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DIEGO PEREIRA NEVES

"BIOMECHANICS OF THE FEEDING PROCESS OF BROILER CHICKS"

"BIOMECÂNICA DO PROCESSO DE ALIMENTAÇÃO DE PINTOS DE CORTE"

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UNIVERSIDADE ESTADUAL DE CAMPINAS
Faculdade De Engenharia Agrícola

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Thesis presented to the College of Agriculture Engineering of the University of Campinas in partial fulfillment of the requirements for degree of Doctor in Agricultural Engineering in the area of Rural Constructions and Ambience.

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Supervisor/*Orientadora*: Prof. Dra. IRENILZA DE ALENCAR NÄÄS

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ABSTRACT

Broiler chickens may exhibit different biomechanical motions patterns of the body parts in relation to the physical properties of feed (size, shape and hardness) while feeding. The anatomical limitations related to age, gender and breed may also impact the feeding mechanical process. To determine the significance of these parameters, measurements related to the biomechanical motions of body parts are required. In particular, the trajectory, dimensions and temporal effects related to the chicken's beak and head movements should be considered. However, determining this information manually from video by a human operator is tedious and prone to errors. The present thesis aims assess the impact of three different feed types on the biomechanics of feeding behaviour of broiler chicks. A total of 19 male broiler chicks were recorded while feeding at 3 and 4-d-old using a high-speed camera with an acquisition rate of 250 fps (frames per second). The feed types considered were: fine mash (F1), coarse mash (F2) and crumbled (F3), in which the geometric mean diameter and the geometric standard deviation were 476µm (2.54), 638µm (2.56), and 1243µm (2.43), respectively. The birds' weight and morphometric traits of the beak (length and width) were measured after the recordings. The birds' head displacement during mouthful and mandibulation phases and the maximum beak gape were measured through computational image analysis. Mouthful phase consisted an uninterruptedly head movement towards feed in an oblique or vertical direction until the feed particle is grasped. Mandibulation phase consisted in one cycle of opening and closing of the beak, in which there is a maximum beak gape. These phases were manually classified, as follows: mouthfuls as 'successful' or 'fail' and mandibulations as catch-and-throw (CT) or slide-and-glue (SG). 'Successful mouthful' was when the bird successfully grasped the feed, and 'fail mouthful' was when the birds missed the feed. Catch-and-throw is when the feed is repositioned within the beak tip before starting the transport into the oral cavity. Slide-and-glue consists in the displacement of the tongue up to the beak tip in order to glue the feed particles with the aid of the sticky saliva and carry inward oral cavity. The results indicated significant correlations of weak intensity between weight, morphometric traits of the beak, and the biomechanical variables, as well as correlation between maximum beak gape and head displacement. The head displacement was higher in a successful mouthful (0.439 mm ± 0.002) than fail mouthful (0.371 mm ± 0.005). Furthermore, head displacement was more expressive in F3 (0.526 mm ± 0.005), F2 (0.519 mm ±

0.004), and F1 (0.431 mm ± 0.003), respectively. The head displacement was also significantly higher for CT technique (0.245 mm ± 0.001) than SG (0.114 mm ± 0.000). Considering the different feed types, head displacement for CT was higher in F3, F1 and F2, while for SG were higher in F3, F2, and F1, respectively. The maximum beak gape was also higher for CT (0.245 mm ±0.001) than SG (0.114 mm ± 0.00). Moreover, for CT it was higher in F3 and F1 than in F2, while for SG was higher for F1, F3 and F2, respectively. Thus, the different size of the feed particles (granulometry) was potentially the key factor for the chicks' motion while feeding. Besides, this relation was not proportional to the granulometry, explained by higher values for F3 and F1. The occurrence of 'fail mouthful' was 18,0% for F3, 11,2% for F2 and 6,6% for F1, respectively. For mandibulations classification, it was observed a higher frequency of CT in F3 (26,1%), F1 (24,9%), and F2 (17,9%). This situation suggests that the chicks grasped the particles in the beak tip more properly for swallowing with the granulometry 638μm (F2) than 476μm (F1), and 1243μm (F3), explained by the less motion and necessity of repositioning the feed particles. Overall, the high-speed camera technology combined with computational image analysis adopted in this experiment was an effective method for motion analysis. It is desirable a better understanding of the mechanical limitations of the birds' jaw apparatus while feeding in order to determine the relationship between different types of feed in biomechanical patterns displayed by the birds.

Key words: broiler chicken, feeding, high-speed cameras, jaw, kinematics.

RESUMO

Os frangos podem exibir diferentes padrões de movimentos biomecânicos as partes do corpo em relação às características físicas do alimento (tamanho, formato e dureza) durante a alimentação. As limitações anatômicas relacionadas com a idade, sexo e linhagem também podem afetar o processo mecânico de alimentação. Para determinar a importância desses parâmetros, as medidas relacionadas aos movimentos biomecânicos de partes corporais são necessárias. Em particular, a trajetória, dimensões e efeitos temporais relacionados com o bico do frango e com a movimentação da cabeça devem ser considerados. No entanto, determinar esta informação manualmente do vídeo por um operador humano é tedioso e propenso a erros. A presente tese tem como objetivo avaliar o impacto de três tipos distintos de ração sobre a biomecânica da alimentação de frangos de corte. O total de 19 pintos de corte machos foram filmados durante a alimentação aos 3 e 4 dias de idade através de uma câmera de alta velocidade com taxa de aquisição de 250 fps (quadros por segundo). As rações avaliadas foram: farelada fina (F1), farelada grossa (F2) e quebrada (F3), no qual o diâmetro geométrico médio e o desvio padrão geométrico foram 476µm (2.54), 638µm (2.56), e 1243µm (2.43) , respectivamente. O peso e a morfometria do bico (comprimento e largura) foram medidos após as gravações. O deslocamento da cabeça das aves durante as fases ‘mouthful’ e ‘mandibulação’ e a abertura máxima do bico foram mensurados por de análise computacional de imagem. A fase ‘mouthful’ consistiu no movimento da cabeça de forma ininterrupta direção oblíqua ou vertical em direção à ração até que a partícula de alimento fosse capturada. A fase ‘mandibulação’ consistiu em um ciclo de abertura e de fechamento do bico, na qual existe uma abertura máxima do bico. Estas fases foram classificadas manualmente como: ‘mouthful’ como 'sucedido' ou 'fracassado' e ‘mandibulações’ como ‘catch-and-throw’ (CT) ou ‘slide-and-glue’ (SG). O ‘mouthful sucedido’ consistiu quando a ave capturou o alimento com sucesso, e a ‘mouthful fracassado’ quando a ave errou a partícula de alimento. ‘Catch-and-throw’ consistiu no reposicionamento da partícula na ponta bico antes de iniciar o transporte para o interior da cavidade oral. ‘Slide-and-glue’ consistiu na deslocação da língua até a ponta em bico para aderir as partículas de alimento com o auxílio da saliva pegajosa e transportar para o interior da cavidade oral. Os resultados indicaram correlações significativas de fraca intensidade entre o peso, as características morfométricas do bico e as variáveis biomecânicas, bem como correlação entre a abertura máxima do bico e o deslocamento cabeça. O deslocamento da cabeça foi maior no 'mouthful sucedido' (0,439 mm ± 0,002) em relação ao 'mouthful fracassado' (0,371 mm ± 0,005). Além disso, o deslocamento da cabeça foi mais expressivo em F3 (0,526 mm ± 0,005), F2 (0,519 mm ± 0,004) e F1 (0,431 mm ± 0,003), respectivamente. O deslocamento da cabeça também foi significativamente maior para CT (0,245 mm ± 0,001) do que SG (0,114 mm ± 0,000). Considerando os diferentes tipos de ração, o deslocamento da cabeça para CT foi maior em F3, F1 e F2, enquanto que para SG foram maiores em F3, F2 e F1, respectivamente. A abertura máxima do bico também foi maior para CT (0,245 mm ± 0,001) do que SG (0,114 mm ± 0,00). Além do mais, para CT foi maior no F3 e F1 que em F2, enquanto que para SG foi maior para F1, F3 e F2, respectivamente. Assim, os diferentes tamanhos das partículas de ração (granulometria) foi, potencialmente, o fator chave para o movimento dos pintos durante a alimentação. Além disso, esta relação não foi proporcional à granulometria, explicada por valores mais elevados em F3 e F1. A ocorrência de 'mouthful fracassado' foi 18,0% para F3, 11,2% para F2 e 6,6% para a F1. Para a classificação das mandibulações, observou-se a maior frequência de CT em F3 (26,1%), F1 (24,9%) e F2 (17,9%), respectivamente. Esta situação sugere que os pintos capturaram as partículas na ponta bico de maneira mais adequada para a deglutição com a granulometria 638µm (F2) do que 476µm (F1) e 1243µm (F3), explicada pela menor movimentação e necessidade de reposicionamento das partículas de alimento. De forma geral, a tecnologia de câmeras de alta velocidade combinada com análise computacional de imagem adotada neste experimento foi um método eficaz para análise de movimentação. É desejável uma melhor compreensão das limitações mecânicas do aparelho bucal das aves durante a alimentação, a fim de determinar a relação entre os diferentes tipos de alimentos sobre os padrões biomecânicas exibidos pelas aves.

Palavras chave: frango de corte, alimentação, câmera de alta velocidade, mandíbula, cinemática.

SUMMARY

DEDICATION

I dedicate this work with all my love and gratitude to my parents, Jairo and Nodeli.

Also dedicate it to all professionals in the field of animal production.

Finally, I dedicate to all livestock animals which benefit our food and therefore deserve our utmost respect.

DEDICATÓRIA

Dedico este trabalho com todo o meu amor e gratidão aos meus pais, Jairo e Nodeli.

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EPIGRAPH

"Only those who will risk going too far can possibly find out how far one can go."

"Somente quem se arrisca a ir longe sabe até onde pode chegar."

THOMAS STEARNS ELIOT

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1 GENERAL INTRODUCTION

Chicken and turkey are the most common meat sources of the poultry industry with the greatest growth reflected in the food global demand increase, especially in developing countries. 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.

The diet composition is an aspect of high economic value in commercial poultry industry not only because it is primarily responsible for the growth response of birds, but importantly the largest cost in the production cycle. The processing method and the grain type interfere differently on the economic viability and animal physiological responses. The advantages of using processed feed have been well recognized, even though it represents a high manufacturing cost.

Under natural conditions, birds have to deal with different types of feed, which have different energy and protein levels. 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. Thus, the feed particles size is considered an important factor for the regulation of the consumption.

Biomechanical studies have been widely investigated using high speed camera technology in various species of animals, and have been highlighted for its effectiveness in several areas of study, including animal behaviour assessments. A better understanding of the biomechanical patterns involved in the intake process of broiler chickens could lead to an improvement of flock performance, minimize feed manufacturing costs, and improve animal welfare.

This thesis is presented with the following sections: the justification, the objectives, chapter 1 (literature review), chapter 2 (part of the methodology regards to image analysis), chapter 3 (material and methods, results and discussion), final remarks, and annex.

1.1. Justification

Most researches on performance and feeding behaviour of broiler chicken has been reported with respect to productivity indices and physiological responses, but there is a lack of scientific knowledge about the biomechanical features involved in this process. Past and recent studies 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 few studies are found related to the biomechanical features while feeding, no one is related to the modern broiler' strains for egg or meat production. Therefore, the present research aims to approach this subject by verifying the influence of the feed physical properties upon the biomechanical motion of the birds jaw apparatus. The hypothesis of this study is that the feed particle size influences the chicks head kinematics and beak gape. The high speed camera combined with techniques of computational image analysis is a notable 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. The findings should possibly bring new perspectives for feed evaluation and its processing methods, as well as a better understanding of the limitation of the birds' movements in order to meet animal welfare concerns.

1.2. Objectives

1.1.1 General objective

To evaluate the influence of the feed physical characteristic on the biomechanics of the feeding process of broiler chickens at pre-initial phase.

1.1.2 Specific objectives

- To evaluate the influence of three different feed types with different particle sizes on the biomechanical motion of broilers chicks during feeding;

- To verify the correlations between the weight and morphometric traits of the chicks' beak (length and width) on biomechanical motion during feeding;
- To validate the computational image analysis technique presented in Chapter 2 of this thesis regarding to chicks' head displacement and maximum beak gape assessments;
- To describe the biomechanical process of the chicks' feeding behaviour through classifying and comparing both mouthful and mandibulation feeding phases according to the characteristics of the movement, beyond the maximum beak gape reached in each mandibulation.

CHAPTER 1

The literature review section is presented in a scientific article format and was published as a review paper at the **Brazilian Journal of Poultry Science**, v. 16(2), pp. 1-16, 2014. Available at: < http://www.scielo.br/pdf/rbca/v16n2/a01v16n2.pdf >

FEEDING BEHAVIOUR OF BROILER CHICKENS: A REVIEW ON THE BIOMECHANICAL CHARACTERISTICS

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.

Keywords: feedstuff, feeding behaviour, jaw apparatus, motion.

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 (McLester & 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 (Pennycuick, 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 (Gussekloo *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 fiber 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 Der 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 Der 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 analyse 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).

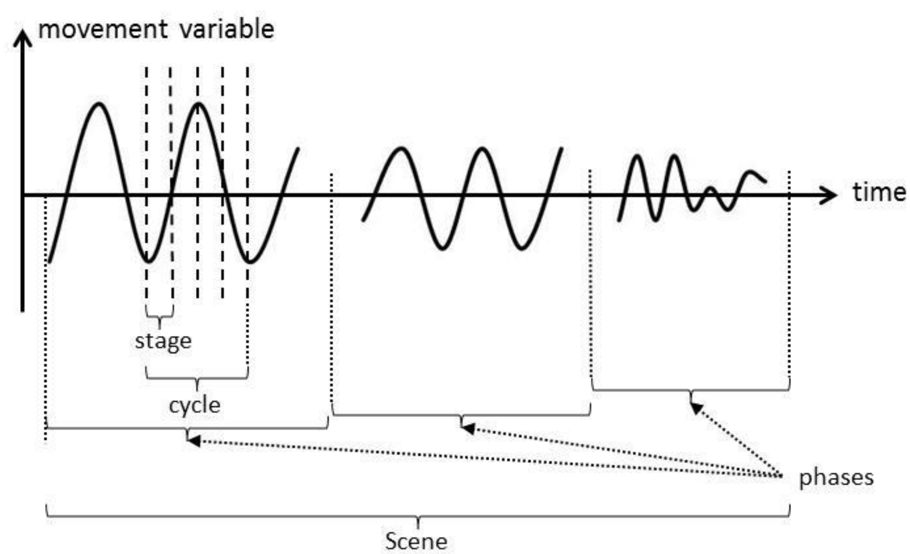

Figure 1. Schematic representation of the subdivision of a feeding behaviour pattern. Adapted from Zweers (1982).

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 oesophagus 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).

A better understanding of the patterns of biomechanical mechanisms involved in the bird’s intake process is desirable, especially because in commercially farmed birds this subject is not well documented. 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. 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 1.042µm. 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 1180µm, and for adult birds greater than 2360µm.

Nir *et al.* (1994b) observed higher consumption in mash diets with particles of 769µm for broilers at pre-starter phase (1-7 days old) when compared with GMD of 525µm and 1260µm. 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 716µm of

DGM up to 21 days of age. On the other hand, no differences were seen in the crumbled diet with 690 and 974µm 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 15-40µm (Hetland & Svihus, 2001). Recent and past publications suggest that at least 20-30% of the particles should present a size greater than 1000µm (Svihus, 2011) or 1500-2000µm (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 favoured 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 (Lecznieski *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 & Prestløkken, 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 disfavours 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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CHAPTER 2

The computational image analysis method used in this thesis was submitted for scientific publication at the "Computers and Electronics in Agriculture", and is presented in a scientific article format.

IMAGE ANALYSIS METHOD TO EVALUATE BEAK AND HEAD MOTION OF BROILER CHICKENS DURING FEEDING

ABSTRACT: During feeding broiler chickens may exhibit different biomechanical movements in relation to the physical properties of feed such as size, shape and hardness. Furthermore, the chicken's anatomical limitations such as age, gender and breed in conjunction with feed type and feeder design parameters may also have an influence on biomechanical movement of the body parts related to feeding (i.e. head and beak). To determine the significance of these parameters during feeding, measurements related to the biomechanical motions of these chickens' body parts are required. In particular, the trajectory, dimensions and temporal effects related to the chicken's beak and head movements should be considered, as well as the number of mandibulations necessary to prepare the feed for swallowing. However, determining this information manually from video by a human operator is tedious and prone to errors. To overcome this limitation, the present study demonstrates a machine vision technique which visually identifies the important biomechanical variables attributed to broiler feeding behaviour from high speed video footages. A total of 88 mandibulations from three five-day-old broiler chickens were analysed while feeding on a mash ration. The following biomechanical variables were considered: (i) eye position (reference to determine the head motion); (ii) beak opening speed; (iii) beak closing speed; (iv) beak opening acceleration; (v) beak closing acceleration; and (vi) maximum beak gape (*i.e.* inter-beak distance). Image analysis algorithms were developed to automatically detect and record these variables. The accuracy of the method was found to be less than 1 mm, unachievable by the human observation. Results also suggested that beak opening motion was almost at a constant speed (acceleration was close to zero), whether closing phase presented accelerated motion. The developed image analysis method will facilitate efficient and repeatable acquisition of biomechanical data of a chicken while feeding. Such information has the potential to be used to benchmark the physical properties of feed and the way in which it is processed as well as informing aspects of feeders' design which reduce feed wastage.

Key-words: biomechanics, eating behaviour, high speed camera, image analysis, jaw apparatus.

1. INTRODUCTION

The poultry industry is considered as one of the most active meat producing industries requiring frequent increases in production to satisfy the worldwide demand for poultry meat. The largest broiler chicken producers by country are the United States, China and Brazil with the United States and Brazil contributing to two-thirds of poultry-meat exports globally (FAO, 2012; USDA, 2012). Feed costs are the main drivers of profitability on commercial poultry farms, so minimizing feed wastage is desirable. Advances in poultry nutrition are largely responsible for the exceptional growth rate responses of current domesticated species. In addition to nutritional value the feed properties should also ensure it is palatable and easy to consume and digest by the birds.

Past research have investigated the impact of both chemical and physical characteristics of the feed on animal responses, and the economic feasibility regarding feed processing methods (Thomas, et al., 1998; Perez & Oliva-Teles, 2002), feed particle size (Nir, et al., 1990; Nir, et al., 1994a; Nir, et al., 1995; Amerah, et al., 2007), feed material form (Greenwood, et al., 2004; Nir, et al., 1994b; Skinner-Noble, et al., 2005; Zang, et al., 2009), and more recently the influence of feeders' features on birds' preferences (Neves, et al., 2010; Roll, et al., 2010) on birds' preference. To date, the scientific research about broilers' feeding performance and behaviour is based on productivity indexes, physiological responses and the impact of environmental conditions. However, little is known about the biomechanical responses of birds during feed consumption.

Biomechanics can be described as a physical (mechanical) movement displayed or produced by living systems (McLester & Pierre, 2008). Studies in biomechanics are of interest to various professional fields, such as zoology, medical, biomedical engineering, and kinesiology (study of human movement) (Hall, 1999). The detection of jaw movement has been previously inspected (Wainwright, 1991; Pennycuick, 1992; Van Der Heuvel and Berkhoudt, 1998; Ropert-Coudert et al., 2004) for identifying features that characterize prey ingestion on eleven captive animal species of mammals, birds and turtles, carnivorous and herbivorous feeding habits and either marine or terrestrial environments were investigated. Stefen et al. (2011) used the digital bi-planar high-speed X-ray system to investigate jaw movements during incisor action and mastication in beaver.

The mechanical process exhibited by domestic chicken during feeding is similar to that of pigeons and can be divided into different phases starting with the identification of a potential feed particle and ending with ingestion. Terminology for the different phases exhibited includes fixation, approach or pecking, grasping, withdrawal, stationing, transporting, collecting and swallowing (Moon & Zeigler, 1979; Zeigler, et al., 1980; Zweers, 1982; Bermejo, et al., 1989; Van Der Heuvel & Berkhoudt, 1998). These phases are described according to the position of the feed within the beak and the motion and position of the specific parts of the chicken's body during the process (head height, upper and lower beak displacement, sliding movement of the tongue and the eye blink). Furthermore, the feeding behaviour of these birds was described as stereotyped movement patterns, considering both duration and temporal organization of the variables involved the process (Zweers, 1982; Van Der Heuvel & Berkhoudt, 1998). The bird can adapt certain movement patterns depending on the type of feed, but such behaviours are subordinate to limitations of morphological structure and mechanical construction (Zweers, 1982).

Most research on broiler feeding behaviour addresses the productivity indices and birds' physiological responses. This paper aims to present a methodology to evaluate the biomechanical motion of broiler chickens during feeding through computational image analysis, considering the movement characteristics of the birds' beak and head.

2. MATERIAL AND METHODS

2.1 Birds and facilities

The experiment was performed at the Ambience Laboratory in the School of Agricultural Engineering (FEAGRI), State University of Campinas (UNICAMP), Campinas-SP, Brazil in July of 2011. Eighty broiler chickens of 1-d-old (Cobb® strain) were reared in a climate chamber with tubular feeders and bell drinkers. Standard broiler housing was adopted (Cobb-Vantress, 2009). Among them, three birds at 5-d-old were randomly chosen for this study.

2.2. Experimental procedure

The broiler chicks were placed individually in a rectangular glass box with a feed tray containing mash-type ration. A high-speed camera (Mikrotron EoSens®, Mikrotron GmbH, Unterschleißheim, Bavaria, Germany) with Nikon lens 50 mm/F 1.4 with an acquisition rate of 300 fps (frames per second) was setup and used to record the birds during feeding. This acquisition rate resulted in 0.003 ms time delay between frames. With the aid of a tripod, the camera was positioned to fit the bird's head and the feed tray in a perpendicular-lateral direction, in the field of view of the camera. A white paper sheet was placed in the background, to provide proper contrast between the bird and its surrounds and to assist with segmentation during the image analysis (Estrella & Masero, 2007). The recording glass box was placed in the external environment with direct sunlight incidence, and the birds stayed there individually just during the recordings, and then came back to the climate chamber. Thus, no artificial light source was used for this specific situation, as the natural day-light was capable to illuminate the scene. A computer was connected to the camera to store and to manage the data.

2.3. Biomechanical variables

The biomechanical variables analysed were (i) eye position (to identify the head motion); (ii) beak opening speed (measured in pixel ms^{-1}); (iii) beak closing speed (measured in pixel ms^{-1}); beak opening acceleration (measured in pixel ms^{-2}); (v) beak closing acceleration (measured in pixel ms^{-2}); and (vi) maximum beak gape (i.e. inter-beak distance, measured in pixels).

The feed tray diameter (47mm) was used for calibration. A total of 88 mandibulations (sequences of opening and closing beak sequences) were analysed corresponding to a total of 2640 frames. The developed code meets specifications and it fulfils its intended purpose. One third of the frames (880) were used for the code development, and two thirds (1760) were used as specific test cases for the validation of the algorithm.

2.4. Image analysis

A machine vision procedure comprising of four steps (Figure 1) was developed in Matlab® software (MathWorks, Inc., Natick, Massachusetts, USA). These four steps were eye detection as a reference point to determine the position of bird’s head; head extraction to remove redundant background information during analysis, beak tips detection to analyse the biomechanical behaviour (maximum beak gape, speed and acceleration) and feed particle removal to prevent a mistake during the beak tip detection when a particle occludes the beak tip.

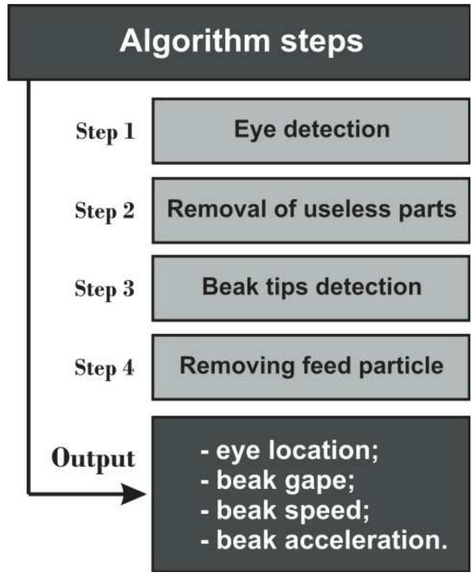

Figure 1. The four image analysis steps to measure eye location, beak-gape, beak speed and beak acceleration.

Unlike the methods used by Horster et al. (2002), in which involved physic markers placed on the birds' body, the analysis involved calculation of a reliable reference point on the chicken so that body features relative to this point could be identified. The methodology in this study required no bird training or unusual management; and the machine vision algorithm was able to determine the eyeball and tip of the upper and lower beak automatically.

Step 1: Eye detection

To calculate the eye position, a thresholding process was applied to the video-frame based on the colour difference between the eyeball and the body of the chicken. All artefacts except the eyeball were then removed from the resulting image (Figure 2A). After segmentation, the coordinate of the centre area of the eye was measured from the x and y axis of the image (Figure 2B; red point refers to the centre of eyeball area).

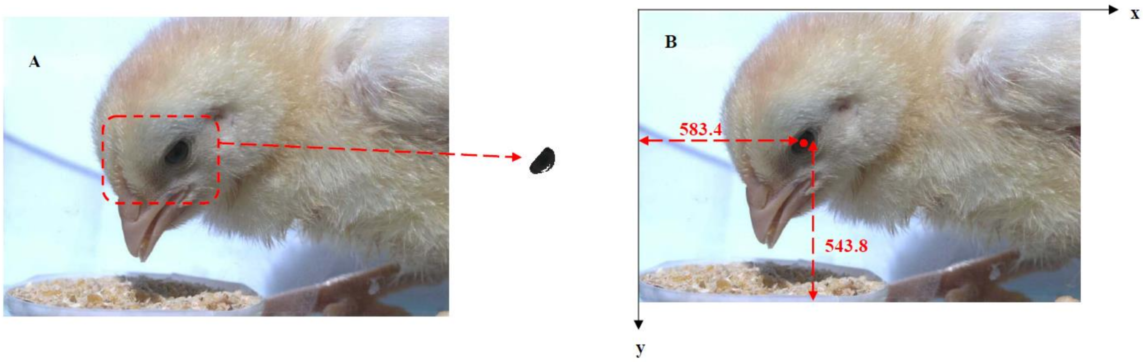

Figure 2. Original image and the eyeball segment (A), and eye position detection (B).

Step 2: Removal of redundant segments

After finding the eye position, a region of interest (corresponding to rectangle of 610x740) was defined around the centre of the eye for all video frames. This area was then extracted to remove other parts of the body by multiplying unwanted parts of the image with zero in order to avoid redundant information, and so enhance the beak tip detection. (Figure 3).

Figure 3. Representative image of extracted non-useable parts of the frame.

Step 3: Beak tip detection

To find the beak tips, Otsu's threshold was applied to the image to convert it into binary format (Otsu, 1979) (Figure 4). The algorithm then commenced a search for the beak tips from the bottom left of the binary image (arrow directed from the left to the right). If the beak was opened, the first non-zero pixel was identified as part the lower beak tip. If the beak was closed, the first non-zero pixel was identified as part of the upper beak.

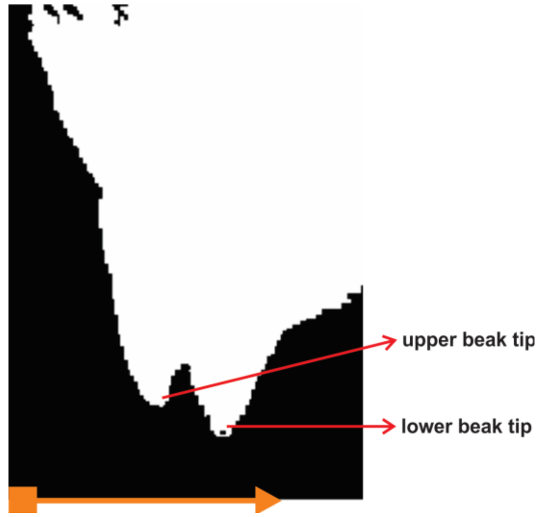

Figure 4. Binarized image of the chicken's head and starting point of search algorithm to find the beak tips location.

Step 4: Removing feed particle

The feed particles in some frames occluded the beak tip hindering its precise detection (illustrated in Figures 5A and 5C). In order to identify and remove the feed particle from the image the following algorithm was applied:

$$I_{new_{x,y}} = \begin{matrix} 0 \; \{r_{x,y} \mid 160 < r_{x,y} \leq 255\} \\ 1 \; \{r_{x,y} \mid 0 \leq r_{x,y} \leq 160\} \end{matrix} \qquad (1)$$

Here r is the red channel of the unsigned 8 bit image and x and y denote the Cartesian co-ordinates of the old image r and the new image with the feed particle removed$I_{new_{x,y}}$ (Figure 5D).

A **B** **C** **D**

Figure 5. Original frame showing the feed particle occluding the beak tip (A); (B) binarized image with the feed represented in blue; (C) detail of the feed particle occluding the beak; and extracted feed particle from the image (D).

After this process, a region of interest was defined around the beak (250x210 square) so that the maximum beak-gape could be defined. First, the boundary of the beak was found within the area so that the two beak tips corresponding to the end points could be identified (Figure 6A). Then, the Euclidian distance between the two beak tips (blue line) was measured. When the beak was closed, only one tip was detected, and the Euclidian distance was zero (Figure 6B). The Euclidian distance was also used to measure the beak tips distance during feeding to calculate the speed and acceleration of movements (Figures 7 A and B). Both opening and closing speeds were determined using the ratio between the displacement of the upper and lower jaw (at the beak tips) in respect to the time interval.

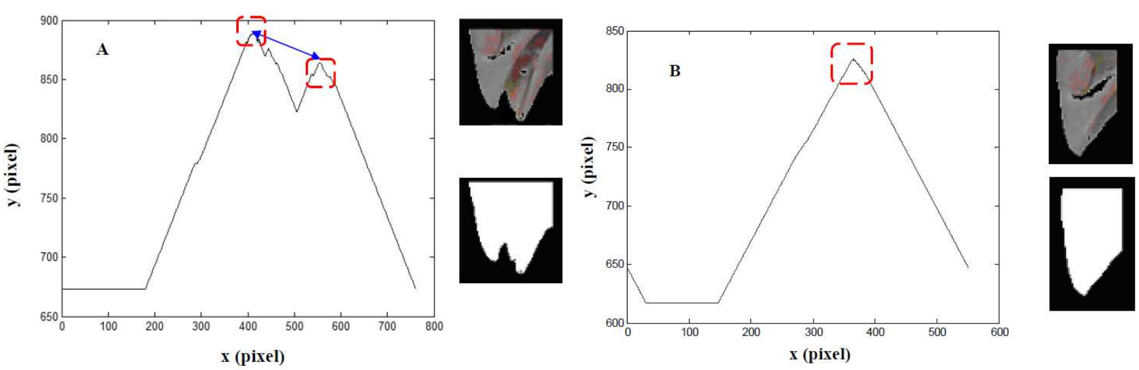

Figure 6. Upside down picture of opened (A) and closed (B) beak.

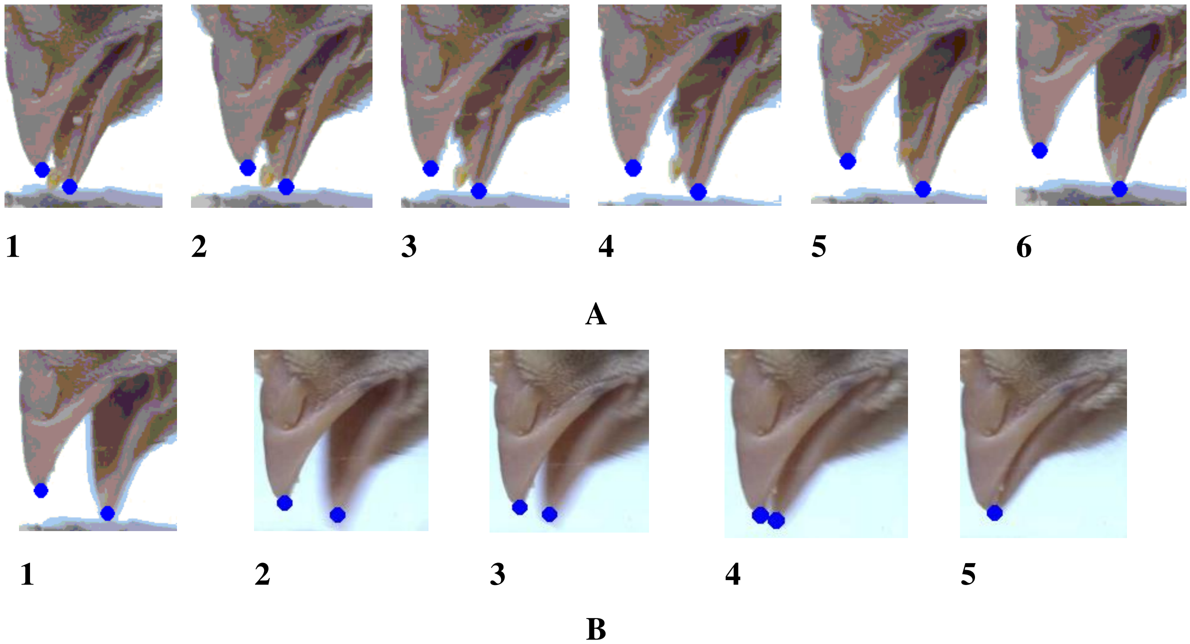

Figure 7. Representation of a beak opening (A) and closing (B) sequences.

Human visual observations of the video footages were performed offline on randomly selected frames, and the upper and lower beak opening and closing was manually assessed with a rule directly in the monitor by an inspector. To compare automated with manually labelled beak movements the values found were computed and graphically compared to the software output. To validate the algorithm, video frames of feeding chicken were randomly chosen and the eye location and distance between the upper and lower beak tips were manually measured and compared to the algorithm output (Excel file).

3. RESULTS

3.1. Beak-gape validation

The results of two successive beak opening and closing sequences were compared between manual and automatic beak-gape measurement (Figure 8A). The results of the manual and automatic measurements which are beak gape measured manually on the x-axis and the beak gape measured automatically on the y-axis (Figure 8B). According to the regression analysis these two measurement methods are highly correlated during opening and closing except during maximum beak gape.

Figure 9 shows the difference between manual and automatic measurement. Majority of the error has occurred around the maximum beak gape, which in the worst case was 0.55 mm error. Furthermore in almost of all the cases, the automatic measurement was better, more precise than manual measurement. This bias may have occurred due to differences in the discrimination of the tip of the beak between the manual measurement and automatic image analysis method.

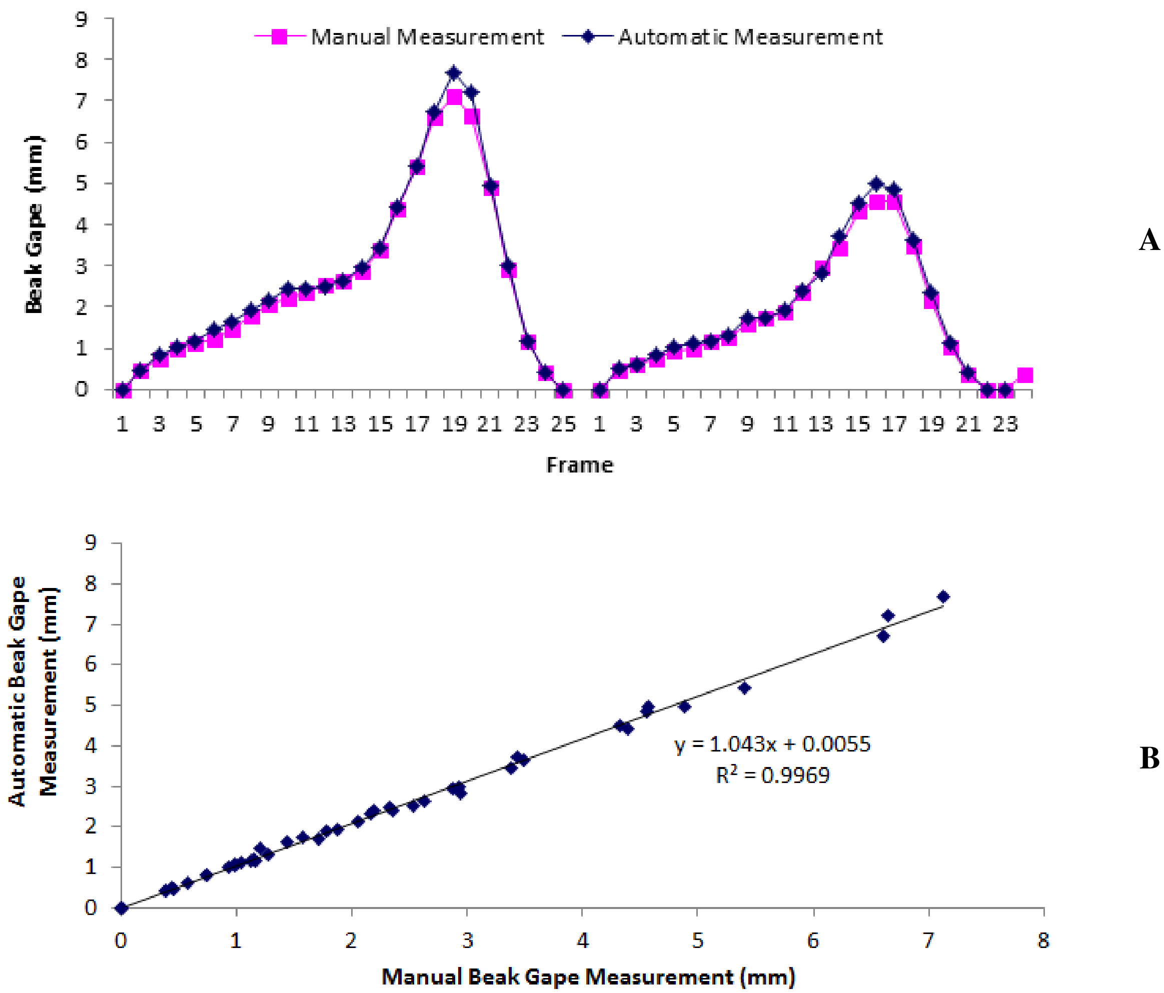

Figure 8. Comparison between algorithm output and manual measurement of beak-gape sequences (A) and (B).

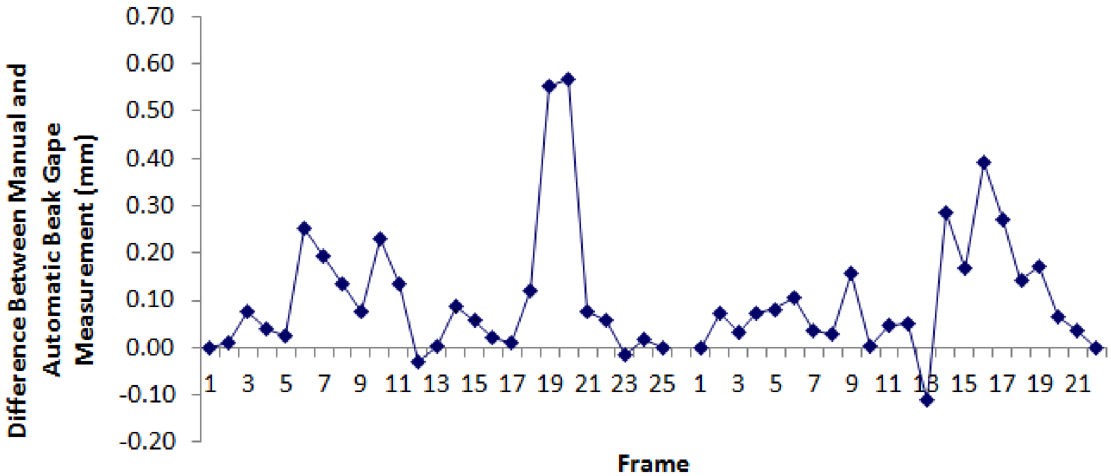

Figure 9**.** Difference between manual and automatic measurement for beak gape.

3.2. Eye position validation

The manual process performed by the individual inspector could not detect precisely small differences between consequent frames and has record the same number for subsequent frames (Table 1). However, in contrast, the algorithm finds the differences between the eye position measurements in subsequent frames, even if the difference was small.

Table 1. Results of eye positioning at x and y axis for manual and automatic measurement (randomly selected frames).

	Manual measurement (mm)		**Automatic measurement (mm)**	
Frame	Eye position (x)	Eye position (y)	Eye position (x)	Eye position (y)
1	32.25	27.93	35.678	30.817
2	32.49	28.65	35.834	29.993
3	31.73	29.21	35.231	29.259
4	31.63	29.23	34.982	29.263
5	31.42	29.31*	34.735	29.290
6	31.18	29.31*	34.501	29.294
7	30.94	29.31*	34.287	29.257
8	30.80	29.31*	34.091	29.199
9	31.33	29.78	34.636	28.771
10	31.63	29.82	35.186	28.641
11	31.98	29.90	35.151	28.590
12	31.68	29.04	35.161	29.462
13	34.09	27.45	37.465	30.974
14	35.21	25.24	38.573	28.024

*Same value for manual measurements.

Figure 10 shows the difference between the eye position in x and y coordinates for the manual and automatic image analysis process. The maximum error and standard error for x and y coordinates by the image analysis method was 3.49mm ± 0.101 and 2.89mm ± 0.104, respectively. In the majority of the cases, the error in y coordinate was less than 1 mm and close to zero. However, in a similar manner to the beak-gape, the human observer measured the eye position uppermost than the algorithm output.

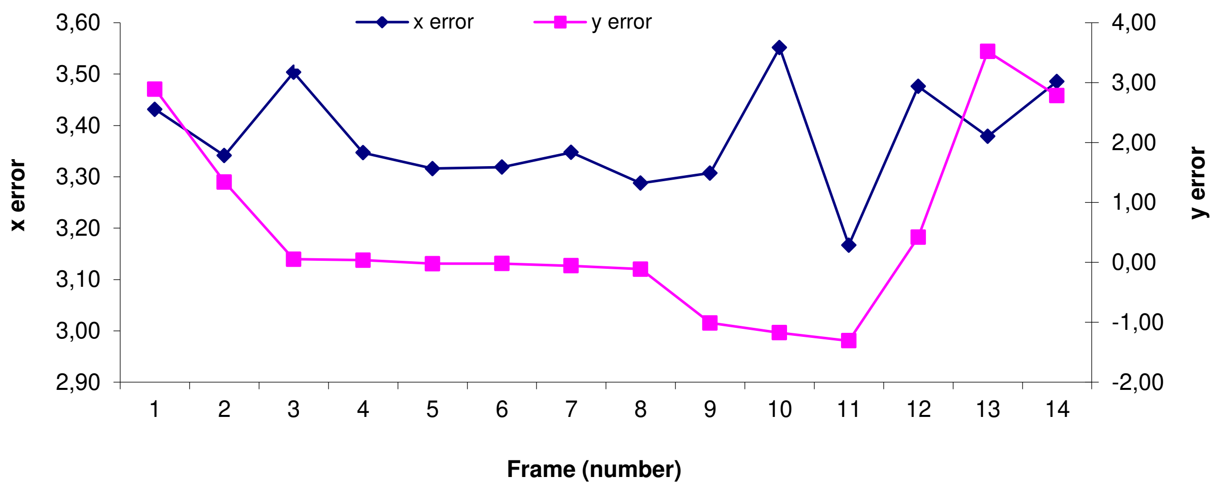

Figure 10. Difference between manual and automatic measurement for eye position.

3.3. Speed and acceleration

Another feature of the algorithm is the measurement of both beak speed and acceleration during its opening and closing. The output graphs shown in Figure 11 and 12 present two consecutive opening and closing sequences of beak-gape, speed, and acceleration, respectively. These graphs were derived from the same data as in the beak-gape graph shown in Figure 8. As it can be seen in Figure 11 the speed of the beak during the opening phase is initially small and increases up to maximum beak gape which occurs around frame 18. Figure 12 shows that during opening the acceleration is close to zero indicating that the speed presents little change over the course of time. However, closing phase presented accelerated motion. The average of closing speed (1.44 mm frame^{-1}) is approximately three times larger than opening (0.46 mm frame^{-1}) which showed chickens closed their beak with higher speed.

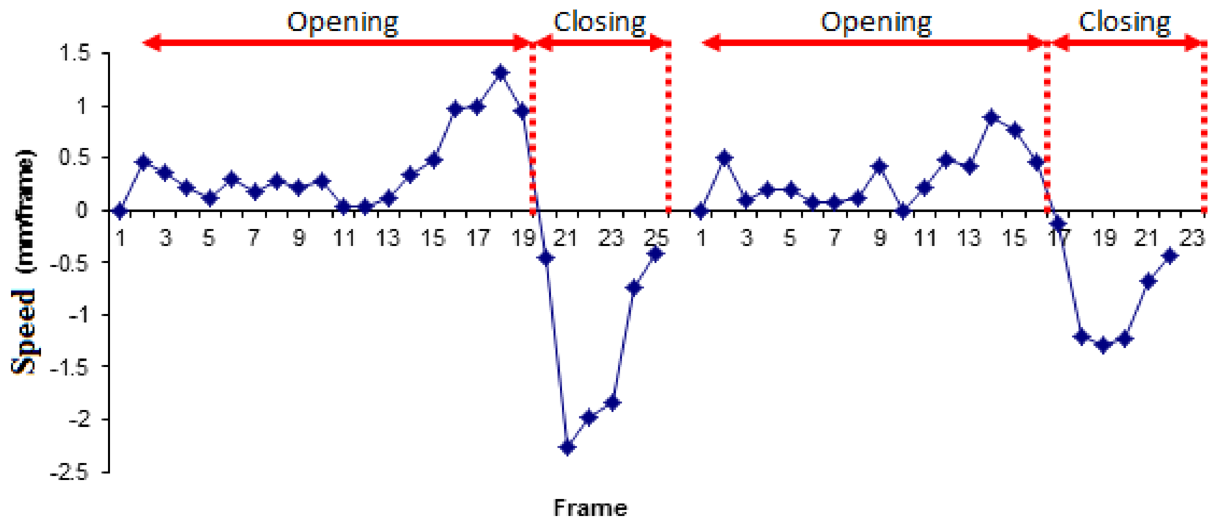

Figure 11**.** The speed of two consecutive beak opening and closing sequences.

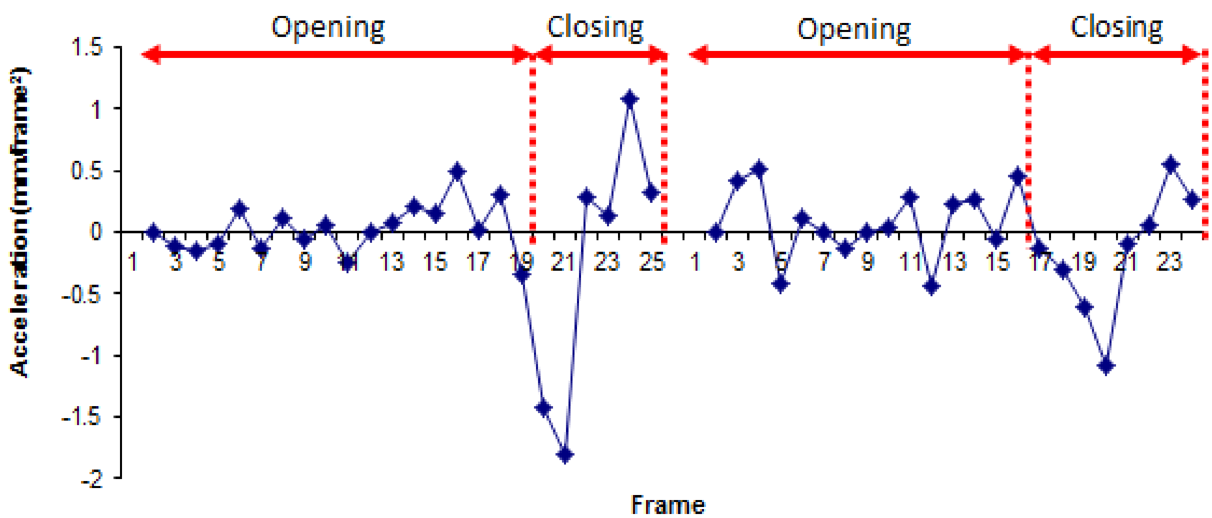

Figure 12. The acceleration of two consecutive beak opening and closing sequences.

4. DISCUSSION

During broilers growth it is important that the feeders and drinkers are properly arranged and well managed. Several studies indicate that some design features, such as size, location, geometry, spacing and angle of feeders can affect the behaviour of animals (Buskirk, et al., 2003; Wolter, et al., 2009). Developing a precise and non-invasive method for assessing motion in relation to the feeders' usage remains a challenge (Lu & Chang, 2012). Some advantages are found when using high speed cameras and computational image analysis for motion assessments, 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).

In some cases the birds rotate its head while feeding, so it is necessary to correct the measurement of beak tips distance. Horster et al. (2002) previously described the head and neck motions of pigeons while pecking small grains. The typical pecks for each pigeon were traced off the monitor's screen for a detailed analysis. Using similar referent marks, here we were able to detect the beak movement during feeding. In order to correct the head rotation, a calibration line on the head was necessary. In this case the algorithm could be rotational invariant. Therefore, due to arbitrary rotations of chick's head its value does not change, because it is calibrated according to the reference line. Furthermore, for eye detection the background should not be set with similar to the eye, because the algorithm works based on colour difference between eye and other parts of the image. In addition, it can be modified by the size of the chicken's eye, which can be corresponding to its age. To compensate different colours of feed particles, colour threshold would be modified based on the colour difference of beak and feed. This modification can be acquired manually or automatically to get best discrimination results between beak and feed.

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 a unit to analyse feeding behaviour (Nielsen & Whittemore, 1995). The appetitive phase of chickens can be characterized by the foraging behaviour, which is the time that the birds explore 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 catchment of a feed particle.

Poultry selects different sizes of feed particles on the first week of 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 (Nir et al., 1994a; Addo et al., 2012). The contact perception contributes to the identification of the feed whereas broiler chickens have the ability to discriminate different types of diets associating the feed physical features with nutritional content (Emmans & Kyriazakis, 2001).

CONCLUSIONS

In the present study, the algorithm calculates eyeball centre position and beak tips automatically, and without additional training of the birds. An algorithm for eye positioning (to track head displacement) and beak-gape measurement was developed using high speed camera. This algorithm might be utilized as software for studying eating behaviour of broilers and can be used for on-line monitoring of continuous image recording. The accuracy of the algorithm is less than 1 mm and can be improved by using a camera with higher resolution.

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 influence of feeder design. In this sense, the high speed camera combined with techniques of computational image analysis is a useful technology to aid such assessments. Some biomechanical patterns that happen in a very short period of time cannot be detected by conventional cameras, and the use of proper non-invasive markers should facilitate the identification of the key parts of the body during image analysis. Furthermore, this non-invasive technique for evaluating animal behaviour allows natural body movement.

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CHAPTER 3

The methodology, results, and discussion of this thesis was submitted for scientific publication at the "Biosystems Engineering", and it is presented in a scientific article format.

BIOMECHANICS OF THE FEEDING BEHAVIOUR OF BROILER CHICKS IN RELATION TO THE FEED PARTICLE SIZE

ABSTRACT: Several studies on broilers' feeding behaviour focused on productivity and physiological responses, but few studies have considered the biomechanical patterns involved in this process. This paper aims to assess three different feeds upon the biomechanics of the feeding behaviour of broiler chicks. Nineteen male broiler chicks were recorded during feeding at 3 and 4-d-old using a high-speed camera (250 frames per second). The assessed feed types were: fine mash (F1), coarse mash (F2) and crumbled (F3), in which the geometric mean diameter (GMD) and the geometric standard deviation (GSD) were 476μm (2.54), 638 μm (2.56), and 1243 μm (2.43), respectively. The chicks' weight and morphometric traits of the beak (length and width) were measured. Computational image analysis was used to evaluate the birds' head displacement during 'mouthful' and 'mandibulation' phases, beyond the 'maximum beak gape' in each mandibulation. These phases were manually classified by human inspector, as follows: mouthfuls as 'successful' or 'fail', and mandibulations as 'catch-and-throw' (CT) or 'slide-and-glue' (SG). The results indicated significant correlations of weak intensity between weight, morphometric traits of the beak, and the biomechanical variables, as well as correlation between maximum beak gape and head displacement. Generally, the head displacement was more expressive in F3 (0.526 mm ± 0.005), F2 (0.519 mm ± 0.004), and F1 (0.431 mm ± 0.003), respectively. Furthermore, this variable was significantly higher for CT (0.245 mm ± 0.001) than SG (0.114 mm ± 0.000). CT head movements were higher in F3, F1 and F2, while for SG were higher in F3, F2, and F1, respectively. The maximum beak gape was also higher for CT (0.245mm ±0.001) than SG (0.114 ± 0.00). Thus, the different sizes of the feed particles, so called granulometry, were probably the key factor for the chicks' motion during feeding. Besides, this relation was not proportional to the granulometry, explained by higher values for F3 and F1. The occurrence of 'fail mouthful' was 18,0% for F3, 11,2% for F2 and 6,6% for F1. For mandibulation classifications, it was observed a higher frequency of CT in F3 (26,1%), F1 (24,9%), and F2 (17,9%), respectively. This situation suggests that the chicks grasped the particles more properly for swallowing with the granulometry 638 μm, explained by the lower performed motion and necessity to reposition the feed particles within the beak.

Key words: beak, chicken, granulometry, high-speed camera, kinematics, motion analysis.

1. INTRODUCTION

Chicken and turkey are the most common meat sources of the poultry industry. The largest chicken meat producer countries are United States, China, Brazil and European Union. 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).

The diet composition is an aspect of high economic worth in commercial poultry industry. It is the mainly responsible for the growth response of birds, and represents the largest cost in the production cycle (Ávila et al., 1992). For instance, the broilers' energy supplies are responsible for 70% of the feed cost (Skinner et al., 1992) and, the processing method and the grain type interfere differently on the economic viability and animal physiological responses. The advantages of using processed feed have been well recognized, even though it represents a high manufacturing cost.

Birds are able to select different sizes of feed particles very early on life. Both format and structure of the beak determine the size of the feed particles and the amount of feed ingested. Thus, the granulometry of the particle is important for the regulation of the consumption. Granulometry is defined as the measurement of feed particle size. 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) (ASAE, 1983). Despite domestication and selection for fast growth, broiler chickens did not lose the ability to discriminate different feeds (Emmans & Kyriazakis, 2001). It has been proposed that the birds associate the feed physical forms with its nutritional content, which the contact perception contributes to the identification of the feed. Therefore, the feed physical format and size play a key role in the intake process.

The advantages of processed diet are well known. Pelleted ration for broiler chickens promotes better 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); better development of the digestive tract (Shamoto & Yamauchi, 2000; Engberg et al., 2002; Dahlke et al., 2003; Zang et al., 2009); better nutrient intake and 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); and greater digestibility (Moreira et al., 1994; Vargas et al., 2001; Goodband et al., 2002; Freitas et al., 2008; Zang et al., 2009), Moreover, reduces the particles discrimination (Gadzirayi et al., 2006; Lara et al., 2008), diminish the time spent at the feeders (Yo et al., 1997; Ferket & Gernat, 2006), and energy expenditure during eating (Nir, et al., 1994c; Leeson et al., 1999; Jensen, 2000; López et al., 2007), and decreases the feed wastage during transportation and delivery at the feeders (Jensen, 2000; Gadzirayi et al., 2006).

Biomechanics is considered the study of the body kinematics, integrating physics and biology (Domenici & Blake, 2000). It also can be seen 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 the simple physical movement displayed or produced by biological systems (McLester & Pierre, 2008). Nowadays, this subject is considered a tool to investigate issues of ecology, physiology and evolution. It also can be advantageous for assessments, forecasts and understanding of certain behaviours.

A better understanding of the mechanical patterns of the birds' feeding intake is desirable, especially for poultry industry. To date, most research on feeding behaviour approaches productivity indices and bird physiological responses, but limited studies have considered a biomechanical approach. Determining the motion patterns of the birds' body parts related to feeding might be an effective method for determining the relationship between different types of feed in biomechanical motion displayed by the birds. Furthermore, the high speed camera technology combined with techniques of computational image analysis is a remarkable tool to assist these analyses. Some behavioural patterns that happen in a very short period of time cannot be detected by conventional cameras. Besides, it is a non-invasive technique for evaluating animal behaviour and allows natural body movement (Neves et al., 2014).

The objective of this study was to assess the impact of three different feeds on the biomechanics of the feeding behaviour of broiler chicks through high-speed videos and computational image analysis.

2. MATERIAL AND METHODS

The experiment was conducted at the Federal University of Grande Dourados, in the city of Dourados/MS, Brazil, in October 2013. It was approved by the Ethics Committee (Protocol number: 030/2013-CEUA/UFGD).

A total of 19 male broiler chicks from an experimental aviary were recorded with a high speed camera during feeding at 3 and 4 days old. The recordings were conducted in a chamber located at 200m from the experimental aviary. To standardize the light intensity and shadow patterns on all videos samples the windows of the chamber were sealed in order to block the natural light entrance, wherein the unique light source came from a LED spotlight.

The high speed camera (Weinberger®, Visario 1500, Nürnberg, Alemanha) was setup at acquisition rate of 250fps (frames per second) at a resolution of 1536 x 1024 pixels. Nikon 50 mm/F 1.4 length was used. The camera arrangement allowed framing the chicks' head while feeding at a distance of 1.0 m from a lateral-perpendicular orientation. A computer was connected to the camera and used to operate it and store the data. The LED spotlight was placed alongside of the camera. The birds were recorded in a wood box (100cm length, 50m width, 60m height), which presented a translucent glass side directed towards the camera. The floor was covered with the same litter material as the aviary. Inside the box there was another glass box (20 cm length, 150 cm width, 180 cm height) with an open upper face and a glass feeder disposed inside. A blue EVA (Ethyl Vinyl Acetate) sheet was placed in the background to increase the contrast between the bird and its surroundings. All these apparatus remained fixed during the whole experiment.

2.1. Treatments and variables

The treatments consisted in three different feed types: fine mash (F1), coarse mash (F2), and crumbled (F3). The granulometry test was performed according to Zanoto & Bellaver (1996) method. The geometric mean diameter (GMD) and geometric standard deviation (GSD) of the feeds were 476µm (2.54) for F1, 638 µm (2.56) for F2, and 1243 µm (2.43) for F3. The F1 was the same as F2 after milling in a grinder with a 3mm sieve, beyond the addition of a little water to minimize the particles' suspension due to dust formation. The F3 consisted in a pelleted feed after crushed in smaller particles. All of the feeds were commercially used. The variables considered in this experiment are shown in Figure 1 and described in Table 1.

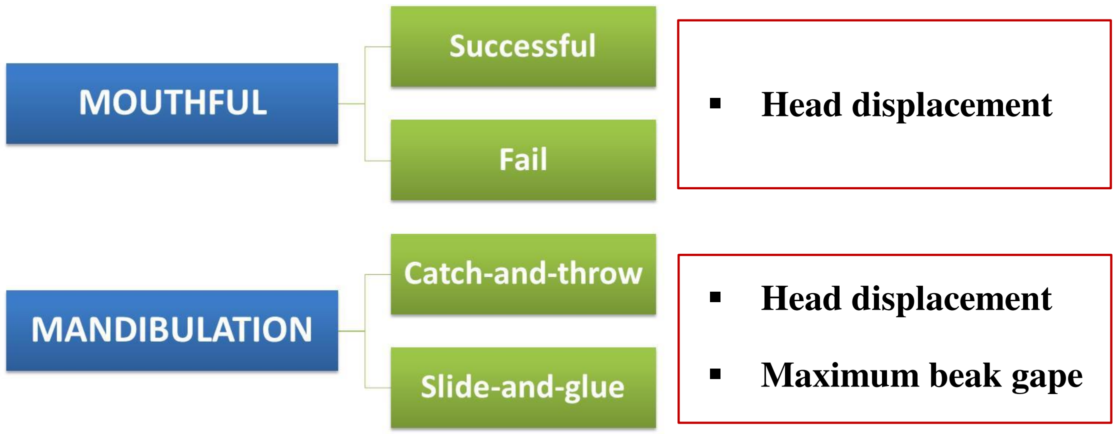

Figure 1. Schematic representation of the feeding phases, their classifications, and the respective assessed biomechanical variables.

Table 1. Description of the considered morphometric traits, the biomechanical variables and the feeding phases and their classifications.

	Variables	Description
Morphometric traits	Beak length	The Euclidean distance from the tip of the upper beak to the edge of the beak that forms a perpendicular with the nostril orifice.
	Beak width	The Euclidean distance from the width of the bird's beak at the level of the nostril orifice.
Biomechanical	Head displacement	The bird's head movement during feeding.
	Maximum beak gape	Maximum aperture of the beak in each mandibulation.
Feeding phases and classifications	Mouthful*	Starts when the bird moves its head uninterruptedly towards feed in an oblique or vertical direction and feed particle is grasped. The elevation of the upper jaw occurs prior to the depression of the lower jaw, and the tongue is retracted. The eyes are partially closed. It is finished when the beak starts the opening movement for the subsequent mandibulation.
	Successful	It is when the bird grasps the feed particle.
	Fail	It is when the bird misses the feed and so the mouthful does not result in a grasped particle, which the beak might touches the substract or not.
	Mandibulation*	Consists in a cycle of opening and closing of the beak. The opening action starts when beak starts its opening, but not necessarily when the beak is totally closed. It finishes when the beak reaches its maximum aperture. The closing action starts from the maximum beak gape to its closing, not necessarily to its full closure.
	Catch-and-throw (CT)	The feed particle is eventually repositioned in the beak before starting the transport into the oral cavity. It can be repeated as often as needed or possibly skipped when the particle is properly grasped. Large head jerks are evident.
	Slide-and-glue (SG)	Consists in the displacement of the tongue up to the tip of the beak in order to glue the feed particles with the aid of the sticky saliva and convey it into the oral cavity. Small head jerks might be displayed.

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

2.2. Experimental procedure

An hour before the recordings the chicks had their feed limited in order to stimulate the appetite (Estrella & Masero, 2007). Subsequently, the birds were randomly chosen from the experimental aviary and then transported to the recording chamber. Birds remained in specific cases with the same bedding material and bell-type drinker as the aviary, but still feed restricted. Before the recordings, the beak was marked at strategic points using black gouache paint in order to facilitate the image analysis by identifying the both upper and lower beak tips. Thereafter, each bird was individually placed on the glass box. The feed types were placed in different feeders and offered separately, so they were replaced after 8s video was captured. Thereafter, the chicks were weighted, and morphometric traits of the beak (length and width) were measured with a digital caliper. The video calibration was a picture with a scale ruler placed within the feeder.

2.3. Image analysis

A machine vision procedure comprising of four steps (Figure 2) was developed in Matlab® software (MathWorks, Inc., Natick, Massachusetts, USA). These four steps were eye detection as a reference point to determine the position of chicks' head; head extraction to remove redundant background information during analysis, beak tips detection to analyse the maximum beak gape, and feed particle removal to prevent a mistake during the beak tip detection when a particle occludes the beak tip. This methodology required no bird training or unusual management procedures, unlike the methods used by Horster et al. (2002), in which involved physical markers placed on the birds' body. The machine vision algorithm was able to determine the eyeball area and tip of both upper and lower beak automatically.

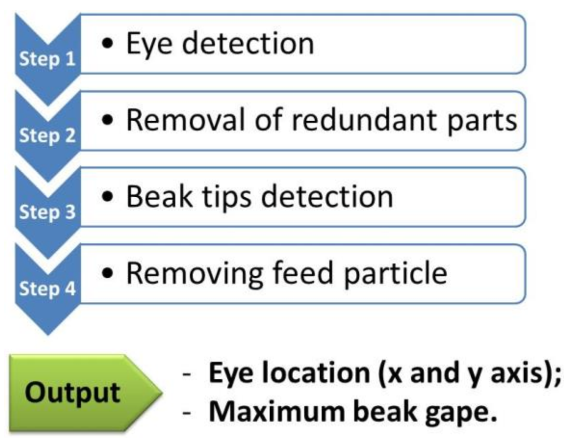

Figure 2. The image analysis flowchart representing the four steps of the algorithm to detect the eye position and maximum beak.

- *Step 1: Eye detection*

To calculate the eye position, a thresholding process was applied to the video-frame based on the colour difference between the eyeball and the body of the chicken. All artefacts except the eyeball were then removed from the resulting image (Figure 3A). After segmentation, the coordinate of the centre area of the eye was measured from the x and y axis of the image (Figure 3B; red point refers to the centre of eyeball area).

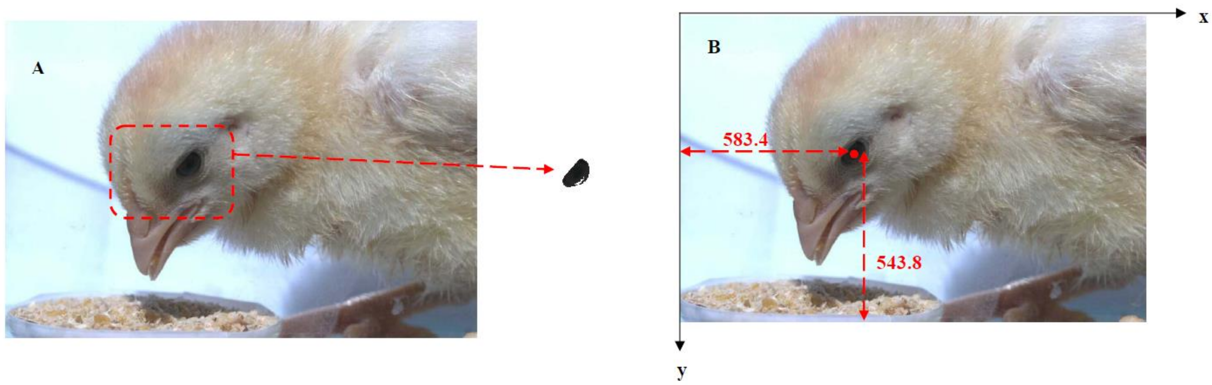

Figure 3. Original image and the eyeball segment (A), and eye position detection (B).

- *Step 2: Removal of redundant segments*

After finding the eye position, a region of interest (corresponding to rectangle of 610x740) was defined around the centre of the eye for all video frames. This area was then extracted to remove other parts of the body by multiplying unwanted parts of the image with zero in order to avoid redundant information, and so enhance the beak tip detection.

- *Step 3: Beak tip detection*

To find the beak tips, Otsu's threshold was applied to the image to convert it into binary format (Otsu, 1979). The algorithm then commenced a search for the beak tips from the bottom left of the binary image (arrow directed from the left to the right; Figure 4). The first non-zero pixel was identified as part the lower beak tip.

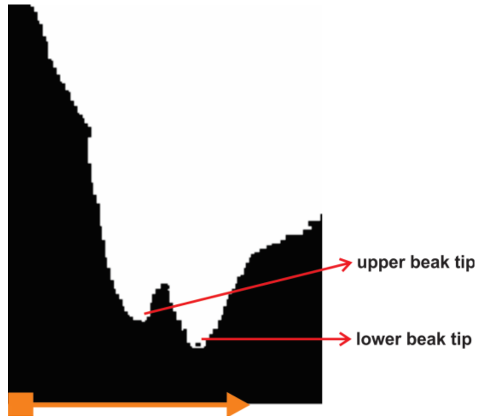

Figure 4. Binarized image of the chicken's head and starting point of search algorithm to find the beak tips location.

- *Step 4: Removing feed particle*

The feed particles in some frames occluded the beak tip hindering its precise detection (illustrated in Figures 5a and 5c). In order to identify and remove the feed particle from the image the following algorithm was applied:

$$I_{new_{x,y}} = \begin{matrix} 0 \; \{r_{x,y} \mid 160 < r_{x,y} \leq 255\} \\ 1 \; \{r_{x,y} \mid 0 \leq r_{x,y} \leq 160\} \end{matrix} \quad (1)$$

Here r is the red channel of the unsigned 8 bit image and x and y denote the Cartesian coordinates of the old image r and the new image with the feed particle removed $I_{new_{x,y}}$ (Figure 5d). After this process, a region of interest was defined around the beak (250x210 square) so that the maximum beak gape could be measured. First, the boundary of the beak was found within the area so the two beak tips corresponding to the end points could be identified (Figure 6). Then, the Euclidian distance between the two beak tips (blue line) was measured (Equation 2) and the output came in Excel sheet.

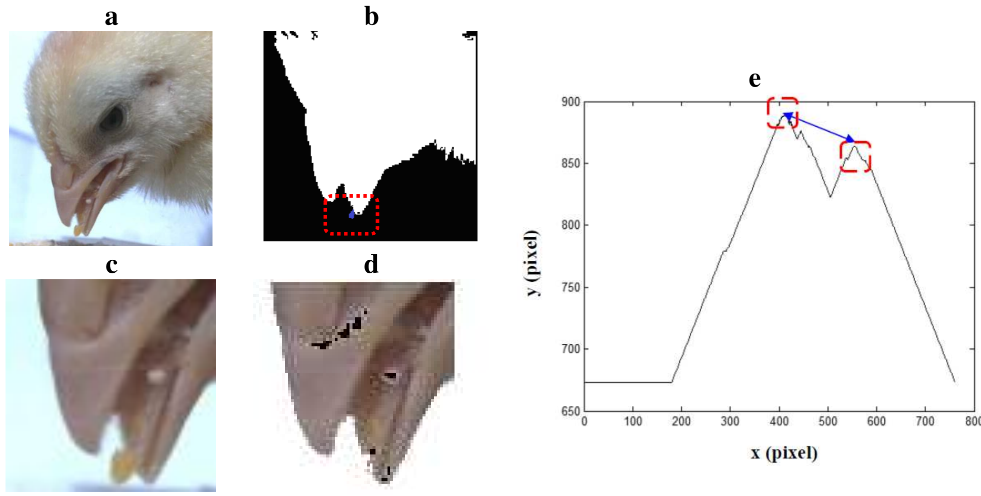

Figure 5. Original frame (a); binarized image with the feed represented in blue (b); detail of the feed particle occluding the beak (c); extracted feed particle from the image (d), and upside down picture representing the Euclidian distance between upper and lower beak tips (e).

2.4. Dataset overview and statistical analysis

Each video sample consisted of 8s time interval (total of 2.048 frames). The 19 chicks were recorded during the intake of the three feed types, totalling 57 video footages. Both 'mouthfuls' and 'mandibulations' occurred differently, so the time intervals in each one were also distinct. It was detected 761 mouthfuls and 1.858 mandibulations in all video footages, which reached 72.650 video frames analysed.

General descriptive analyses were performed, followed by Spearman's test in order to identify the correlations among chicks' weight, morphometric traits of the beak and the biomechanical variables. This test was applied due to the remarkable presence of outliers observed in the dataset, in which non-parametric tests use median as reference. The Mood's Median test was used to compare the biomechanical variables and their classifications, and in-between feed types. The Chi-Square test was applied to analyse the frequency of occurrence of the biomechanical variables among feed types. Minitab 15® software (Minitab Inc., Pennsylvania, USA) was used to carry out all statistical analysis.

3. RESULTS

3.1. Relation between weight, morphometric traits and biomechanical variables

The Spearman's test indicated a weak correlation (P-Value: 0.000) between weights, morphometric traits of the beak (length and width), and the biomechanical variables (head displacement for both 'mandibulation' and 'mouthful' and 'maximum beak gape') (Table 2). Nevertheless, the strongest correlations were found between mandibulation head displacement and maximum beak gape (0,253); weight and beak length (0,241); and weight and maximum beak gape (-0,210).

Table 2: Correlation test between weight, morphometric traits (beak length and width) and the biomechanical variables (maximum beak gape, mouthful head displacement and mandibulation head displacement).

	Weight	**Beak length**	**Beak width**	**Mandibulation head displacement**
Beak length	0,241*	-	-	-
Beak width	0,186*	-0,001	-	-
Mouthful head displacement	-0,006	-0,007*	-0,044*	-
Mandibulation head displacement	-0,101	-0,064*	-0,107*	
Maximum beak gape	-0,210*	-0,090*	-0,138*	0,253*

Spearman's test;

*P-Value = 0.000

3.2. Relation between the feed type and biomechanical variables

The Mood's Median test indicated some significant differences of the biomechanical variables and their classifications by feed types (Table 3), even though the data profile being scattered as can be seen in Boxplot graphics at Figures 6a, 7a, and 8a.

The head displacement for mouthful phase (Figure 3; Table 3) indicated that 'successful mouthful' (0.439 mm ± 0.002) was significantly higher than 'fail mouthful' (0.371 mm ± 0.005). Moreover, 'successful mouthful' were significantly higher for F3 (0.526 mm ± 0.005) and F2 (0.519 mm ± 0.004) than F1 (0.431 mm ± 0.003). The 'fail mouthful' showed a higher head displacement for F3 (0.395 mm ± 0.008), F2 (0.363 mm ± 0.008), and F1 (0.314 mm ± 0.010), respectively.

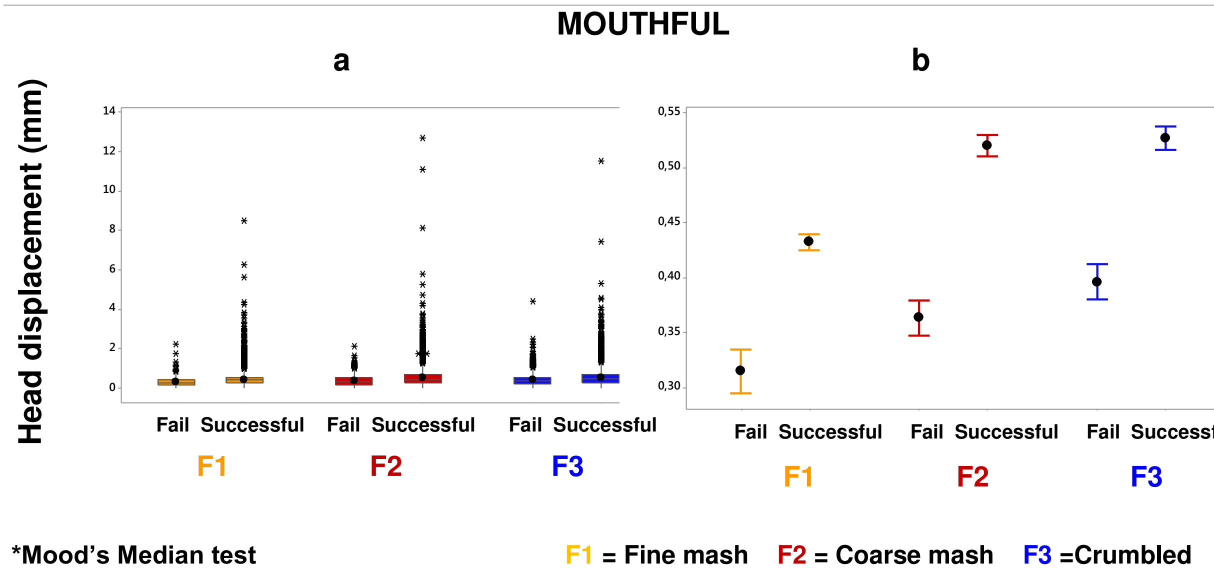

Figure 6. Graphics of Boxplot (a) and Interval Plot (b) of head displacement of mouthful phase by their classification and feed type.

The head displacement for mandibulation phase (Figure 7; Table 3) indicated that CT (0.245 mm ± 0.001) was significantly higher than SG (0.114 mm ± 0.000). Additionally, significant differences were found between the feed types, in which head displacement for CT was higher in F3 (0.277 mm ± 0.003), F1 (0.242 ± 0.002), and F2 (0.115 ± 0.001), respectively, while for SG was higher in F3 (0.119 mm ± 0.001), F2 (0.115 ± 0.001), and F1 (0.108 ± 0.001).

Regarding the maximum aperture of the beak during mandibulations (Figure 8; Table 4), the results indicated a higher maximum beak gape for CT (0.245mm ±0.001) than SG (0.114 ± 0.00). Moreover, the maximum beak gape in CT was higher in F3 (5.359 ± 0.003) and F1 (5.238 ± 0.003) than in F2 (4.983 ± 0.002), and in SG was higher for F1 (3.224 ± 0.001) than F2 (2.810 ± 0.001) and F3 (2.890 ± 0.001).

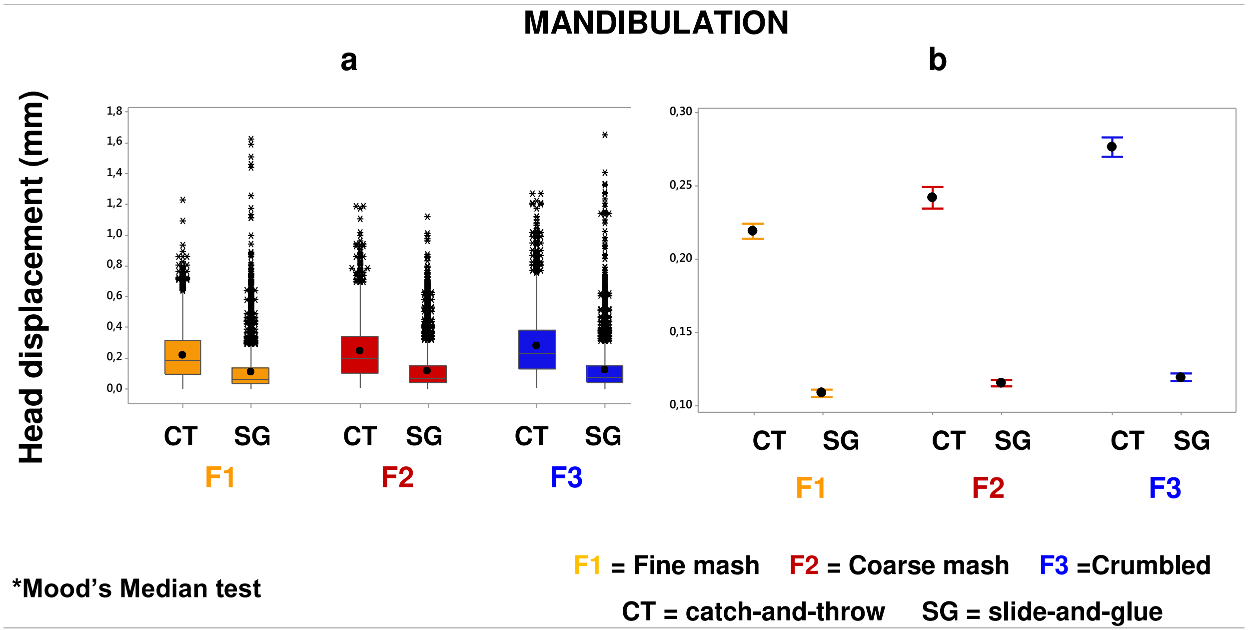

Figure 7. Graphics of Boxplot (a) and Interval Plot (b) of head displacement of mandibulation phase by their classification and feed type.

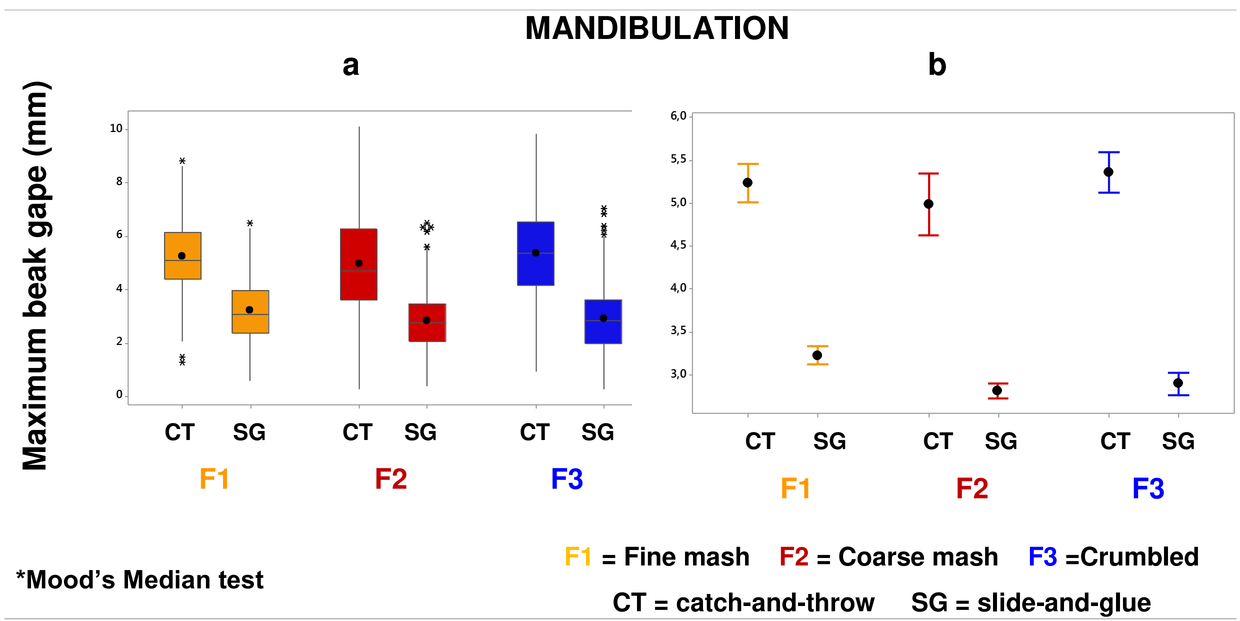

Figure 8. Graphics of Boxplot (a) and Interval Plot (b) of head displacement of mouthful by their classification and feed type.

Table 3. Data of head displacement for mouthful and mandibulation phases and their classifications by feed type.

	Classification	Feed type	Mean (mm)	SE	SD	Variance	Minimum	Median	Maximum	Total frames
Mouthful head displacement	Successful	F1	0.431	0.003	0.338	0.114	0.000	0.382	8.486	9,629
		F2	0.519	0.004	0.456	0.208	0.000	0.431	12.735	9,795
		F3	0.526	0.005	0.444	0.197	0.000	0.450	11.556	7,568
	Total N Successful	F1+F2+F3	0.489	0.002	0.416	0.173	0.000	0.414	12.735	26,992
	Fail	F1	0.314	0.010	0.235	0.055	0.006	0.273	2.222	680
		F2	0.363	0.008	0.273	0.074	0.002	0.307	2.134	1,237
		F3	0.395	0.008	0.329	0.108	0.000	0.329	4.382	1,662
	Total Fail	F1+F2+F3	0.371	0.005	0.298	0.088	0.000	0.313	4.382	3,579
	Total (Successful +Fail)	F1	0.425	0.003	0.334	0.111	0.000	0.376	8.486	10,309
		F2	0.501	0.004	0.442	0.195	0.000	0.416	12.735	11,032
		F3	0.502	0.004	0.428	0.183	0.000	0.427	11.556	9,230
	Total	F1+F2+F3	0.476	0.002	0.406	0.164	0.000	0.404	12.735	30,571
Mandibulations head displacement	CT	F1	0.219	0.002	0.163	0.026	0.000	0.180	1.230	3,819
		F2	0.242	0.003	0.186	0.034	0.001	0.193	1.189	2,491
		F3	0.277	0.003	0.201	0.040	0.003	0.230	1.273	3,333
	Total CT	F1+F2+F3	0.245	0.001	0.184	0.034	0.000	0.201	1.273	9,643
	SG	F1	0.108	0.001	0.125	0.015	0.000	0.061	1.627	11,527
		F2	0.115	0.001	0.124	0.015	0.000	0.067	1.118	11,448
		F3	0.119	0.001	0.133	0.017	0.000	0.071	1.652	9,461
	Total SG	F1+F2+F3	0.114	0.000	0.127	0.016	0.000	0.066	1.652	32,436
	Total (CT+SG)	F1	0.135	0.001	0.144	0.020	0.000	0.078	1.627	15,346
		F2	0.138	0.001	0.145	0.021	0.000	0.079	1.189	13,962
		F3	0.160	0.001	0.168	0.028	0.000	0.096	1.652	12,911
	Total	F1+F2+F3	0.144	0.000	0.153	0.023	0.000	0.083	1.652	42,079

CT = catch-and-throw; SG = slide-and-glue; SE = Standard Error; SD = Standard Deviation;
F1 = fine mash; F2 = coarse mash; F3 = crumbled;
Mood's Median test;
P-Value = 0.000.

Table 4. Data of maximum beak gape by feed type and their classifications.

	Classification	Feed type	Mean (mm)	SE	SD	Variance	Minimum	Median	Maximum	Total frames
Maximum beak gape	CT	F1	5.238	0.112	1.408	1.982	1.259	5.099	5.238	158
		F2	4.983	0.183	2.038	4.153	0.255	4.701	10.121	124
		F3	5.359	0.122	1.717	2.949	0.919	5.355	9.837	198
	Total CT	F1+F2+F3	5.222	0.078	1.718	2.951	0.254	5.079	10.121	480
	SG	F1	3.224	0.053	1.134	1.286	0.570	3.070	6.499	458
		F2	2.810	0.046	1.056	1.115	0.360	2.745	6.489	522
		F3	2.890	0.064	1.281	1.641	0.254	2.816	7.051	398
	Total SG	F1+F2+F3	2.971	0.031	1.164	1.355	0.254	2.850	7.051	1,378
	Total (CT+SG)	F1	3.740	0.060	1.495	2.236	0.570	3.573	8.835	616
		F2	3.233	0.061	1.563	2.445	0.254	2.906	10.121	646
		F3	3.721	0.075	1.849	3.418	0.254	3.401	9.837	596
	Total	F1+F2+F3	3.558	0.038	1.656	2.743	0.254	3.264	10.121	1,858

CT = catch-and-throw; SG = slide-and-glue; SE = Standard Error; SD = Standard Deviation;
F1 = fine mash; F2 = coarse mash; F3 = crumbled;
Mood's Median test;
P-Value = 0.000.

3.3. Incidence of both mouthful and mandibulation classifications by feed type

Considering the overall dataset, ‘successful mouthful’ was more frequent (685 times) than ‘fail mouthful (76 times), and SG (1,378 times) more frequent than CT (480 times). The Chi-Square test was applied to analyse the differences in the incidence of these classifications between feed types. It can be seen that ‘fail mouthful’ was more frequent in F3 (18,0%), F2 (11,2%), and F1(6,6%), respectively (Figure 9a). Additionally, CT was more frequent in F3 (26,1%) and F1 (24,9%) than F2 (17,9%) (Figure 9b).

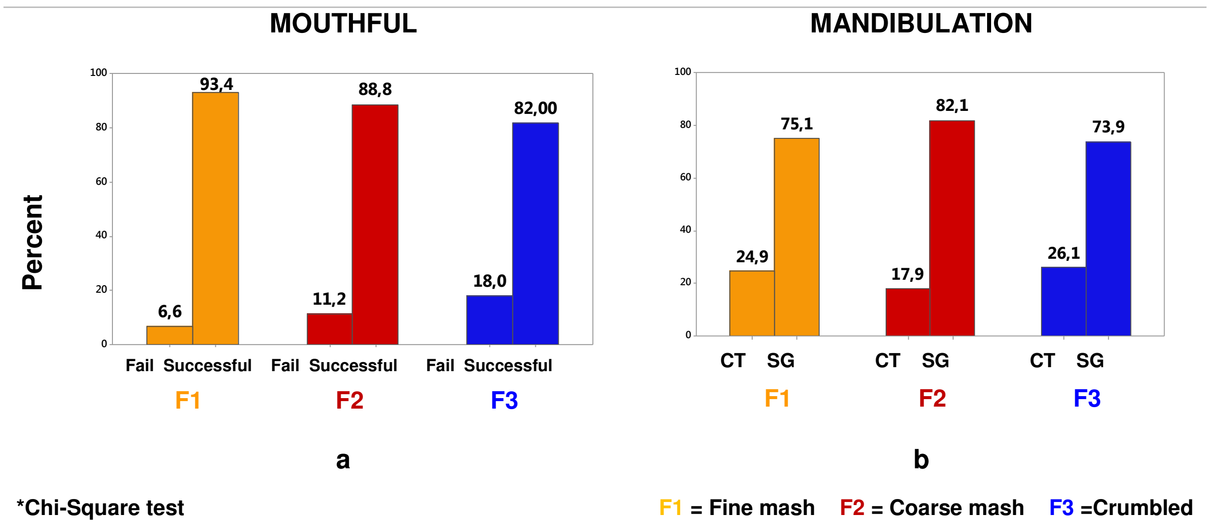

Figure 9. Bar graphics showing the occurrence (%) of mouthfuls classifications (fail and successful) (a), and mandibulations classifications (CT - catch-and-throw and SG - slide-and-glue) (b) by feed type.

4. DISCUSSION

4.1. Relation between weight, morphometric traits of the beak and biomechanics

Overall, weak correlations were found between weight, morphometric traits of the beak (length and width), and the biomechanical variables. Thus, it is not possible to assert that the chicks’ weight had a strong correlation with the size of the beak. It has been suggested that the size, shape and weight of body segments are more important for the forces associated with the movement (known as kinetics) than the appearance of the movement (kinematics) (Hall, 1999; Serway & Jewett, 2004). Thus, this approach makes sense, whereas the biomechanical variables considered in the present study are related to kinematics (*i.e.* the appearance of the movement).

On the other hand, the correlation between the maximum beak gape and the head displacement in the mandibulation phase, even low, suggests that the greater the chick's beak aperture, the higher is its head's displacement. This relationship could be explained by the cranial kinesis presented in all species of birds (Bock, 1964; Zweers, 1982; Feduccia, 1986; Bout & Zweers, 2001; Gussekloo & Bout, 2005). This feature is considered very important due to facilitation the utmost elevation of the upper jaw (Bout & Zweers, 2001; Gurd, 2006; Estrella & Masero, 2007; Gurd, 2007). The quadrate bone plays a key role, as it can be seen like a central operating mechanism in the whole process. Additionally, the cranial kinesis in domestic chickens is coupled, *i.e.* there is relationship of dependence of both upper and lower jaws, although a certain degree of independence may occur (Van Der Heuvel, 1992). Consequently, the chicken's jaw is a unique structure that moves entirely, hence this explains the positive correlation between the 'maximum beak gape' and 'head displacement' found in this study.

Nevertheless, the mechanical variables and their maximum values are defined by mechanical limitations (Pennycuick, 1992), and morphological development (Nir et al., 1990; Nir et al., 1994b), mainly gut and gizzard (Hetland et al., 2002; Hetland et al., 2004; Gabriel et al., 2006). Additionally, it has been reported the lack of experience of naive birds to handle the feed properly (Yo et al., 1997). Thus, it is likely that the correlation with body parts dimension and motion should be more evident in older birds due general body development.

By this approach, it is expected that further studies on this issue may enhance predictions for feeding efficacy of broiler chickens at a commercial level through biomechanical assessments. Furthermore, it may offer novel techniques to evaluate feeding behaviour in other species of captive animals, since it is desirable the maximization of the feeding efficiency at a lowest manufacturing cost.

4.2. Relation between the feed particle size and chicks' biomechanical profile

If the weight and the morphometric traits did not affect the chicks' biomechanical features considerably, the feed physical characteristics, however, may have been a key factor in the chicks' motion during feeding. The results found in this experiment showed that the head displacement was higher in a 'successful mouthful' than when they fail and miss the feed. Furthermore, head motion in both cases was different in between the feed types, which was more expressive in crumbled type (F3) than in fine (F1) and coarse (F2) mash types. A possible explanation for this fact is that the chicks were able to identify the target particle more precisely at F3, and then perform an uninterrupted movement towards it. Birds spend less time searching and selecting the larger particles, especially in mash types (Nir et al., 1994a), as probably is the case in this experiment. Both F1 and F2 were mash diets, and besides they had a higher size variation (GSD) than F3, which probably stimulated greater particle selection before feed grasping (mouthful phase).

The head motion displayed by the chicks' during mandibulations clearly showed a higher motion when birds adopted catch-and-throw (CT) than slide-and-glue (SG), which was expected. CT motion was also higher for F3, F2 and F1, respectively. Previous studies suggest that birds select different sizes of feed particles on the first week of life, and the beak format regulates the size and feed to be eaten. Broiler chickens have the ability to classify different types of diets by the physical features according to nutritional content (Emmans & Kyriazakis, 2001). Thus, the granulometry and format of the particles play a key role for the intake process (Nir et al., 1994a; Quentin et al., 2004; Carré et al., 2005; Addo et al., 2012). In this experiment the higher maximum beak gape was observed in CT, and also was higher for those fed F3 and F1 than in F2, respectively. Chicks quickly respond to the stimulus of feed intake immediately after hatching (Vieira & Pophal, 2000; Noy & Sklan, 2002), and decide whether to accept or reject the feed particle. The tactile cells control the reflectivity and taste, even though the number of taste buds is small (Sainsbury, 1980). The F3 was crumbled type and both F1 and F2 were mash type, so their tastes could be different, but this was not considered in this study. Interestingly, the GMD (GSD) of the feeds was 1243μm (2.43) for F3, 638μm (2.56) for F2 and 476μm (2.54) for F1, and this could be an indicative that the size of the feed particles probably have influenced the biomechanical motions. Several studies reported a relationship between particle sizes, feed consumption (Nir et al. (1994b), and physiological responses (Nir et al., 1994a; Dahlke et al.; 2001; Amerah et al., 2008; Svihus, 2011). Moreover, the relationship between feed's sizes and the chicks' motion during feeding found in this experiment was not always proportional for maximum beak gape, which for CT was larger for F3 and smaller F1, while in SG was higher for

F1. The birds may open the beak just enough to catch and handle the feed, regardless the beak size or feed format. It was previously described that the opening beak amplitude is gauged according to the particle size and the initial beak opening is used to control the amplitude (Zweers, 1982; Van Der Heuvel & Berkhoudt, 1998).

A key motivation in the processed rations is to obtain the maximum nutritional potential at minimal cost (Thomas et al., 1998). It has been strongly recommended that at the initial growth phase mash or crumble diets should be offered because the young birds are unable to ingest pellets and cannot regulate feed intake according to the energy level (Faria et al., 2006). Additionally, several studies indicate that the feed physical form impacts the performance of broiler chickens, particularly the processed ones, promoting better 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); better development of the digestive tract (Shamoto & Yamauchi, 2000; Engberg et al., 2002; Dahlke et al., 2003; Zang et al., 2009); better 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), and greater digestibility (Moreira et al., 1994; Vargas et al., 2001; Goodband et al., 2002; Freitas et al., 2008; Zang et al., 2009). Moreover, the adoption of processed feed has been also recommended in order to reduce feed particles discrimination (Gadzirayi et al., 2006; Lara et al., 2008); time spent in the feeders (Yo et al., 1997; Ferket & Gernat, 2006); energy expenditure during feeding (Nir, et al., 1994c; Leeson et al., 1999; Jensen, 2000; López et al., 2007); and also to decreasing feed wastage (Jensen, 2000; Gadzirayi et al., 2006). In this sense, the biomechanical assessments should be an effective method to evaluate the impact of the feed physical features (size, shape and hardness) via the mechanical motions exhibited by the birds.

4.3. Biomechanical variables classifications by feed type

It was observed that the broiler chicks missed the feed while trying to catch it differently in each feed type, which the incidence of 'successful mouthful' was 18,0% (F3), 11,2% (F2), and 6,6% (F1). For mandibulations classification, it was observed a higher frequency of CT in F3 (26,1%) and F1 (24,9%) than in F2 (17,9%). This situation suggests that while feeding with F1 and F3, the birds needed to manipulate the feed in order to reposition them before swallowing more times than F2. Thus, when the bird adopted CT technique instead SG, the head displacement and the maximum beak gape were higher. The muscles can be considered as biological motors that consume chemical energy and perform mechanical work. In general, 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 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 produce, the tension and the contraction frequency. These are the mechanical variables, and their maximum values are gauged by mechanical limitations (Pennycuick, 1992). Therefore, it can be imply that kinetics is related to energy expenditure. If so, the chicks expended more energy when adopted CT technique, which was more incident in crumble type. On the other hand, the well-known benefits of processed diets could possibly compensate this energy expenditure, but this relationship was not accessed in this study.

4.4. Methodological aspects

During the image analysis stage, at some frames it was not possible to detect the centre of the eye area precisely. This was evident at some specific circumstances, such as the rotational motion of the birds' head; when the bird winked or even when the nictitating membrane went through the eyeball surface, which changed the eye colour; and when the lateral edge of the feeder covers the eyeball view. Choosing another detectable landmark in the chicks may improve this analysis. About the identification of upper and lower beak tips, the difficulty appeared was when the bird kept part of the beak below to the feed layer at the feeder, in which the beak tips became totally occluded.

The use of a high-speed camera technology combined with computational image analysis in this experiment seems to be an effective method for motion analysis, mainly to represent a non-invasive technique, besides allow natural body movement (Neves et al., 2014). Methodological drawbacks can show up by adopting other methods, such as surgical intervention for implant insertion (Bergmann et al., 2001; Stansfield et al., 2003), use of electrical stimulation, and post mortem examination. These methods can lead to a non-real situation and lack of functional movements, beyond the stress to which the individual could be subjected and labour intensiveness (Gussekloo et al., 2001). Developing a precise and non-invasive process within the living body remains a great challenge in the field of biomechanics study (Lu & Chang, 2012).

5. CONCLUSIONS

Significant correlations of low intensity between weight, morphometric traits of the beak, and the biomechanical variables were found. Then, it is not possible to assert that the chicks' weight has a strong correlation with the beak morphometric features. The correlation between maximum beak gape and head displacement, even weak, suggest that the larger is the beak aperture, higher is the head displacement, explained by the couple cranial kinesis.

The chicks missed the feed while trying to grasp it more times in crumbled diet than in both mash types analysed, explained by the higher incidence of 'fail mouthful'. A higher head displacement was observed when the birds adopted the 'catch-and-throw' technique than 'slide-and-glue'. Also, catch-and-throw motion was higher for crumbled, coarse mash and fine mash, respectively, while 'slide-and-glue' motion was higher for fine mash. Thus, the feeds' granulometry probably was the key factor in the chicks' motion during feeding. Additionally, this relationship was not proportional, elucidated by higher values of biomechanical motions in the higher and smaller feed particle sizes.

Overall, the methodology adopted in this study seems to be effective for motion analysis on chickens feeding behaviour. It is believed that this method may be potentially adapted for other situations and different species of captive animals. Further studies are needed to investigate the influence of the feed physical features upon the biomechanical patterns performed by the birds. It should be considered the size, shape and hardness of the feed; the anatomical limitations at different growth phases, genders, and strains; and the energy expenditure estimation.

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2. FINAL REMARKS

The biomechanical variables considered in the present study (head displacement and maximum beak gape) were different in the both 'mouthful' and 'mandibulations' phases in relation to the feed types. 'Catch-and-throw' motion was higher for crumbled, coarse mash and fine mash diets, respectively, while 'slide-and-glue' motion was higher for fine mash diet. This relationship (motion *versus* granulometry) was not proportional, explained by higher motion values in the highest and smallest granulometry. Overall, this experiment indicated some important relationships between feed type and biomechanical features displayed by the broiler chicks, in which the granulometry of the feed particles probably was the key factor in the birds' biomechanical features during feeding.

The high-speed camera technology combined with computational image analysis used in this experiment has shown as an effective method for motion assessments. Some behavioural patterns that happen in a very short period of time cannot be detected by conventional cameras. Besides, it is a non-invasive technique for evaluating animal behaviour and allows natural body movement. These techniques had the potential to be adapted in future studies considering the impact of body motion at different growth phases, genders, strains, others animal species, for energy expenditure estimation, and also the impact of the feeder design on the intake process.

The benefits of the processed ration in the performance of broiler chickens is well recognized, and, despite its high manufacturing cost, presents more advantages than the mash diets. Moreover, the feasibility of feed manufacturing may vary in different regions according to the availability of raw material and the level of technology adopted by feed plants. So far, most researches on the poultry feeding behaviour addresses the productivity indices and bird's physiological responses, but few studies have considered the biomechanical characteristics involved in this process. Hence, the methodology presented in this thesis has the potential to upgrade feeding behaviour assessments for poultry. Either farmers or feed manufacturers might be benefited by improving animals' feeding efficiency focusing in a lowest manufacturing cost. Besides, it is desirable a better comprehension of the animals' anatomical limitations in order to contemplate matters of animal welfare through biomechanical approach.

3. ANNEX

Table 1. Feed nutritional description of Bocfrango® initial phase ration (mash type) guaranteed by the manufacturer regarding the F1 and F2 diets used in this experiment.

Ingredient	Amount
Calcium (Min./Max.)	10,00 – 14,5 g/kg
Minimum Ether Extract	25,00 g/kg
Crude Fiber (Max.)	50 g/kg
Phosphorus (Min.)	6.000,00 mg/kg
Lysine (Min.)	7.000,00 mg/kg
Mineral Matter (Max.)	80,00 gr/kg
Methionine (Min.)	2.800,00 mg/kg
Crude Protein (Min.)	210,00 g/kg
Sodium (Min.)	1.400,00 mg/kg
Moisture (Max.)	125,00 g/kg

Table 2. Feed nutritional description of crumbled type ration from BRF-S/A® (SIF MS 05357) regarding the F3 diet used in this experiment.

Ingredient	Amount	Ingredient	Amount
Moisture (Max.)	130,00 g	Vitamin B2 (Min.)	7,00 mg
Crude Protein (Min.)	210,00 g	Vitamin B6 (Min.)	3,70 mg
Ether Extract (Min.)	52,00 g	Vitamin B12 (Min.)	14,50 µg
Mineral Matter (Max.)	50,00 g	Biotin (Min.)	200,00 mg
Crude Fiber (Max)	30,00 g	Folic Acid (Min.)	1.993,00 mg
Calcium (Max.)	10.000,00 mg	Pantothenic Acid (Min.)	19.990,00 mg
Calcium (Min.)	8.900,00 mg	Nicotinic Acid (Min.)	49.932,00 mg
Phosphorus (Min.)	5.300,00 mg	Manganese (Min.)	90,00 mg
Lysine (Min.)	12,00 g	Zinc (Min.)	90,00 mg
Methionine (Min.)	5.900,00 mg	Copper (Min.)	150,00 mg
Threonine (Min.)	8.500,00 mg	Iron (Min.)	60,00 mg
Colina (Min.)	1.600,00 mg	Selenium (Min.)	0,45 mg
Vitamin A (Min.)	11.500,00 U.I.	Iodine (Min.)	1,00 mg
Vitamin D3 (Min.)	3.400,00 U.I.	Sodium (Min.)	2.000,00 mg
Vitamin E (Min.)	81,00 U.I.	Nicarbazin (Min.)	40,00 mg
Vitamin K3 (Min.)	4,90 mg	Maduramycin (Min.)	3,75 mg
Vitamin B1 (Min.)	2,00 mg		