelihood method (REML; Patterson & Thompson 1971). Speed, cadence and step length were all transformed to logarithms for analysis: the medians are presented, as a more resistant representation of the average, along with the approximate standard error of the median (#SE median [representing the first-order approximation of the SE of the median, calculated from median × SE of log median]; Kendall & Stuart 1963). The other parameters appeared to have a more normal distribution, and so the means (and SEs) are given. Statistically significant differences between the groups were calculated by Student's t-tests, using the maximum SE of the differences between groups to give a conservative estimate.

Results

Median speed was very variable, and there was no significant overall change as the birds grew (Figure 4). During growth, the Sel-Al birds' median speed was significantly lower than that of all the other groups ($P < 0.05$–0.001) at all times except during week five. The relaxed groups showed no significant differences in median speed at any stage. At cull weight, the Sel-Al birds showed a significantly lower median speed ($P < 0.001$) than birds in all of the other groups, but there was no significant difference in median speed between the birds in the other groups.

Median cadence decreased significantly ($P < 0.01$–0.001) with age in all groups except the Sel-Rd group. The median cadence of Sel-Al birds was significantly lower than that of the Rxd-Rd birds throughout the first six weeks ($P < 0.05$–0.001) and of the Rxd-Al ($P < 0.001$) and Sel-Rd birds ($P < 0.05$) for the first four weeks. There was no significant difference in median cadence at any stage between the relaxed groups (Figure 5).

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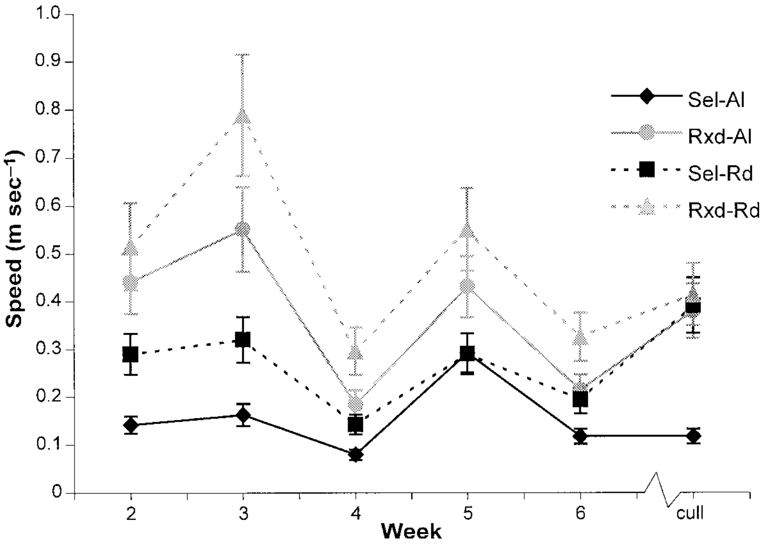

Figure 4 Median speed (m sec^{-1}) for each group of birds gait-analysed at weekly intervals.

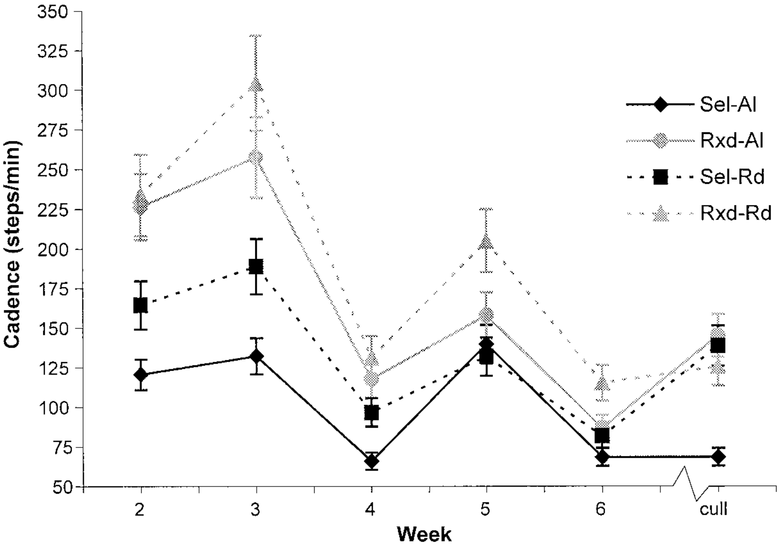

Figure 5 Median cadence (steps per minute) for each group of birds gait-analysed at weekly intervals.

Median step length showed a significant increase as the birds grew ($P < 0.05$–0.001) (Figure 6). Sel-Al birds took significantly shorter steps throughout growth than the restricted-fed birds of either strain, except at week four ($P < 0.05$–0.001). At cull weight, Sel-Al birds had significantly shorter median step lengths than birds in all other groups ($P < 0.001$), but there was no significant difference in median step length between the birds in the other groups.

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Mean step width increased overall as the birds grew: this increase was significant in the selected groups ($P < 0.001$), but not in the relaxed groups (Figure 7). During growth, mean step width was significantly greater in the Sel-Al than in the Sel-Rd birds at weeks 3, 5 and 6 ($P < 0.05$–0.001), significantly greater than in the Rxd-Al birds throughout ($P < 0.05$–0.001), and significantly greater than in the Rxd-Rd birds from week 3 onwards ($P < 0.05$–0.001). The relaxed groups showed no significant difference in mean step width at any stage during growth. At cull weight, the selected groups had significantly higher ($P < 0.001$) mean step widths than the relaxed groups, but there was no significant difference within strains.

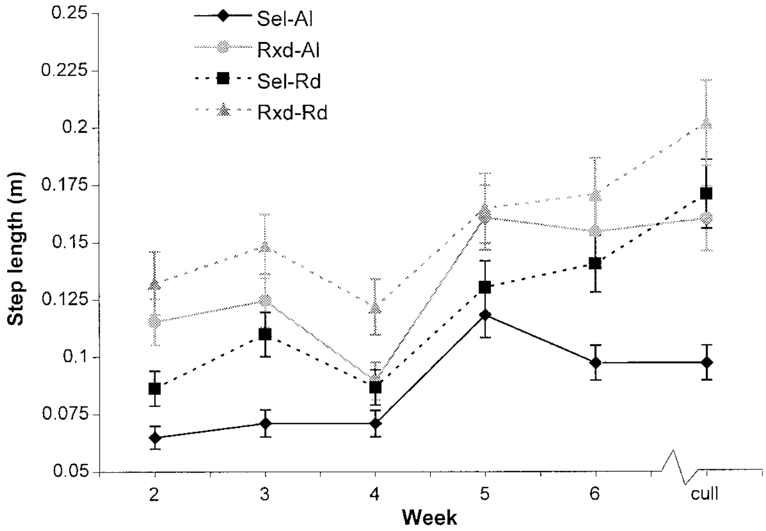

Figure 6 Median step length (m) for each group of birds gait-analysed at weekly intervals.

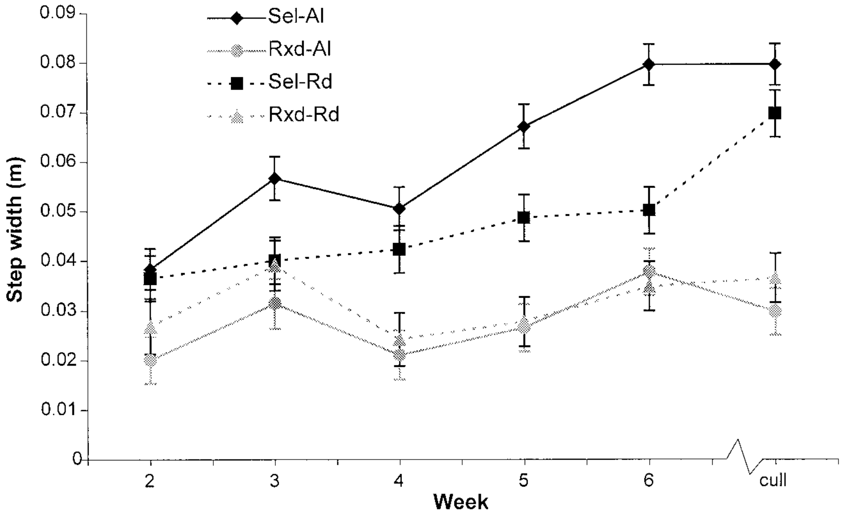

Figure 7 Median step width (m) for each group of birds gait-analysed at weekly intervals.

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Mean step angle (Figure 8) was variable during growth, showing no clear trend; however, the Sel-Al birds had significantly different mean step angles to the other three groups throughout growth ($P < 0.01$–0.001) and at cull weight ($P < 0.001$). There were no significant differences in mean step angle between the restricted-fed selected birds and either of the relaxed strains at cull.

The 'mean' gait cycle for each group of birds, defining the periods spent in swing, stance and double-contact phases, is illustrated in Figure 9. The mean percentage stance time did not change significantly during growth in any of the four groups, and therefore neither did mean percentage swing time, although the overall trend was for the former to increase with age and for the latter to decrease. The Sel-Al birds had significantly greater mean percentage stance times and smaller mean percentage swing times than Rxd-Rd birds ($P < 0.01$–0.001) at all times except during week 6, and than Rxd-Al birds up to week 4 ($P < 0.05$). At cull weight, the selected groups showed no significant difference in mean percentage stance or mean percentage swing times. Sel-Al birds had a significantly greater mean percentage stance time and a significantly shorter mean percentage swing time than either of the relaxed groups ($P < 0.05$–0.01). There were no significant differences in mean percentage stance or swing times between the restricted-fed selected birds and either of the relaxed groups at cull weight.

The mean percentage double-contact time (% dct) did not change significantly with growth in any of the groups, although the overall trend was for it to increase with time. The Sel-Al birds had the highest mean % dct at all times during growth, and it was significantly higher than that of either of the relaxed groups at cull ($P < 0.05$). There was no significant difference in mean % dct between the selected groups, nor between the restricted-fed selected birds and either of the relaxed groups at cull.

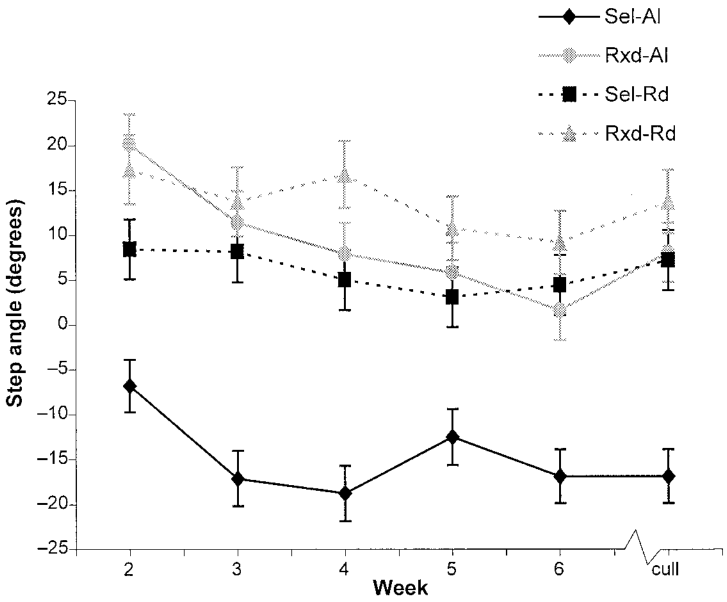

Figure 8 **Median step angle (degrees) for each group of birds gait-analysed at weekly intervals.**

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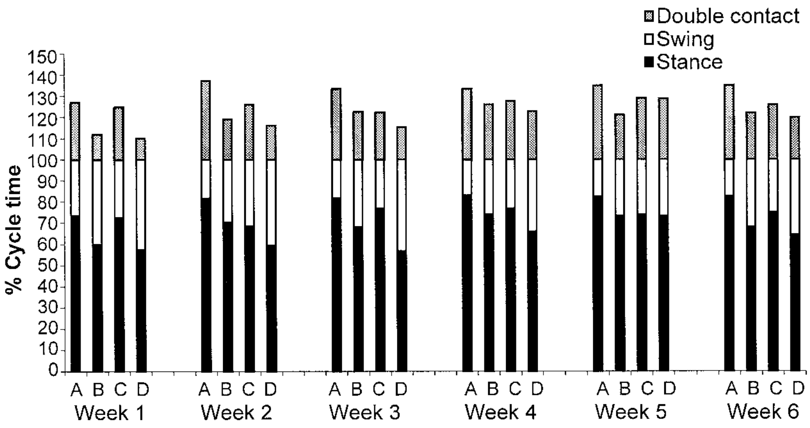

Figure 9 **Illustrating the 'mean' gait cycle for each group of birds, defining the periods spent in swing, stance and double-contact phases. A: Sel-Al; B: Rxd-Rd; C: Sel-Rd; D: Rxd-Rd.**

Discussion and conclusions

The hypothesis that growth rate affects walking ability was tested by comparing the gait of the *ad-libitum*-fed and restricted-fed birds in this study. The morphology study of the same birds (Corr *et al*, pp 145–157, this issue) showed that over the first six weeks, the rapidly growing *ad-libitum*-fed selected birds had the longest legs, which should enable them to take longer steps and so move faster. Their increase in breast muscle and larger girths resulted in a conformation that should cause the steps to be wider than those taken by the other groups. However, the present study showed that these birds walked at significantly slower speeds than the other birds at all stages during growth. Within strains, the restricted-fed birds moved more quickly than the *ad-libitum*-fed birds, possibly because they were lighter and perhaps more highly motivated to look for food. The restricted-fed selected birds showed similar speeds to the *ad-libitum*-fed relaxed birds throughout growth, and these groups were approximately matched for bodyweight, suggesting that speed in the restricted-fed birds probably has more to do with bodyweight than urgency to find food.

Speed, cadence and step length

Speed is a function of step length and step frequency, and each should be considered separately. As leg length increased during growth, step length showed a significant increase in all groups. At the same age, however, despite having longer legs, the *ad-libitum*-fed selected birds took significantly shorter steps and moved more slowly. In a previous study of Brown Leghorns using the same equipment, it was demonstrated that at low speeds (as seen in the present experiment), speed was influenced more by cadence than by step length (Corr *et al* 1998). Leg length should affect step length more than cadence, which would explain why the extra leg length of the *ad-libitum*-fed selected birds did not affect their speed. However, increased leg length in other species results in increased step or stride length (Sutherland *et al* 1988), rather than in the shorter steps demonstrated by the *ad-libitum*-fed selected birds. There are several possible explanations for the short step lengths of the *ad-libitum*-fed selected birds. These birds have a greater pectoral muscle mass (Corr *et al*, pp 145–157, this issue), and this may displace the centre of gravity cranially, requiring the

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feet to be placed further cranially under the body for support. This would be achieved mostly by flexion of the hip joint, which is limited (Jacobson & Hollyday 1982). As soon as the bird moved forward, the centre of gravity would fall outside the area of support, and the other foot would have to be quickly replaced to re-establish the equilibrium. The period during which the bodyweight is taken on one leg is also the period of greatest instability. Decreasing step length decreases the swing phase, during which time one leg is off the ground; decreasing step or stride length is a commonly used method of improving stability, as seen in the gait of young children (Todd *et al* 1989) and elderly humans (Murray *et al* 1969), and in various types of pathological gait (Whittle 1991). Taking shorter steps is also a more efficient way of walking at slower speeds, as the excursions of the centre of gravity are reduced; the centre of gravity is raised when the feet are together and lowered when the craniocaudal distance between the two feet is greatest (Cavagna & Margaria 1966). This 'conserves' energy, decreasing the force that has to be applied to the ground to raise and reaccelerate the centre of gravity with each step.

As speed did not change significantly despite the increase in step length during growth, it was not surprising to find a significant decrease in cadence in all groups except the restricted-fed selected birds. This is in agreement with studies on human gait, which have shown a decrease in cadence with age as stride length increases (Sutherland *et al* 1988; Todd *et al* 1989). In contrast, Biewener *et al* (1986) showed that stride frequency in birds remained constant with age; however, these birds were tested on a treadmill and may not have demonstrated normal walking gait patterns.

Reducing cadence is another way of reducing the duration of single support, as a decrease in cadence increases the cycle length mainly by increasing the duration of the stance phase (and therefore the double-support time; Whittle 1991). The cadence of the *ad-libitum*-fed selected birds was lower than that of any of the other three groups.

The slower speeds, shorter steps and lower cadences in the *ad-libitum*-fed selected birds could be a response to instability. A subject remains stable as long as the line of force passing vertically down from the centre of gravity remains within the area on the ground that is supporting it (Whittle 1991). Increasing the support base allows for a wider 'margin of error' in positioning the centre of gravity, exemplified by the use of canes and crutches by elderly or disabled people (Whittle 1991). The results of the present study suggest that broilers increase their support base in two ways: by taking wider steps, and by altering the position in which the feet are placed on the ground.

Step width and support base

Step width increased significantly as the selected birds grew, in contrast to the relaxed birds. Within the strains, there was no significant difference between the groups, which suggests that growth rate did not have an effect; if the expanding girth of the birds was forcing the legs further apart, the other groups would have similar step widths on reaching the same girths — but this was not the case. Previous work on Brown Leghorns (Corr *et al* 1998) reported step widths of approximately 0.02 m, which is similar to the relaxed birds in this study. In contrast, the steps taken by the selected birds in the present study were almost three times as wide. Various studies have shown that while walking base decreases with age in normal human bipeds (Todd *et al* 1989; Whittle 1991), increases in walking base are reported in less able subjects such as the elderly (Murray *et al* 1969) and people with proprioceptive or balance defects, such as arise in cerebellar ataxia and Parkinsonism (Gabell & Nayak 1987; Cunha 1988). Various studies in animals have also demonstrated that step width increases

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markedly in lameness, confirming that it is a useful measure of the degree of difficulty in walking (Clarke & Parker 1986; Sheets *et al* 1987; Farage-Elawar 1989).

The increased step width of the *ad-libitum*-fed selected birds is strong evidence that they are unstable during locomotion. A markedly increased walking base makes locomotion difficult however, as accelerating the centre of gravity in marked lateral excursions wastes a lot of energy. Human bipeds with wide walking bases adapt by using lateral trunk-bending to position the centre of gravity over the stance leg. The more rounded bodies and fused synsacral vertebrae of birds make such bending of the vertebral column difficult, and instead birds have to tip the body laterally to position the centre of gravity over the stance leg. A similar pattern is seen in elderly people, where the vertical movement of the head (reflecting the movement of the centre of gravity) is reduced, and the lateral movement is increased (Murray *et al* 1969). In 'normal' human walking, gait optimisations result in these vertical and lateral displacements being approximately equal (Saunders *et al* 1953).

The support base can also be increased by turning the feet outward (like having stabilisers on a bicycle), which increases the lateral support without requiring the centre of gravity to displace any further laterally, as it remains above the actual leg. This gait pattern was demonstrated by the *ad-libitum*-fed selected birds, whereas birds in all of the other groups pointed the toes inward. The relaxed birds and the restricted-fed selected birds all showed lower degrees of inward-turning of the foot (1.6–20.1°) than did Brown Leghorns (average 33.3°; Corr *et al* 1998), suggesting a degree of instability in all the broilers. The fact that the restricted-fed selected birds' feet turned inward could indicate that growing more slowly reduces locomotor instability.

Rotating the feet outward must have consequences for the skeletal system, which raises the question of cause and effect: do problems in bone development result in limbs that rotate outward, or does the requirement to increase stability by rotating the foot outward produce forces which alter bone growth? The fact that bone is remodelled in response to the functional demands placed upon it tends to suggest the latter (Bain & Watkins 1993). Post-mortem examination of these birds (Corr *et al*, pp 145–157, this issue) showed that while none of the birds had an abnormal degree of external rotation of the tibiotarsus, some had internal tibiotarsal rotation (particularly the *ad-libitum*-fed birds). No evidence of tibial dyschondroplasia was found on histological examination of the proximal epiphyseal tibiotarsal sections, although some birds showed slightly greater tibial plateau angles than are considered normal. Duff and Thorp (1985a,b) have previously reported a high incidence of internal rotation in *ad-libitum*-fed broilers, which they suggested was pathological; however, a subsequent publication by Lynch *et al* (1992) quotes the normal range for tibiotarsal torsion as –5° to 20°, making allowance for a mild degree of internal torsion. The results of the present study suggest that mild internal torsions have no significant effect on gait.

It is interesting that the *ad-libitum*-fed selected birds were the only group to point their toes outward, despite the higher incidence of internal tibiotarsal rotation. Even in birds with external rotation, the degree of rotation seems insufficient to explain the extent to which the foot was turned outward in this particular group. The examination was limited to the tibiotarsus, however, and obviously rotation can occur elsewhere in the limb; the study by Duff and Thorp (1985a) demonstrated external rotation of the femur and internal rotation of the tarsometatarsus. Further work needs to be undertaken to determine the effect of torque on the joints and tendons, as this may further compromise walking ability.

Other studies have demonstrated that the foot is placed with the medial toe pointed inward in normal chicks, but more in line with the direction of walking in lame birds (Sheets *et al*

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1987). An increased angle of 'toe-out' has also been reported in the gait of elderly people (Murray *et al* 1969).

Gait cycle

As timing of the phases of the gait cycle changes with cycle length (and therefore speed), comparisons are more valid if events are described as percentages of the total cycle time. In 'normal' human walking, the stance phase accounts for approximately 60% of the gait cycle and the swing phase for 40%. For each stance period of a particular foot, the opposite foot is also in contact with the ground for 10% of the time, known as the period of double support (Whittle 1991). While the gait pattern of the restricted birds in the present study approximated these timings, the *ad-libitum*-fed selected birds had much longer stance and double-contact periods for each foot, and shorter swing periods. Again, the gait pattern of the *ad-libitum*-fed selected birds showed similarities to those of less stable humans, such as children and the elderly, both of which use shorter swing phases and/or longer stance and double-contact periods (Murray *et al* 1969; Todd *et al* 1989). There have been few other studies on birds that have measured cycle timing. A study by Jacobson and Hollyday (1982) reported absolute value ranges but, as the times vary depending on speed, it is difficult to make useful comparisons with these results.

The longer stance and double-contact times and the shorter swing periods of the *ad-libitum*-fed selected birds complement previous findings in supporting the hypothesis that these birds are attempting to improve their stability. In particular, the increased length of the double-contact periods means that there is a wider support base for a greater time (balance being maintained while the centre of gravity is positioned between the feet, rather than over one foot as it is during the stance period). There are also other benefits to keeping the foot in contact with the ground for longer periods. The morphological study (Corr *et al*, pp 145–157, this issue) showed that the *ad-libitum*-fed selected birds were moving larger masses on relatively shorter lever arms (composed of immature bone), resulting in greater stresses on the skeleton. Assuming that a given load has to be moved, the total force exerted by a limb (the 'impulse') is equivalent to force × time. For a given impulse, increasing ground contact time enables the peak forces to be reduced, decreasing the strains on the bones and helping to keep them within 'safe limits'. Exceeding 'safe limits' can cause excessive microdamage, which can result in pathological remodelling and eventually failure of the bone (Rubin & Lanyon 1985; Frost 1994a,b). The period of single leg contact is the period of greatest stress, when the whole bodyweight is loaded onto a single leg. Studies on unilateral weight-bearing in poultry have reported an increased incidence of abnormalities such as tibial dyschondroplasia in the weight-bearing or 'over-loaded' limb (Duff 1986; Thorp & Duff 1988). It is therefore beneficial to share the load between the two legs for as much time as possible by increasing double-contact times.

Animal welfare implications

This study has shown that the abnormal gait patterns demonstrated by *ad-libitum*-fed selected broilers can be broken down into parameters which can be objectively measured. Many of the gait patterns demonstrated by the *ad-libitum*-fed broilers serve to increase stability during walking and are a likely consequence of the morphological changes in these birds — especially the rapid growth of breast muscle moving the centre of gravity forward and the relatively short legs compared to the birds' bodyweight (Corr *et al*, pp 145–157, this issue). This altered gait would be very inefficient and would rapidly tire the birds, which could help to explain the low level of activity seen in modern broilers. Thus, even if the abnormal gait

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pattern results from biomechanical limitations rather than from pain, the welfare of the birds will be compromised if, for example, they are less capable of reaching the feeders or drinkers.

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References

Bain S D and Watkins B A 1993 Local modulation of skeletal growth and bone modelling in poultry. *Journal of Nutrition 123*: 317-322

Bennett R M, Christiansen K and Clifton-Hadley R S 1999 Direct costs of endemic diseases of farm animals in Great Britain. *Veterinary Record 145*: 376-377

Biewener A A, Swartz S M and Bertram J E A 1986 Bone modelling during growth: dynamic strain equilibrium in the chick tibiotarsus. *Calcified Tissue International 39*: 309-395

Cavagna G A and Margaria R 1966 Mechanics of walking. *Journal of Applied Physiology 21*: 271-278

Clarke K A and Parker A J 1986 A quantitative study of normal locomotion in the rat. *Physiology and Behaviour 38*: 345-350

Cook M E, Patterson P H and Sunde M L 1984 Leg deformities: inability to increase severity by increasing body weight of chicks and poults. *Poultry Science 63*: 620-627

Corr S A, McCorquodale C C and Gentle M J 1998 Gait analysis of poultry. *Research in Veterinary Science 65*: 233-238

Corr S A, Gentle M J, McCorquodale C C and Bennett D 2003 The effect of morphology on the musculoskeletal system of the modern broiler. *Animal Welfare 12*: 145-157

Cunha U V 1988 Differential diagnosis of gait disorders in the elderly. *Geriatrics 43*: 33-43

Duff S R I 1986 Effect of unilateral weight-bearing on pelvic limb development in broiler fowls: morphological and radiological findings. *Research in Veterinary Science 40*: 393-399

Duff S R I and Hocking P M 1986 Chronic orthopaedic disease in adult male broiler breeding fowls. *Research in Veterinary Science 41*: 340-348

Duff R I and Thorpe B H 1985a Patterns of physiological bone torsion in the pelvic appendicular skeletons of domestic fowl. *Research in Veterinary Science 39*: 307-312

Duff R I and Thorpe B H 1985b Abnormal angulation/torsion of the pelvic appendicular skeleton in broiler fowl. *Research in Veterinary Science 39*: 313-319

Farage-Elawar M 1989 Enzyme and behavioural changes in young chicks as a result of carbaryl treatment. *Journal of Toxicology and Environmental Health 26*: 119-131

Frost H M 1994a Perspectives: a vital biomechanical model of synovial joint design. *The Anatomical Record 240*: 1-18

Frost H M 1994b Perspectives: a biomechanical model of the pathogenesis of arthroses. *The Anatomical Record 240*: 19-31

Gabell A and Nayak L 1987 Variability of gait: implications for gait analysis. *International Journal of Rehabilitation Research 10*: 75-79

Gentle M J and Corr S A 1995 Endogenous analgesia in the chicken. *Neuroscience Letters 210*: 211-214

Haye U and Simons P C M 1978 Twisted legs in broilers. *British Poultry Science 19*: 549-557

Hester P Y 1994 The role of environment and management on leg abnormalities in meat-type fowl. *Poultry Science 73*: 904-915

https://doi.org/10.1017/S0962728600025616 Published online by Cambridge University Press

Hester P Y, Krueger K K and Jackson M 1990 The effect of restrictive and compensatory growth on the influence of leg abnormalities and performance of commercial male turkeys. *Poultry Science 69*: 1731-1742

Hocking P M 1994 Assessment of the welfare of food restricted male broiler breeder poultry with musculoskeletal disease. *Research in Veterinary Science 57*: 28-34

Jacobson R D and Hollyday M 1982 A behavioural and electromyographic study of walking in the chick. *Journal of Neurophysiology 48*: 238-256

Kendall M G and Stuart A 1963 *The Advanced Theory of Statistics, Vol 1, Edn 2* p 231. Charles Griffin and Company Ltd: London, UK

Kestin S C, Gordon S, Su G and Sorenson P 2001 Relationships in broiler chickens between lameness, liveweight, growth rate and age. *Veterinary Record 148*: 195-197

Kestin S C, Knowles T G, Tinch A E and Gregory N G 1992 Prevalence of leg weakness in broiler chickens and its relationship with genotype. *Veterinary Record 131*: 190-194

Leterrier C and Nys Y 1992 Composition, cortical structure and mechanical properties of chicken tibiotarsi: effect of growth rate. *British Poultry Science 33*: 925-939

Lilburn M S 1994 Skeletal growth of commercial poultry species. *Poultry Science 73*: 897-903

Lynch M, Thorp B H and Whitehead C C 1992 Avian tibial dyschondroplasia as a cause of bone deformity. *Avian Pathology 21*: 275-285

McGeown D, Danbury T C, Waterman-Pearson A E and Kestin S C 1999 Effect of carprofen on lameness in broiler chickens. *Veterinary Record 144*: 668-671

Murray M P, Kory R C and Clarkson B H 1969 Walking patterns in healthy old men. *Journal of Gerontology 24*: 169-178

Nestor K E, Bacon W L, Moorhead P D, Saif Y M, Havenstein G B and Renner P A 1987 Comparison of bone and muscle growth in turkey lines selected for increased body weight and increased shank width. *Poultry Science 66*: 1421-1428

Nestor K E, Bacon W L, Saif Y M and Renner P A 1985 The influence of genetic increases in shank width on body weight, walking ability and reproduction of turkeys. *Poultry Science 64*: 2248-2255

Patterson H D and Thompson R 1971 Recovery of inter-block information when block sizes are unequal. *Biometrica 58*: 545-554

Pickup H E, Cassidy A M, Danbury T C, Weeks C A, Waterman A E and Kestin S C 1997 Self selection of an analgesic by broiler chickens. *British Poultry Science 38*: S12-S13

Rubin C T and Lanyon L E 1985 Regulation of bone mass by mechanical strain magnitude. *Calcified Tissue International 37*: 411-417

Sainsbury D W B 1999 Broiler chickens. In: Ewbank R, Kim-Madslien F and Hart C B (eds) *Management and Welfare of Farm Animals: The UFAW Farm Handbook* p 236. Universities Federation for Animal Welfare: Wheathampstead, UK

Saunders J B, Inman V T and Eberhardt H D 1953 The major determinants in normal and pathological gait. *The Journal of Bone and Joint Surgery 35-A (3)*: 543-558

Sheets L, Hassanein R S and Norton S 1987 Gait analysis of chicks following treatment with tri-ortho-cresyl phosphate in ovo. *Journal of Toxicology and Environmental Health 21*: 445-453

Sutherland D H, Olshen R A, Biden E N and Wyatt M P 1988 *The Development of Mature Walking*. Mac Keith Press: London, UK

Thorp B H and Duff S R I 1988 Effect of unilateral weight-bearing on pelvic limb development in broiler fowls: vascular studies. *Research in Veterinary Science 44*: 164-174

Todd F N, Lamoreux L W, Skinner S R, Johanson M E, St Helen R, Moran S A and Kirklin Ashley R 1989 Variations in the gait of normal children. *The Journal of Bone and Joint Surgery 71-A (2)*: 196-204

Vestergaard K S and Sanotra G S 1999 Relationships between leg disorders and changes in behaviour of broiler chickens. *Veterinary Record 144*: 205-209

Webster J 1994 *Animal Welfare: A Cool Eye Towards Eden* pp 155-156. Blackwell Science: Oxford, UK

Whittle M 1991 *Gait Analysis: An Introduction*. Butterworth–Heinemann Ltd: Oxford, UK

https://doi.org/10.1017/S0962728600025616 Published online by Cambridge University Press