



Feeding Behaviour of Broiler Chickens: a Review on the Biomechanical Characteristics

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ABSTRACT

Feed related costs are the main drivers of profitability of commercial poultry farms, and good nutrition is mainly responsible for the exceptional growth rate responses of current poultry species. So far, most research on the poultry feeding behaviour addresses the productivity indices and birds' physiological responses, but few studies have considered the biomechanical characteristics involved in this process. This paper aims to review biomechanical issues related to feed behaviour of domestic chickens to address some issues related to the feed used in commercial broiler chicken production, considering feed particle size, physical form and the impact of feeders during feeding. It is believed that the biomechanical evaluation might suggest a new way for feed processing to meet the natural feeding behaviour of the birds.

INTRODUCTION

The poultry industry is the most dynamic sector within the global meat business during the last decade, with the greatest growth reflected in the food global demand increase. It is expected that, in the next years, the meat industry will increase production driven by global population growth, especially in developing countries. Chickens and turkeys are the most common sources of poultry meat, but there is also commercially available meat from ducks, geese, pigeons, quails, pheasants, ostriches and emus. Consumer preference also has been changing in many developed countries, characterized by greater demand for low-calorie foods and changes in lifestyle, which reduces the consumer time spent on food preparation. By this approach, the chicken meat highlights and the largest producer countries are United States, China, Brazil and European Union, being Brazil and United States are also the main exporter countries. These two countries together provide two-thirds of global trade (FAO, 2010; FAO, 2012; USDA, 2012).

Feedstuff is an aspect of high economic importance in the rearing of commercial poultry not only because it is primarily responsible for the growth response of birds, but mainly because it represents the largest cost in the production cycle (Ávila *et al.*, 1992). For instance, the broilers' energy requirements are responsible for 70% of the cost of the ration (Skinner *et al.*, 1992) and, besides, the processing method and the grain type interfere differently on the economic viability and animal performance. The advantages of using processed feed have been well documented, although they represent a high cost for manufacturing. Under natural conditions, birds have to deal with different types of feed, which have different energy and protein levels. Despite domestication and selection for fast growth, broiler chickens did not lose their ability to discriminate different types of diets (Emmans & Kyriazakis, 2001). It has been suggested that the birds associate the feed physical characteristics



with nutritional content, which indicates that the contact perception contributes to the identification of the feed.

Most researches on performance and behaviour of broiler chicken feeding has been with respect to productivity indices and physiological responses, but there is a lack of scientific knowledge of the biomechanical features of the bird feeding process. Chickens present cranial kinesis, which is characterized by the movement of the upper jaw in relation to the skull, a key factor in feeding efficiency found in all species of birds (Bock 1964; Zweers 1982; Feduccia 1986; Bout & Zweers, 2001; Gurd 2006; Estrella & Masero, 2007; Gurd, 2007). Past and recent publications have reported this feature in many species of fish, rodents and birds, as well as in humans. In domestic chickens (*Gallus gallus domesticus*); however, even though a few studies are found regarding the biomechanical issues of the intake process, no one is related to the modern captive breed strains for egg or meat production.

This review paper aims to approach what is known to date about the biomechanical features of the feeding behaviour of chickens. It addresses issues related to feed characteristics used in commercial broiler chicken production, with regard to feed particle size, physical form and the influence of feeders.

General concepts of biomechanics and historical context

Biomechanics can be defined as the study of the mechanical model of the body and its movements, integrating physics and biology (Domenici & Blake, 2000), or as the mechanics of movement in living creatures, being a discipline of biology that combines biophysics, physiology, physics, engineering and medicine (Low & Reed, 1996), or even simple physical (mechanical) movement displayed or produced by biological systems (McIester & Pierre, 2008). Despite biomechanics being a relatively young discipline recognized in scientific research, its considerations are also of interest to several other scientific disciplines and professional fields, such as zoology, medical (orthopaedics, cardiology, sports medicine, physiotherapy), biomedical engineering or biomechanics, or kinesiology (study of human movement) (Hall, 1999).

Giovanni Borelli (1608-1679) is considered a pioneer in the studies of biomechanics. He integrated physiology and physical science to describe the human and animal movements, and offered thoughts on the function of

muscles. The invention of the light microscope in the latter part of the seventeenth century greatly aided the study of physiology, but the advent of photography in the nineteenth century played a key role, and allowed a more detailed study of human and animal locomotion. Some knowledge of electricity was also developed in this period, which led to the use of electrical stimulation and electromyography. In the twentieth century, the invention of the electron microscope influenced the understanding of mechanical changes on a cellular level (Low & Reed, 1996).

Currently, biomechanics is seen as an academic subject and with the advancement of computer and microelectronics it is now possible to use measurement systems in more complex fields. High resolution cameras, high storage capacity and digital image processing for a relatively affordable cost make the transformation of qualitative for quantitative techniques possible, with a level of accuracy comparable to traditional punctual measuring methods. In this sense, the high speed camera is an apparatus that has been highlighted for its effectiveness in several areas of study, including animal behaviour assessments.

The study of biomechanics and motion analysis

In the study of biomechanics, it must be consider the consequences of movements produced by forces, integrating biological features with traditional mechanics (the effect of forces and energy in the motion of bodies). The static and the dynamic are two sub-branches of mechanics used to study the anatomical and functional aspects of living organisms. Static is the study of systems that are in a state of constant motion, *i.e.* both at rest (without movement) or in motion at a constant speed. Dynamics is the study of systems in which the acceleration is present. Kinematics and kinetics are subdivisions of biomechanical study. Kinematics is the description of motion features including the pattern and velocity of the body segments which generally translates the degree of coordination that an individual displays. Whereas kinematics describes the appearance of movement, kinetics is the study of forces associated with movement (Hall, 1999; Serway & Jewett, 2004). Anthropometric factors, *e.g.* size, shape and weight of body segments, are other important concerns in kinetic analysis (Hall, 1999).

Among other essential purposes, animals depend mainly on muscles to propel themselves for locomotion



and food handling. Muscles are biological motors that consume chemical energy and perform mechanical work. Generally the function of muscles is considered within the 'metabolism' together with other processes, e.g. thermoregulation, which also consumes oxygen and generates heat. The power of muscles is generally viewed only by the capacity of enzyme energy supply. However, the rate at which muscles can perform the work is limited by three variables: the stress it may exercise, the tension and the contraction frequency. These are the mechanical variables, and their maximum values are defined by mechanical limitations (Pennycuik, 1992).

Nowadays biomechanics can be considered a "tool" to investigate matters of ecology, physiology and evolution. It also can be useful for assessments, forecasts and understanding of behaviours. Some structures of animals (e.g. jaw, teeth, claws, beaks and horns) may be regarded as tools and/or weapons with certain physical characteristics, and the kind of forces applied may influence their utilization. These forces can be used to handle, break or tear the food; for different ways of feeding (suction, crushing and handling through the jaw); for biting, cutting the skin, breaking bones or killing (Domenici & Blake, 2000). Several factors affect the execution of eating action, such as competition, energy consumption, risk of predation, prey availability and predator performance. Performance includes the ability of a predator to locate, capture and manipulate the prey, all being influenced by their morphology (Wainwright, 1991).

Biomechanical studies have been widely investigated using high speed camera technology in various species of animals, e.g. insects (Dangles *et al.*, 2006; Wu *et al.*, 2008; Nguyen *et al.*, 2010; Truong *et al.*, 2012); fish (Korff & Wainwright, 2004; Herrel *et al.*, 2005; Huber *et al.*, 2008; Wroe *et al.*, 2008; Huber *et al.*, 2009; Mara *et al.*, 2009; Habegger *et al.*, 2010; Tran *et al.*, 2010); rodents (Bracha *et al.*, 2003; Sakatani & Isa, 2004; Herbin *et al.*, 2007; Morita *et al.*, 2008; Beare *et al.*, 2009; Fu *et al.*, 2009; Stefen *et al.*, 2011); reptiles (Deban & O'Reilly, 2005; Herrel & O'Reilly, 2006; Fuller *et al.*, 2011; Schaerlaeken *et al.*, 2011); birds (Westneat *et al.*, 1993; Estrella & Masero, 2007; Abourachid *et al.*, 2011; Dawson *et al.*, 2011; Smith *et al.*, 2011); as well as in humans (Arampatzis *et al.*, 1999; Yoganandan *et al.*, 2002; Imura *et al.*, 2008; Shan, 2008; Bakker *et al.*, 2009; Steeve, 2010). The main topics treated are flight features, bite force analysis, cognitive functions assessments by real-time tracking, anatomical and physiological study of

locomotion, evaluation of mandibular motion and muscle activity during ingestion or vocalization, the effect of food type on feeding efficiency, 3-D bones reconstruction for motion morphology assessments, among others.

At some time, several reasons induced the domestication of birds. These include: communication (pigeon); vestment (ostrich), sport (falcon), decoration (peafowl), religion (Egyptian goose); and pet (cage birds). Nowadays, the main aims of domestication are egg and meat production. Economically, these activities are very important, since producing poultry meat, and eggs are very efficient ways to transforming vegetable mass into meat protein (FAO, 2010). In the upper limbs, the birds have wings moved by powerful pectoral muscles, consisting of a very well developed structure and the skeletal bones are significantly lighter. These features have given the birds a high mobility, allowing their dispersion throughout the environment and consequently their adaptation to a variety of environments. These adjustments led to different types of secondary anatomic variations of the beak, oral cavity, feathers, wings, legs and feet (King, 1986). Thus, a better comprehension of the biomechanics of each element is helpful for studying disease aetiology, and for making treatment decisions and general motion assessments.

On the other hand, some methodological drawbacks could be encountered when it is necessary to adopt a surgical intervention for implant insertion, which could involve ethical concerns and technological limitations (Bergmann *et al.*, 2001; Stansfield *et al.*, 2003), beyond the stress to which the individual could be subjected. In addition, the labour intensiveness, utilization of electrical stimulation and *post mortem* examination can lead to a non-real situation, such as the lack of functional movements (Gussekkloo *et al.*, 2001). Developing a precise and non-invasive method for measuring the internal force within the living body still remains a great challenge in the field of biomechanics and motion analysis (Lu & Chang, 2012). Motion analysis can be an effective method for identifying beneficial and damaging elements when a moving system of a living organism is performing a task. Some advantage via the utilization of high speed cameras and computational image analysis for motion assessments has been achieved, especially with respect to its relatively low cost, versatility in analysis, commercial availability of the hardware and possibility of system upgrade according to need (Sakatani & Isa, 2004).



Chicken intake process: anatomical and biomechanical approaches

The digestive system of the chicken is considered simple, short and extremely efficient. The beak collects the food, and the bird decides whether to accept or reject it through the tactile cells. This decision is based on reflectivity and taste, even though the number of taste buds is small. No evidence has been produced to suggest that chickens have any real ability to smell. The food is swallowed whole with a little saliva, through the oesophagus to the crop, in which the fibre is softened, and the food is acidified by lactic acid. From the crop, the food passes into the proventriculus, which secretes acid and pepsin, an organ that best resembles the stomach of a mammal. Thereafter the food passes into the gizzard, an organ with powerful muscles that contract rhythmically to reduce the thickness of the content. After that, the food passes through various regions of the intestine by peristaltic contractions, and it is at this stage that digestion and nutrient absorption occur. The digestion also occurs to a lesser extent in the caeca, two bags that are located at the junctions of the small and large intestines, the latter being responsible for the absorption of water. From here the faeces move into the cloaca for evacuation, which is also related to the excretion of urine, acceptance of delivery of sperm and the passage of egg outwards (Sainsbury, 1980).

The birds have one of the most skilled skulls of living vertebrates, besides the pneumatisation by epithelial extensions of air sacs, a fact that allows alleviates the weight, they are kinetic. The cranial kinesis is related to the movement of the upper jaw, or part of it, in relation to the skull, which is a characteristic found in all species of birds (Bock, 1964; Zweers, 1982; Feduccia, 1986; Bout & Zweers, 2001; Gussekloo & Bout, 2005). This is not an exclusive feature of birds, as it is also found in fish, reptiles and amphibian fossils (Bock, 1964). The skull of birds can be divided into functional units: the braincase, the upper jaw, the bone structure that comprises the palate, the jugal bar and quadrate, and the lower jaw. These functional units operate together in which the quadrate bone plays a key role during the beak movement (Van Den Heuvel, 1992).

There are many proposed functions of cranial kinesis which can be highlighted: the highest elevation of the upper jaw, reducing the force required to open the beak, keeping the beak closed without muscular effort, higher beak closing speed, shock absorption, increased capacity of food selection, maintenance of the primary axis of orientation and attachment of

the buccal apparatus muscles (Bock, 1964; Bout & Zweers, 2001; Gurd, 2006; Estrella & Masero, 2007; Gurd, 2007). Furthermore, the cranial kinesis can be uncoupled or coupled. Uncoupled is when the upper and lower jaws move independently. Coupled kinetics occurs owing to two separate mechanisms, or a combination of both. In most birds, the presence of postorbital ligaments and the lacrymomandibular is the main morphological feature of this system. When one of these ligaments is stretched to the maximum, the lower jaw cannot be depressed without the quadrate bone swinging forward while the opposite occurs in beak closing motion, establishing a relationship of dependence of both upper and lower jaws, although a certain degree of independence in this mechanism may exist (Bock, 1964).

The domestic fowl has a prokinetic skull mainly characterized by a postorbital ligament, also known as the squamosomandibular ligament, whereby the skull connects with the mandibular process. Other species can also present rhincokinetic or amphikinetic skulls, differing in the location of the jaw joint. Therefore, the chicken jaw is a unique structure that moves entirely. When the beak is usually closed, the ligaments are not tensioned, and the system is considered at rest. The coupled cranial kinesis in domestic fowl does not play a dominant role in the feeding process. The jaw is lowered 20ms after the lifting of the upper jaw, indicating that the coupled cranial kinesis does not occur while the food is grasped, but can occur eventually. Similar characteristics may occur in subsequent cycles for the transport of food into the oral cavity during the food manipulation. However, the coupled kinesis is used when the bird closes its beak, as it is not possible to depress the upper jaw without raising the lower jaw (Van Den Heuvel, 1992).

The feeding behaviour of animals can be divided into appetitive phases, corresponding to the demand for feed and consummatory act, which is the real feed intake. The assessments may be related to bite events and/or visits to feeders (Slater, 1974; Berdoy, 1993; Nielsen, 1999) in which these could be considered as a unit to analyze feeding behaviours (Nielsen & Whittemore, 1995). There is no real chewing in birds, the tongue is rigid and tactile sensibility is mainly perceived when the particles are touched and seized by the beak tip (Picard *et al.*, 2002). The appetitive phase of chickens can be characterized by the foraging behaviour, which is the time that the bird explores the environment searching for food, as reported by (Yo *et al.*, 1997), who found that two thirds of young bird pecks do not result in the prehension of a feed particle.



The mechanical process of feeding in domestic chicken is similar to that of pigeons (Table 1). It is suggested that, within the phases 'grasp' and 'mandibular motion', the opening beak amplitude is gauged according to the particle size and the initial beak opening is used to control the amplitude. For the 'grasp' phase, the birds use visual information and for 'mandibular motion' tactile information. Moreover, the feeding behaviour of these birds can be defined as stereotyped movement patterns. These stereotyped patterns create an eating-response sequence and such sequences create an event feeding scene or a feeding bout (Figure 1). The reason why these movements are defined as stereotyped is on account both of duration and temporal organization of the variables in the process. This standard is based on the Variation Coefficient. Considering the appearance of stereotyped variables that compose a feeding scene of pigeons (Zweers, 1982) and chickens (Van Der Heuvel & Berkhoudt, 1998), the feeding behaviour can be considered as a result of Fixed Action Patterns, more than just a pattern. Actually, the bird can adapt certain movement patterns depending on the type of food, but such behaviours are subordinate to limitations of morphological structure and mechanical construction (Zweers, 1982).

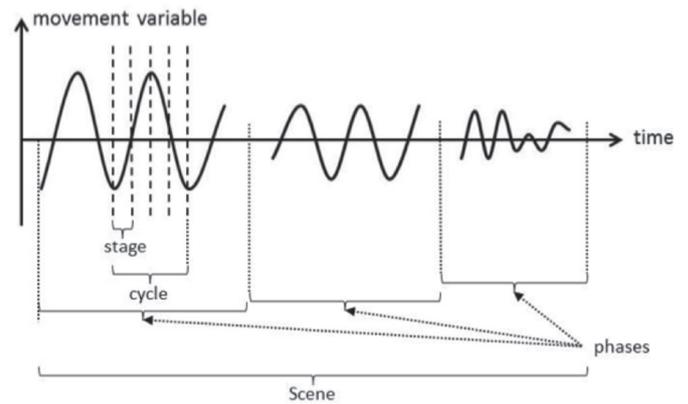


Figure 1 – Schematic representation of the subdivision of a feeding behaviour pattern. Adapted from Zweers (1982).

A better understanding of the patterns of biomechanical mechanisms involved in the bird intake process is important. Commercially farmed birds are not well documented subject. Nevertheless, this knowledge could lead to a better understanding of the feeding process, focusing on maximizing performance and animal welfare at farm level, since ration has a high impact on farm profitability.

Feed: the raw material, processing methods and the physical form

The production of feed for livestock aims at reducing the cost of the manufacturing process without compromising the quality of the final product.

Table 1 – Summarized description of the phases of the pigeon and chicken feeding scenario.

Phase	Description
Fixation	The head still stable above the seed, the eyes wide open. The distance between the eye and the target is about 5-8 cm. Beak is closed, but fluctuations could be seen in the openings of the beak and tongue movements for swallowing seeds ingested previously.
Approach or pecking	Starts when the bird moves its head uninterruptedly towards food in an oblique or vertical direction. The beak opens, and the elevation of the upper jaw occurs prior to the depression of the lower jaw and the tongue is retracted. The beak opens slightly more than the seed size. The eyes are partially closed.
Grasping	Starts with the maximum beak opening in the last part of the approach phase. The beak tip apprehends the seed and the eyes are completely closed.
Withdrawal	Starts right after the 'grasping' phase. Food is retained in the beak tip, and head is withdrawn in an upward motion. There may be a delay when the beak strikes against the substrate.
Stationing	The food is eventually repositioned by "catch-and-throw" movements. These serve to reposition the seed in the beak before starting the transport. This phase can be repeated as often as needed or possibly skipped when seed is properly grasped.
Transporting	Transports the seed from the beak tip into the pharynx level though the "catch-and-throw" or "slide-and-glue" movements or a combination of both. The "slide-and-glue" technique, usually adopted with smaller particles, consists in the displacement of the tongue up to the tip of the beak in order to glue the food with the aid of the sticky saliva and convey it into the oral cavity.
Collecting	Small seeds are accommodated at the base of the tongue while the bird keeps feeding. It does not occur with large seeds.
Swallowing	Final transportation of the seed into the esophagus with one or more movements of the pharynx, tongue, small beak openings and head jerks. Two mechanisms: "scraping" which is the continuation of "slide-and-glue" for small seeds and "peristaltic" which is a continuation of "catch-and-throw" for larger seeds.

Adapted from (Moon & Zeigler, 1979; Zeigler *et al.*, 1980; Zweers, 1982; Bermejo *et al.*, 1989; Van Der Heuvel & Berkhoudt, 1998).



Amongst the purposes of feed processing, there are mostly the changes of particle size and increased density of feed. A key factor in the processing is to obtain the maximum nutritional potential of the feed at minimal cost (Thomas *et al.*, 1998). This is achieved by altering the natural state of ingredients to improve their nutritive potential, and, therefore, the pelleting process is most widely used by the livestock feed industry (Meurer *et al.*, 2008). Generally the rations for broiler chickens are offered in mash, pelleted, extruded or crumbled physical forms. The mash rations are processed in the form of crumbs by mixing ground ingredients and also form the raw material for other varieties of ration. The pelleted type is the mash one which is pressed under high temperature, pre-cooked and subsequently moulded in the shape of small cylinders, so called pellets. The extruded rations are composed of mash ration subjected to baking at high pressure, humidity and temperature, but such processes are applied in a short time compared with that of pelleted ones. Finally, the crumbled rations are those pelleted or extruded which are crushed to form particles larger than those of mash feed and smaller than pellets (Thomas *et al.*, 1998). Also, in addition to the type of ration, the nutrient composition of broiler chicken diet is different so as to offer the most appropriate balance for each growth phase: the pre-start (1-7 days), initial (8-21 days), growth (22-35 days) and final (36-42 days). Therefore the use of the most appropriate type of ration must be considered with respect to the different farm contexts, such as regional availability of raw material, the technology level adopted by the feed plants, plus the animal genetic strain and the local weather conditions. By this approach, the best cost-benefit formulation is flexible and there is not a single rule to follow for achieving good yield indices.

The main steps to processing cereals include disruption of the seed coat (removal of the outer protective layers; the shells); exposure of the endosperm; reduction of particle size; agglomeration; mixing; heat treatment; pressure; changes in the structure of starch, and the addition of protein and fat (Thomas *et al.*, 1998). The starch in cereals is in granule form, being highly organized complex resistant to the ingress of water and to the action of enzymes (Joy *et al.*, 1997). Nevertheless, when heated above 100°C in the presence of water the process of gelatinization occurs, which consists in the swelling of granules to temperatures at which a break occurs, with destruction of the molecular order, and with irreversible changes

in its properties (Thomas *et al.*, 1998; Donald 2001; Kishida *et al.*, 2001; Fukuoka 2002; Perez & Oliva-Teles, 2002).

Grain milling is a process which reduces the ingredient size by impact force, cutting or abrasion. This reduction increases both the number of particles as surface area, facilitating the handling and mixing of ingredients. The screening determines the particle size, and the process efficiency varies according to the grain type and machinery used (Koch 1996; Rodgers *et al.*, 2012). For this process, two types of equipment are used: the hammer mill and the roller mill. The hammer mill has a set of hammers at high speed motion which press the particles through a screen. The roller mill consists of one or more pairs of horizontal rollers and the distance between them can vary according to the desired particle size. Efficiency of the process depends mainly on the type of grain, on the moisture contained therein, on the desirable particle size and on the engine power. As described by Koch (1996), in the hammer mill the particles generally have a spherical shape with a large size variation and, in the roller mill the particles tend to be uniform in size, but irregularly shaped, and require less electricity. Different types of grain milled under similar conditions can result in grains of different sizes (Lentle *et al.*, 2006; Amerah *et al.*, 2007; Amerah *et al.*, 2008). Thus, it is suggested different screen sizes be used, according to the type of grain, in order to obtain the desired particle size (Amerah *et al.*, 2007). The data provided by Nir *et al.* (1990) show that the productive yield of broilers is not influenced by the grinding process when the particle size is the same. Meanwhile, Nir *et al.* (1995) found greater weight gain in the use of particles by roller mill, because of the larger particle size and better uniformity of feed. Pelletization can be defined as a process of clustering of milled particles of an ingredient (or a mixture of ingredients), through mechanical processes and in combination with moisture, heat and pressure. The use of thermally processed ration can create a differential in the production of broiler chickens, especially in the pre-start phase. Chicks fed with crumbled diets have greater weight gain and better feed conversion than those fed with mash ones, despite this effect not always being observed until they are 42 days old. It is recommended that pre-starter feed be provided in crumble form, since this promotes nutritional benefits into the first weeks of rearing at an acceptable cost of production (Silva *et al.*, 2004).

Birds are able to select different sizes of feed particles very early on life. The format and structure of the beak



determines the size and type of food to be ingested, and thus the granulometry of the particle is of high importance for the regulation of the consumption. Granulometry is defined as a measure of feed particle size. According to the standard adopted in recent years (ASAE, 1983), the average particle size is given by the geometric mean diameter (GMD) of a representative sample, expressed in millimetres (mm) or microns (μm) and its variation is described as the geometric standard deviation (GSD). The higher the GSD, the more uneven is the feed particle size. It is common for substantial variation to occur in the particle size (630-1450 μm , according to Addo *et al.* (2012) and, therefore, routine monitoring is desirable in the manufacturing process to maintain the quality of the final product in terms of GMD and GSD. As suggested by Nir *et al.* (1994a), the uniformity of feed particles is considered important for good performance for broiler fed mash ration, since the birds spend less time searching and selecting the larger particles.

It is well documented that the particle size after grinding in broiler feed is most critical in mash diets compared to pellet and crumbled (Hamilton & Proudfoot, 1995; Nir *et al.*, 1995; Svihus *et al.*, 2004; Péron *et al.*, 2005; Amerah *et al.*, 2007). Furthermore, the pre-starter diets must be formulated with ingredients of better quality to meet the requirements of the initial stage (Lilburn, 1998), since the birds quickly respond to the stimulus of food intake immediately after hatching (Vieira & Pophal, 2000; Noy & Sklan, 2002). Several studies suggest that chickens at all ages show a preference for larger particles and this fact is marked with increasing age, probably due to the development of both digestive and buccal apparatus (Nir *et al.*, 1990; Nir *et al.*, 1994b). Thus, the increase in granulometry increases body weight at slaughter age and thus the economic feasibility (Hamilton & Proudfoot, 1995), but Parsons, *et al.* (2006) found a drop in performance when the size is greater than 1.042 μm . It has been suggested that chicks prefer the particles of 700-900 μm (Douglas *et al.*, 1990; Nir *et al.*, 1990; Nir *et al.*, 1994b; Nir *et al.*, 1995) or 600-900 μm (Amerah *et al.*, 2007), while Portella *et al.*, (1988), suggest a particle larger than 1180 μm , and for adult birds greater than 2360 μm .

Nir *et al.* (1994b) observed higher consumption in mash diets with particles of 769 μm for broilers at pre-starter phase (1-7 days old) when compared with GMD of 525 μm and 1260 μm . This result may be related to the lower GSD (1630) in relation to other considered sizes (2.000). These findings are in agreement with

Amerah *et al.* (2008) and are also reported by Lott *et al.* (1992), who found higher body weight and better feed conversion in broilers fed with 716 μm of DGM up to 21 days of age. On the other hand, no differences were seen in the crumbled diet with 690 and 974 μm of GMD.

The feeding of chickens with whole grains has been associated with an improvement in gut development and health due to the stimulation of the gizzard (Hetland *et al.*, 2002; Gabriel *et al.*, 2006) and also with a lower incidence of proventricular dilatation (Jones & Taylor, 2001). The gizzard is an organ that plays a key role in the diet of domestic chickens, aiding digestion in both the reduction of particle size through mechanical grinding of the feed, as in the chemical degradation of nutrients, in addition to regulating the feed flow (Hetland *et al.*, 2004). The contents of the gizzard are dumped when the particle size is reduced by 15-40 μm (Hetland & Svihus, 2001). Recent and past publications suggest that at least 20-30% of the particles should present a size greater than 1000 μm (Svihus, 2011) or 1500-2000 μm (Nir *et al.*, 1994a), because finely ground particles can inhibit the functioning of the gizzard. In line with these reports, the findings of López & Baião (2004) suggest that a coarser texture contributes to the performance of broilers fed with mash; crumbled and expanded crumbled diets are favored mainly for carcass yield and the weight of digestive organs, but the intake was the same for mash diets with different GMD. Conversely, Dahlke *et al.* (2001) reported a decrease in consumption and weight gain with rations of smaller particle size, in addition to a worsening in feed conversion with pelleted diet processed from particles with smaller GMD.

In the initial growth stage, generally mash or crumble diet is offered because the birds at this stage are still unable to ingest pellets and do not regulate feed intake according to the energy level (Faria *et al.*, 2006). The physical form of pre-start diet (1-7 days) influences the performance of broilers until the end of the initial phase (8-21 days old), but the effects diminish until slaughter age with no effect on carcass characteristics (Freitas *et al.*, 2009). Several studies are in line with the increase of broiler performance when processed diets are offered, which is mostly explained both by improvements in weight gain and feed conversion (Jones *et al.*, 1995; Scott *et al.*, 1997; Leeson *et al.*, 1999; Lecznieski *et al.*, 2001; Vargas *et al.*, 2001; Greenwood *et al.*, 2004; Silva *et al.*, 2004; Maiorka *et al.*, 2005; Lara *et al.*, 2008); development of the digestive tract (Shamoto & Yamauchi, 2000;



Engberg *et al.*, 2002; Dahlke *et al.*, 2003; Zang *et al.*, 2009); increasing of feed density leading both to nutrient intake and to growth rate (Engberg *et al.*, 2002; McKinney & Teeter 2004; Lemme *et al.*, 2006; Freitas *et al.*, 2008; Meurer *et al.*, 2008; Freitas *et al.*, 2009); greater nutrient digestibility (Moreira *et al.*, 1994; Vargas *et al.*, 2001; Goodband *et al.*, 2002; Freitas *et al.*, 2008; Zang *et al.*, 2009); reduction on particles selectivity by the birds and better palatability (Gadzirayi *et al.*, 2006; Lara *et al.*, 2008); minimization of energy expenditure during feeding (Nir, *et al.*, 1994c; Leeson *et al.*, 1999; Jensen, 2000; López *et al.*, 2007); decreasing of wastage (Jensen, 2000; Gadzirayi *et al.*, 2006); facilitating the production-logistics at feed plants, as many as on farms (Nir *et al.*, 1995; Plavnik & Sklan, 1995; Vargas *et al.*, 2001; McKinney & Teeter, 2004; Greenwood *et al.*, 2004) and; better cost benefit ratio in relation to mash diets (Axe 1995; Dozier III 2001; Meinerz *et al.*, 2001; Vargas *et al.*, 2001; Engberg *et al.*, 2002; Fairfield 2003; López & Baião, 2004; McKinney & Teeter, 2004; Corzo *et al.*, 2011; Oliveira *et al.*, 2011).

Pelleting is the key factor in the profitability of a feed plant. Although there are several benefits of pelleted diet on broiler performance, factories should focus on cost-benefit ratio. For integrated systems, improved feed conversion should pay the cost of the process (Fairfield, 2003). Pelleting also facilitates production-logistics adopted in both feed plants and farms. This is done mainly by minimizing contamination of the feed by reducing the microbial population during processing, which decreases the selectivity by birds avoiding a nutritional imbalance, promotes improvement in the feed flow at feeders, favours the storage and transportation by a greater quantity in less physical space and minimizes the formation of fines (Vargas *et al.*, 2001). Fines are considered those particles that disintegrate from the initial structure of the pellet.

Waste reduction by using pelleted diet can reach 18% in relation to mash type, according to the findings reported by Gadzirayi *et al.* (2006), due to increased particle aggregation and decreased selection of most preferred ingredients by birds. As previously mentioned, pelleted diets aid in the development of the digestive tract, but Meurer *et al.* (2008) pointed out that when both mash and pelleted diets are equalized, the weight gain is equalized, as well. Another issue regarding chickens fed pelleted diets is the reduction of time spent for the consummatory act. Given this, birds increase their resting time, which favours lower energy

expenditure in maintaining and increasing availability of net energy for production (Nir *et al.*, 1994c; Leeson *et al.*, 1999; Skinner-Noble *et al.*, 2005; López *et al.*, 2007; Lara *et al.*, 2008). Furthermore, the average time spent at the feeder depends on the physical form of the feed, which could range from 56 s in pelleted feed and 114 s in mash physical form (Yo *et al.*, 1997). Thus, the duration of poultry meals can influence flock performance, since the increasing feeding time brings on disadvantages for submissive birds that probably will not consume their nutritional requirements for optimal development (Ferket & Gernat, 2006).

On the other hand, some drawbacks of pelleted diets have also been pointed out. Among them can be highlighted a higher accumulation of abdominal fat and increase of the mortality rate in relation to mash diet (Leczneski *et al.*, 2001). The probable reason for this is that birds fed pelleted rations remain inactive longer than active, *i.e.* stay lying longer than walking (Nir *et al.*, 1995; López & Baião, 2004). Moreover, pelleted diet can increase the susceptibility of birds to death by ascites and sudden death syndrome (Garcia Neto & Campos, 2002; Arce-Menocal *et al.*, 2009), this phenomenon being more pronounced in males than in females (Nir *et al.*, 1995). This could be attributed to the reduced number of meals, resulting in a higher intestinal load associated with a faster rate of food transit and greater amount of chime in the intestine, which increases the need for oxygen in the small intestine. Furthermore, increased locomotor disorders (lameness) have been reported with the use of pelleted compared to mash diet (Brickett *et al.*, 2007), in addition to difficulties in maintaining good quality of pellets (Meurer *et al.*, 2008).

An expression used to refer to the quality of the pellet is Pellet Durability Index (PDI, given in %) and nowadays the most widely used method to determine it (ASAE 2003a; ASAE 2003b). Cutlip *et al.* (2008) reported that the best quality pellets (PDI, 90 *versus* 80%) produce a lower feed conversion and higher yield of breast meat. An improvement of only 4% in PDI can contribute significantly to the performance of broilers. Likewise, Moritz *et al.* (2001) suggest that the pellets of high quality (PDI; 87%) improve feed efficiency compared with lower quality (IDP, 62%). Some recent studies indicate that the supply of a lower quality pelleted diet, with the addition of 20 to 35% of milled maize in both growing and final phase of rearing, can promote a better cost-benefit, since performance and meat yield are similar to those birds that are fed only with high-quality pellet (Clark *et al.*, 2009; Dozier III *et al.*, 2009; Dozier III *et al.*, 2010).



The pellets are considered fragile material (Aarseth & Prestløyken, 2003) and their disruption occurs during manufacture, distribution and final delivery to animals on the farm. It is believed that the pneumatic transport at both plant and farm is the main cause of these disruptions (Thomas & Van Der Poel, 1996). Different birds in different parts of the shed can receive different levels of fines and pellets, which will affect the growth rate and uniformity of the flock. The proportion of fines of a ration depends on various factors, such as the types of ingredients, the use of binders, the matrix conditions used in pelleting, amount of moisture, pressure and steam levels and handling. Briggs *et al.* (1999) define a pellet quality as the ability of a pellet to remain intact during handling, supported by Angulo *et al.* (1996) who pointed out that the quality is inversely proportional to the size of feed particles; *i.e.* the smaller the particle size, the greater the surface for absorbing moisture from steam, leading to a better lubrication mixture and, thereby, a better pellet quality. So the processing of pellets with coarse feed particles results in break points and, consequently, produces more fines (Behnke, 2001). Other studies, on the other hand, have reported that the pellets made from different particle sizes do not influence broiler performance (Svihus *et al.*, 2004; Péron *et al.*, 2005). The use of pressure to alter the feed physicochemical properties in combination with water and heat, and the use of pressure to pre-densify the mash feed before pelleting, are key factors for obtaining a pellet with good quality (Thomas *et al.*, 1997).

The quality of the pellets may be the subject of strong disagreement between researchers, and feed manufacturers due to their high effect on animal performance and consequently the cost-benefit ratio in feed processing. The high concentration of fines can annul the benefits of a pelleted feed, increasing the cost and making the process unfeasible to the industry, since the benefits of this process practically disappeared in comparison to the mash feed (McKinney & Teeter, 2004; Meurer *et al.*, 2008). According to Behnke (1996), the factors that most affect pellet quality in a conventional pelleting system are the formulation (40%), conditioning (20%), particle size (20%), die specification (15%) and cooling (5%). The high-quality pellets provide higher carcass weight (Lilly *et al.*, 2011), increase broiler growth by 25% and increase average feed consumption, compared to low quality and mash diet rich in proteins (McKinney & Teeter, 2004). Interestingly, the mash diets indicate a higher feed intake with a similar weight gain to low-quality pellets, suggesting, in this sense, a better digestibility

of low-quality pelleted than mash diet (Lemme *et al.*, 2006). Also, the findings reported by Carré *et al.* (2005) indicate a positive correlation between the pellet durability and feed efficiency. The increase in fines in the diet reduces consumption and weight gain in broiler chickens, and, interestingly, the findings of Quentin *et al.* (2004) agree that this drop is five times higher for genetic selection for rapid growth compared with the slow growth strain. This could imply that these birds exhibit greater sensitivity to feed form, probably due to a limitation both in adaptability and foraging behaviour.

The relative growth rate of the chicks increases approximately 3% per day during the first days of life to 20% per day for five days old and remains at this rate for fifteen days (Nir *et al.*, 1993). Slightly different results from Sell (1996) indicate that the relative growth rate is approximately 12% during the first 4 days, with a gradual increase to a peak of 20% on the sixth day of age and diminishing thereafter. It is, therefore, clear that the feed quality plays a key role in achieving a good flock performance at slaughter time, with superior care at the initial phase. Although there are some negative consequences, it is clear that, in general, processed diets are more convenient than those non-processed (mash diets). However, more studies are needed on the preference of birds for a particular type of feed, which could lead to a better understanding of the feeding processes and then drive us to accurate decision making on feed plant, and thus achieve a better cost-benefit without compromising bird welfare.

Design and management of feeders

At the rearing environment, it is very important that the food sources (feeders and drinkers) are properly arranged and well managed. Several studies indicate that some design features, such as size, location, geometry, spacing and angle, can affect the behaviour of animals. Deployment of design strategies that weaken the agonistic interactions and produce feed wastage during the use of these devices by the animals is common (Buskirk *et al.*, 2003; Wolter *et al.*, 2009). The feed continuously provided for broiler is essential for them to express their genetic potential. The fodder also needs to be delivered in a clean, uniform, and easy to access way. For the initial phase, the tray-feeder type, the infantile-tube and/or the automatic, are used; the latter is generally used at all rearing phases. In addition to the automatic type, the tube type could be used for the intermediate and final phases (Englert, 1998).



The feeders should be uniformly distributed on rearing area. In some models, a partition grid is provided over the feed trough, which function is to homogenize the distribution of birds, reducing competition and decreasing wastage when the birds are feeding. Neves *et al.* (2010) reported that broilers tend to spend more time at the feeders without a partition grid, and this can be explained by the ease of access to the feeding area. Although it cannot be claimed that the birds had a higher intake, the foraging behaviour related to environment exploration was more evident. On the other hand, this preference disfavors wastage issues, always undesirable to the farmer.

Poultry consumes the feed regularly throughout the day, but there is a subtle increase in the intake at the beginning and the end of the light period. In a continuous lighting program, the intake is constant, regardless of the time of day. The nature of the diet is considered the factor that most influences weight gain and feed conversion on broilers. It is essential that the feeding equipment provide ease of access. Although few studies are available, the effect of feeder height has been assessed and is recommended as good management by some guidebooks.

From 35 days, the feeder use should be as low as possible without allowing birds to eat while lying, because this can compromise the integrity of the breast due to corns, and deny access to other birds. It is recommended that the feedstuff layer be kept low within the trough so that particles adhering to the beak drop back into the trough, not onto the ground (Planalto, 2006; Roll *et al.*, 2010b). Therefore, working with tube-type feeders is recommended, with the trough upper edge at bird breast level or lower, but not touching the ground, since movement is an important factor in feeding the flow toward the trough (Roll *et al.*, 2010b). It has been reported that there is no difference in productivity rates (daily weight gain, feed conversion, mortality) as a function of the feeder height; however, at a lower height, the average body weight can be up to 7% higher (Quintana *et al.*, 1998), with a lower percentage of intramuscular fat in the thighs and greater muscle in drumsticks (Roll *et al.*, 2010b).

Another concern of farmers is that the feedstuff mixes with litter material, compromising the quality of the feed. The dust bathing is a natural behaviour of the birds, which is characterized by the act of rubbing on the ground and throwing litter material on the body using the legs and wings (Vestergaard *et al.*, 1990), hence the material is more easily thrown into the troughs of lower height. However, it was not found to

compromise the microbiological quality of feed (Roll *et al.*, 2010b). It has also been suggested that feeders regulated too high can inhibit consumption of the smaller birds and thus contribute to the unevenness of the flock (Ferket & Gernat, 2006). Considering bird preference, Roll *et al.* (2010a) found that broilers tend to consume more feed in feeders of lowest height. In this specific study, only 23% of the birds that fed initially at the low trough moved to the highest one, while 100% of those who at first chose the highest feeder changed to the lowest feeder. In addition, the feeders adjusted near the ground allow all birds, including the less developed, to feed themselves more easily. The authors also suggest that, on average, the birds pass twice the time consuming in the lowest feeder, and although the frequency of visits decreases, no significant difference was observed in feed intake. This situation indicates a negative correlation between the frequency of visits and the amount of ingested feed. With the course of time birds reduce the intensity of consumption probably by reducing the size of the mouthful and by being comfortable in the troughs of lower height.

On the other hand, in laying hens, more advantages were indicated by using higher feeders. In this situation, the birds adopt a posture that discourages other birds from trampling on their backs, thus promoting better conditions of plumage and reducing feather pecking and cannibalism (Freire *et al.*, 1999). Other studies assessing nipple-type drinkers suggest that the increase in height relative to the ground reduces the water consumption in broilers (May *et al.*, 1997; Lott *et al.*, 2001), especially because water intake in this model is not a natural behaviour and because the stretching of the neck is greater, particularly when the animals are puffed, creating a detrimental effect on weight gain, feed conversion, and increasing mortality (Lott *et al.*, 2001; Ipek *et al.*, 2002).

Although many reports recommend height adjustment of the feeders, e.g. back height (Ávila *et al.*, 1992; Agroceres, 2004; Ávila *et al.*, 2006; Aviagen, 2009; Cobb-Vantress, 2010; Albino *et al.*, 2011); crop height (Planalto, 2006); and breast height (Bassi *et al.*, 2006; GloboAves, 2011). Roll *et al.* (2010b) point out, however, some practical reasons to believe that these recommendations may not be ideal for the rational management of broiler chickens: 1) the time spent by the producer to carry out this practice; 2) the feeders which are adjusted to the birds' back height might hamper the ingestion because the birds, in their natural environment, seek and ingest food directly from the ground; 3) the feeders with a very high setting require



more effort to achieve feed, in addition to the need for a higher layer of feedstuff in the trough to facilitate ingestion, which increases wastage; 4) aviaries with very high layers of litter (above 8.0 cm), with advancing age experience a lowering of these layers, leading to an increased distance from the ground to the feeder, which can hamper access to feed for smaller birds; 5) lack of scientific publications justifying the adoption of this practice.

FINAL REMARKS

The benefits of the processed feed in broiler chicken performance is well documented, and, despite the high cost of production, the pelleted diet, even with a lower quality (durability index), has more advantages than the mash type. However, the feasibility of feed manufacturing may vary in different regions according to the availability of raw material and the technology adopted by the feed plants. So far, most research on the poultry feeding behaviour addresses the productivity indices and bird physiological responses, but few studies have considered the biomechanical characteristics involved in this process.

A better understanding of the mechanical process of the bird jaw apparatus during feeding might be an effective method for determining the relationship between different types of ration in biomechanical patterns, and for considering the anatomical variations between different strains, ages and genders, and also the impact of feeder design. In this sense, the high speed camera combined with techniques of computational image analysis is a remarkable technology to aid these assessments. Some behavioural patterns that happen in a very short period of time cannot be detected by conventional cameras. Furthermore, it is a non-invasive technique for evaluating animal behaviour and allows natural body movement.

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