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A Portrayal of Biomechanics in Avian Flight

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A PORTRAYAL OF BIOMECHANICS IN AVIAN FLIGHT

By

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ABSTRACT

The art of avian flight is incredibly complex and sophisticated. It is one of the most energy-intensive modes of animal locomotion, and requires specific anatomical and physiological adaptations. I believe that in order to truly comprehend the beauty and complexity of avian flight, it is necessary to clearly visualize the anatomical adaptations found in birds. To aid in the visualization process, I set out to produce a series of educational animations that focus on the biomechanical requirements for flight. These requirements are numerous and complex, often making the flight process difficult to visualize and understand. The artwork and animations that I have created for this thesis are intended to visually portray the major aspects that are involved in avian flight. The majority of artwork created for this project is comprised of 3D models created and animated Autodesk Maya, including a complete pigeon skeleton, the musculature involved in flight, and the anatomy of the avian respiratory system. These 3D models present the viewer with a completely unique view of avian anatomy that provides a relatively complete overview of the various aspects involved in avian flight. The final movie is composed of three animations that focus on the following subject matter: general adaptations to the avian skeleton, the specialization of the avian wing, and the importance of the avian respiratory system.

TABLE OF CONTENTS

INTRODUCTION

For many of us, birds are a natural presence in our lives to which we have been greatly desensitized. Our lives are virtually surrounded by birds in action: they are outside of our windows, in our parking lots, perched alongside the highways, in our backyards, and in nearly every other outdoor environment of which you can think. Though we encounter these animals every day, hear their songs and see them in the air, how rare it is for us to actually consider the complexities of their lives. We seldom stop to simply observe these animals; how do they move, how do they interact, and more importantly, how do they fly? We see birds in flight so often that we fail to recognize the beauty and rarity of such a form of locomotion.

After taking an ornithology class as an undergraduate student, I became captivated with birds and their ways of life. Aside from the fact that most of them can fly, they are extraordinarily complex creatures that practice fascinating social and sexual interactions, many possessing beautiful and unique feathering patterns. The fact that they are direct descendants of dinosaurs is also an interesting feature that cannot be ignored, but is a topic best saved for another day. Though I find almost all aspects of avian life interesting, for my thesis I chose to focus on the most obvious and complicated characteristic of birds: their ability to fly.

Throughout my years of ornithological interest and study, I sometimes found it difficult to truly grasp how a bird is able to fly. Though there is copious literature on this subject, the entire process of flight is generally poorly illustrated. When researching "avian flight", you are bound to come across many well-written articles or textbook chapters on how birds fly, as well as beautiful photographs and artwork of birds in flight. However, to my knowledge there was neither a high-quality schematic nor animation of the anatomical and physiological elements involved in the entire flight process. The biomechanical requirements for flight are numerous and complex, often making the flight process difficult to visualize and understand. In order to truly comprehend the complexity of avian flight, it is necessary to clearly visualize the anatomical adaptations found in birds.

My goal therefore, was to create artwork demonstrating the biomechanics that are necessary to allow a bird to fly. This artwork would serve as a reinterpretation of existing avian subject matter as well as a new portrayal method of avian anatomy and flight. The artwork and animations that I have created are intended to visually portray the major aspects involved in avian flight.

Though the completed animation and artwork may be informative to a wide audience, it targets an audience of students and professionals that are interested in ornithological studies. It may also be a useful reference for wildlife veterinarians, since an impaired flight can be viewed as avian lameness (such as the broken leg of a horse is often seen as disastrous). A better way of viewing avian flight anatomy could aid

1

in diagnosing an injured bird and evaluate a bird in rehabilitation. After watching the completed animation, the audience will be able to demonstrate an understanding of the subject matter by explaining a number of different aspects of avian flight: the anatomical adaptations of the avian skeleton, the musculature involved in flight and the specialization of the wing, and the importance of the avian respiratory system.

AVIAN ANATOMY

Biomechanics can be defined as the study or application of mechanics of a living organism, specifically to the musculoskeletal system and locomotion. The basis for this thesis, The Biomechanics of Avian Flight, can therefore be described as a project that studies the mechanics of the avian skeleton and muscular anatomy involved in the flight process.

GENERAL AVIAN CHARACTERISTICS

Birds, like mammals, are advanced, endothermic vertebrates and are members of the class Aves, consisting of just over 9000 living species. They arose from reptilian ancestors sometime in the Mesozoic era, about 150-200 million years ago, while the oldest known bird, Archaeopteryx, is know to have lived in the Late Triassic (Benton 2005). All modern birds share these fundamental characteristics: relatively small size, centralized body mass, lack of teeth, high metabolism, feathers, fusion and reduction of bones, pneumatic bones, highly developed central nervous system and vision, forelimbs specialized for flight (wings), and bipedalism with digitigrade feet (walk on their toes) (Proctor and Lynch 1993).

NOTABLE FLIGHT ADAPTATIONS

The art of avian flight is incredibly complex and sophisticated. It is one of the most energy-intensive modes of animal locomotion and requires specific anatomical and physiological adaptations. Although birds possess a similar skeletal plan to other vertebrates, the skeleton of a bird has been specially modified to meet the requirements of flight. A bird's body is exceedingly streamlined in order to induce less drag and allow easier movement through the air. It is also important for a bird's body to be as light as possible. One feature associated with weight reduction is air-filled, or pneumatized, bones (Figure 1.1).
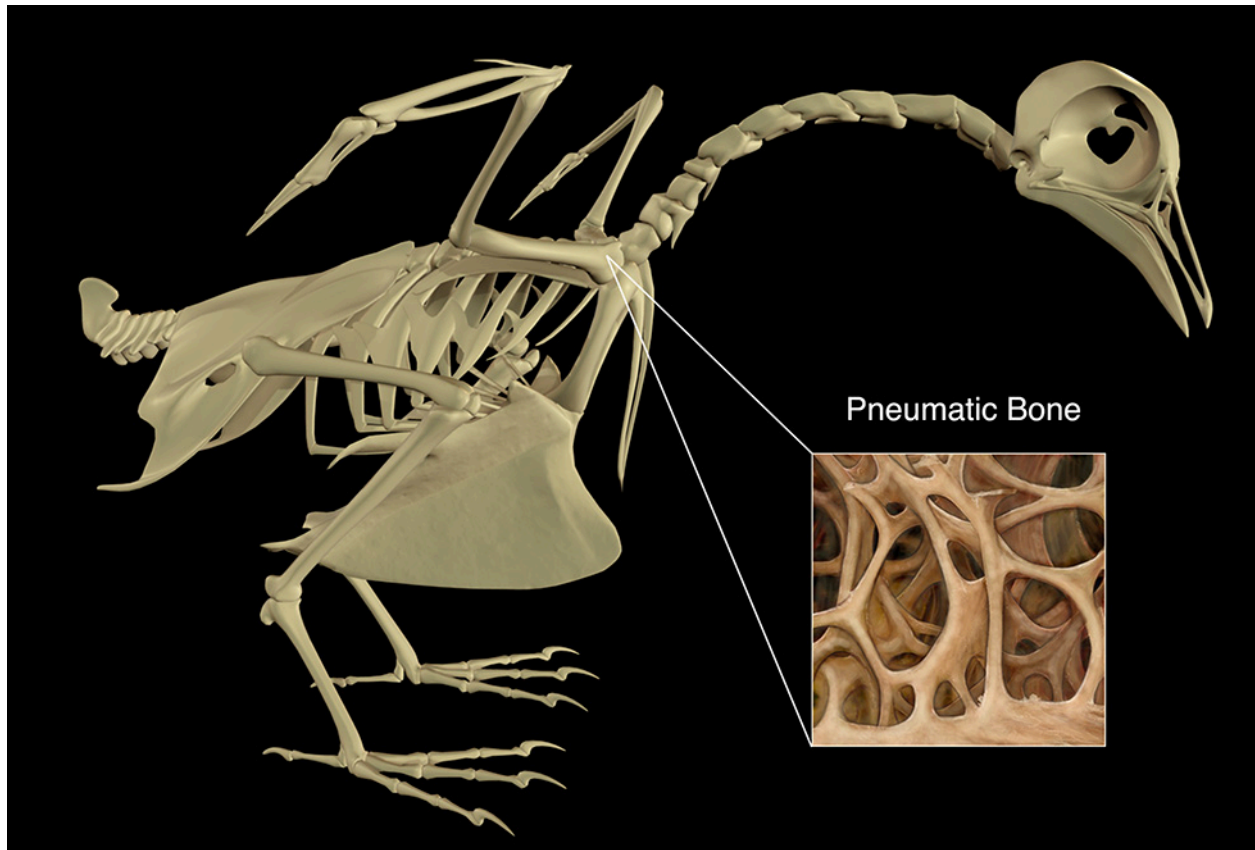
Figure 1.1: Pneumatized section of the avian humerus bone.

The avian humerus, for example, is the only pneumatized bone of the wing and demonstrates how thin-walled bones can be combined with internal struts to create a particularly strong unit (Beaufrère 2009). The largest and most efficient flying birds, such as frigatebirds and albatrosses, have air spaces that are interconnected and pass from the humerus to the digits and across all of the joint spaces (Podulka, et al. 2004). The frigatebird is so specialized for soaring that even though it possesses a seven-foot wingspan, its feathers actually weigh more than its ultralight four-ounce skeleton (Henderson 2008).

The typical avian skeleton also shows significant fusion of bone, producing a rigid skeleton that is able to withstand the forces of flight. Bone fusion is clearly visible throughout the bird's body. The avian hindlimb has been reorganized, with three long bones instead of the traditional two, and toes that have become exceptionally long. In all birds, the femur is relatively short, while the tibiotarsus (drumstick) is typically the longest bone of the hindlimb. This bone is formed by the fusion of the distal tibia and the proximal tarsals. The distal tarsals and metatarsals are fused to form a single structure known as the tarsometatarsus (Podulka, et al. 2004). This is a characteristic shared with modern reptiles, and may be an artifact of evolution of birds from reptiles. Also, all modern birds lack the outermost, or fifth, toe.

A bird's tail is comprised of 4-9 caudal vertebrae that are fused to form the pygostyle, which provides an attachment point for feathers of the tail (Figure 1.2).
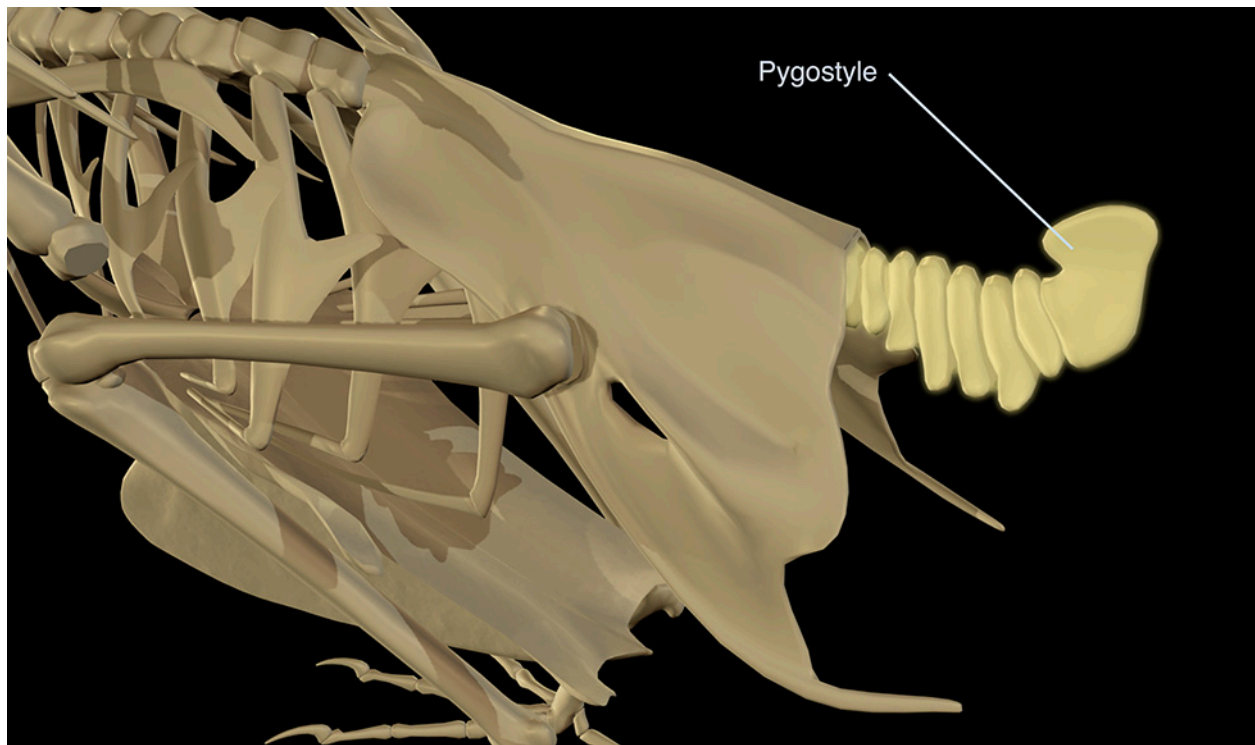

Figure 1.2: The avian caudal vertebrae fused to form the pygostyle.

Despite the simple appearance of a bird's tail, its internal components provide a bird with a great deal of maneuverability and contribute significantly to the flight process (Kaiser 2007). The lumbar vertebrae, the first 6 caudal vertebrae, the ilium, the ischium, and the pubis are fused into the pelvic girdle. The ridge on the posterior surface of the pelvic girdle is referred to as the synsacrum. Central sections of the vertebral column are fused into rigid blocks to cope with the mechanical stresses of flight, as well as simple acts of running and jumping. Because of this, birds (unlike most vertebrates) are notoriously stiff-backed, and have necks that are long and incredibly flexible to compensate (Kaiser 2007).

A bird's skull has also been highly modified to reduce weight and to aid in the ability to fly. Early in the evolutionary process, birds lost their heavy teeth and instead are equipped with a heavy bill (Cameron, et al. 1979). The eyes and brain have become exceptionally large and contribute the greatest amount of weight to a bird's head. The avian skull also possesses only one point of contact with the neck; a single occipital condyle articulates with the first cervical vertebra of the neck, the atlas (Kaiser 2007). This is a characteristic that is shared with dinosaurs and their various reptilian descendants. Mammals

possess two occipital condyles instead of one, and it is believed that this characteristic allows for up and down movement of the head without compressing or pinching the spinal cord. Even without this feature, birds have evolved incredibly flexible necks with a head that has an enormous range of motion. Members of the order Strigiformes (the owls), for example, can rotate their heads through an almost complete circle (Cameron, et al 1979).

One of the most prominent skeletal structures found only in birds is a large, keeled sternum (Figure 1.3).
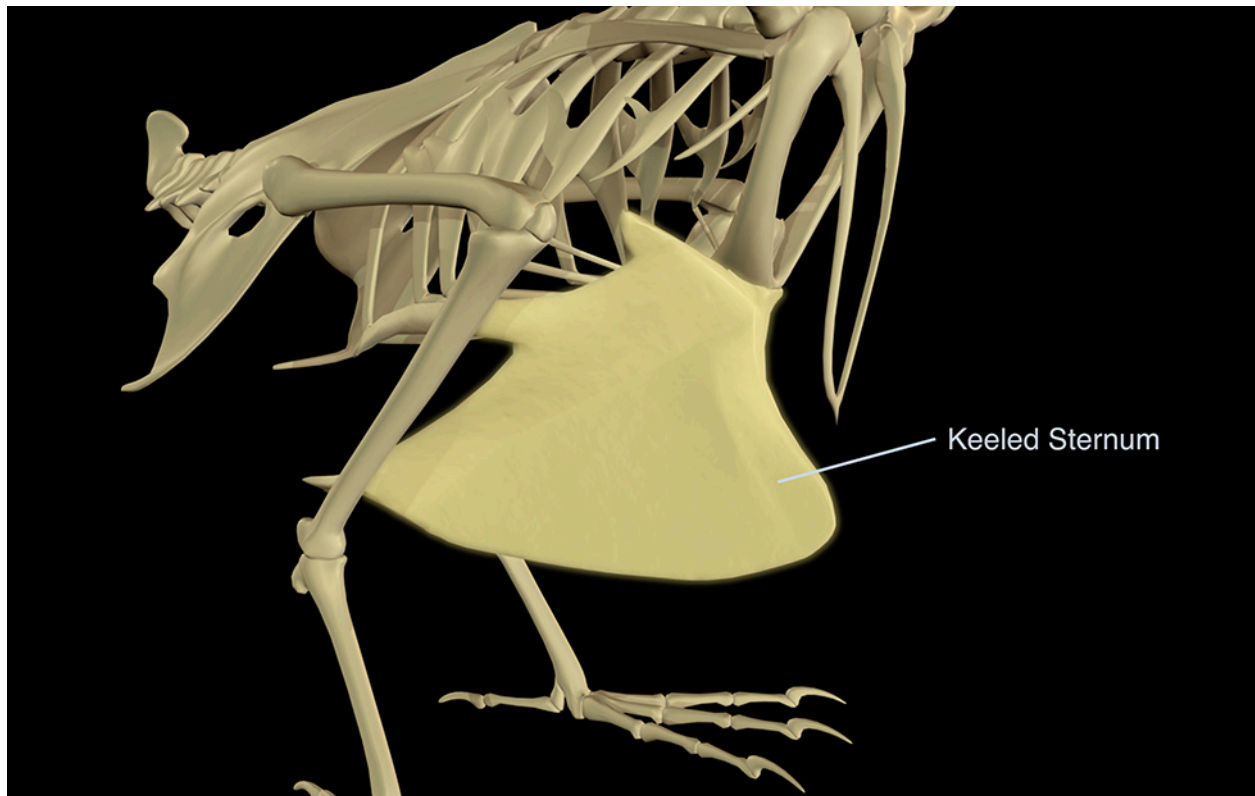

Figure 1.3: The avian keeled sternum.

This midventral keel is found in all flying birds and is an attachment point for large flight muscles. The size of the keel is directly related to the size of the Pectoralis muscle, which is the muscle responsible for the downstroke of the wing, propelling the bird upward and forward during flight (Podulka, et al. 2004). Another important feature in avian flight is the strength of the pectoral girdle. This strength prevents collapse of the chest cavity during flapping flight and may also serve as a spring to rebound some of the energy from the flight muscles.

The two clavicles are fused to form the furcula, more commonly known as the wishbone. It has recently been discovered that this element is unique to theropods and has become yet another important

link between birds and theropod dinosaurs (Podulka, et al. 2004). The specific flight requirements of a bird directly influence the morphology of the furcula, which functions to preserve the symmetry of wing beats and the shoulders, holding the wings away from the sternum during contraction of the wing (Kaiser 2007). The furcula also acts as a spring to restore part of the mechanical forces, and participates in protraction of the wing by action of its muscles (Beaufrère 2009). There are also seven ribs on either side of the vertebral column, each possessing an uncinate process at the posterior margin of the ventral surface. These processes form lateral braces between adjacent ribs and serve to strengthen the chest cavity (Proctor and Lynch 1993).

THE AVIAN PECTORAL LIMB: SPECIALIZATION OF THE WING

Evolution has specially modified the avian forelimb as a wing. Like the other special characteristics of the avian skeleton, it reflects the bird's commitment to flight. Perhaps the most interesting aspect of avian wings is that, unlike the wings of an airplane, they continuously change shape to allow a bird to speed up, slow down, and even hover in mid-air (Henderson 2008).

The pectoral girdle forms the point of wing articulation and is formed by 3 bones on each side of the body: the clavicle (furcula), the coracoid, and the scapula (Figure 2.1).
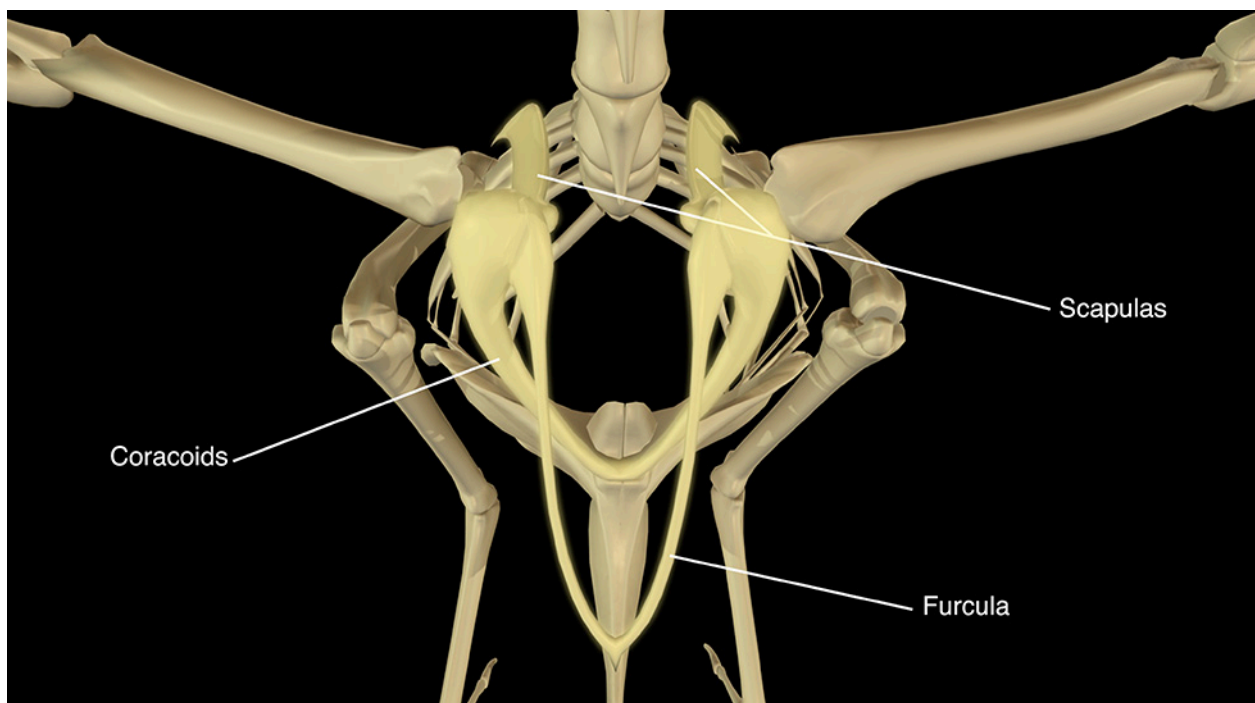

Figure 2.1: The components of avian wing articulation.

The three-way joint between these 3 bones forms an opening known as the triosseal canal, through which the tendon of the Supracoracoideus muscle passes. This triosseal canal serves as part of a pulley system that allows the downward force of the contracting muscles to be redirected to an upward pull on the dorsal surface of the wing (Proctor and Lynch 1993).

The bird's complex shoulder joint, or glenoid articulation, is formed by the coracoid, scapula, and humerus (Beaufrère 2009). These bones function as a powerful brace that hold the shoulder joint, and thus the wing, away from the body while the breast muscles pull oppositely on the wing during flight (Podulka, et al. 2004). The humerus is one of the strongest bones of the wing, and is short and stout relative to the total length of the wing. This is because the main flight muscles of the wing attach only to the humerus and it must resist large forces during flapping flight. The radius and ulna then form the support for the mid-wing. These two bones articulate with each other as well as with the humerus and the carpal bones (Beaufrère 2009) and are entirely analogous to the same structures in mammals.

Most of the distal wing bones have been extensively fused and reduced in order to strengthen the wing. The wrist bones, carpals, and metacarpals have been fused into a single structure known as the carpometacarpus. The avian hand, or manus, has only three digits, the first of which, known as the pollex, or thumb, supports feathers of the alula (which is essential for slow flight, landing, gliding flight, and the prevention of stalling) (Proctor and Lynch 1993).

<div align="center">BREAST MUSCLES</div>

In all flying birds, the breast muscles dominate the body so completely that they may account for almost a third of the total body mass (Proctor and Lynch 1993) (Figure 2.2).
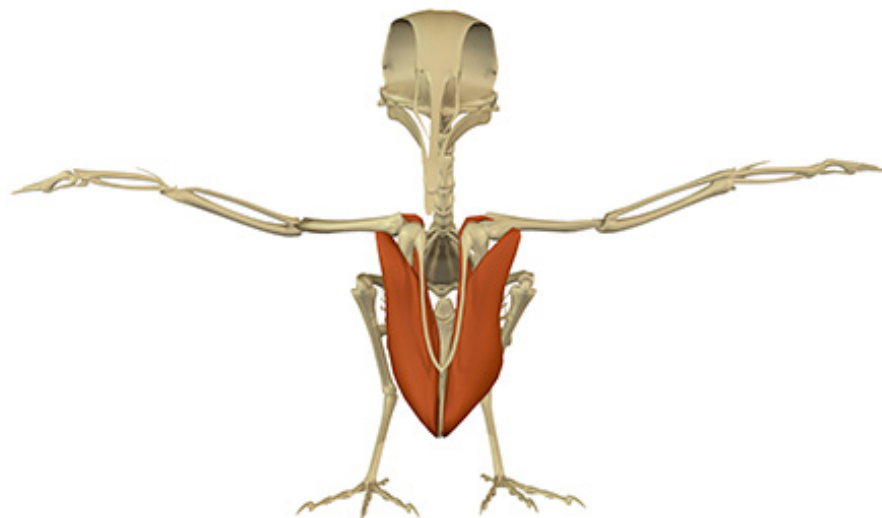

Figure 2.2: The avian breast muscles, comprised of the Pectoralis and Supracoracoideus muscles.

These are the muscles that provide the power needed to achieve flight, and the Pectoralis muscle alone makes up about 15-25% of a bird's body weight. This large, complex muscle originates on the keel of the sternum and inserts on the ventral surface of the humerus, producing the downstroke of the wing. The downstroke involves extension, pronation, and abduction of the manus; extension and rotation of the forearm; and extension and rotation of the arm (Beaufrère 2009). The Pectoralis muscle is the largest muscle in flying birds because it takes the most force to produce lift and thrust. The Supracoracoideus is a fusiform-shaped muscle that also originates on the keel of the sternum, laying deep to the Pectoralis. It passes through the triosseal canal to insert on the dorsal surface of the humerus, rotating (elevating) the wing to produce the upstroke. The upstroke involves flexion, supination, and adduction of the manus; flexion and rotation of the forearm; and flexion and rotation of the arm (Beaufrère 2009). This Supracoracoideus muscle is most critical in the take-off phase of flight, and is somewhat less important in recovering the wing from the downstroke once the bird is airborne (Proctor and Lynch 1993).

MUSCLES OF THE SHOULDER

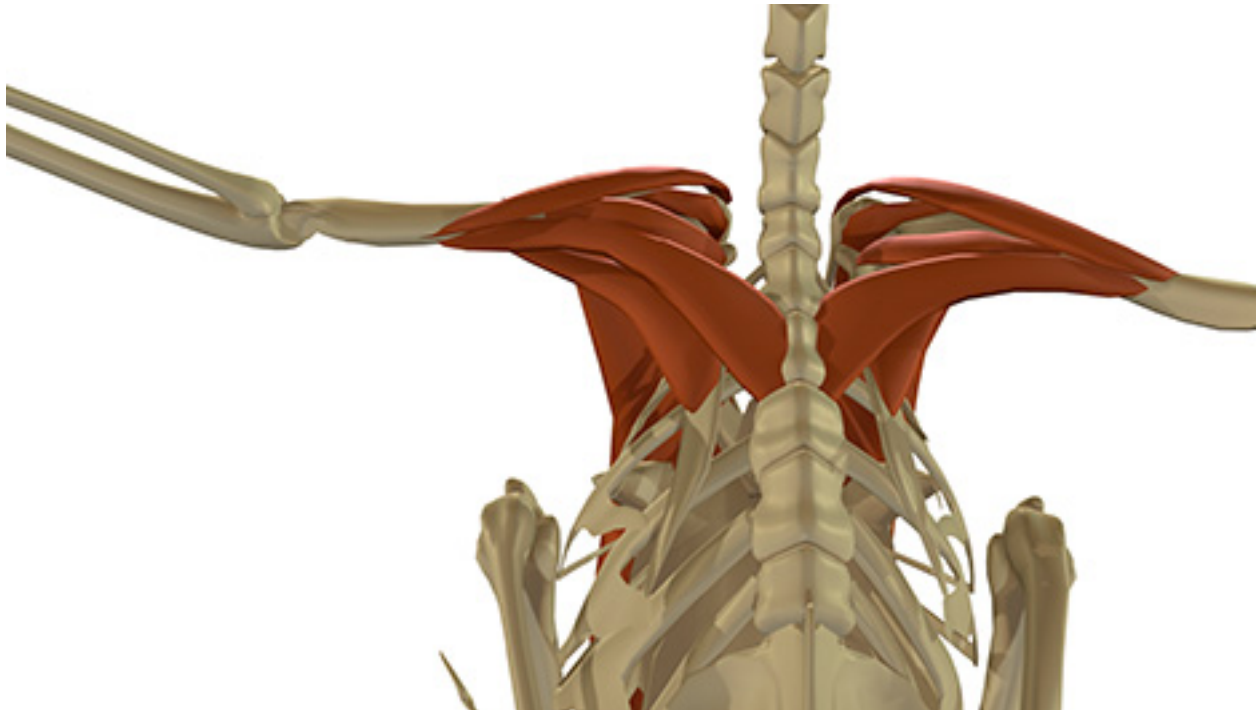There are a number of shoulder muscles that act upon the avian wing (Figure 2.3).

Figure 2.3: The avian shoulder muscles.

The Coracobrachialis originates on the coracoid and sternal ribs, inserting on the proximal surface of the humerus to depress the wing. The Deltoideus originates on the proximal clavicle (furcula), inserts

on the deltoid tuberosity of the proximal surface of the humerus, and functions to flex the shoulder and rotate the wing. The Teres major originates on the lateral caudal surfaces of the scapula, and inserts on the proximal ventral surface of the humerus, elevating and adducting the wing. The Latissimus dorsi is the most superficial muscle layer on the back (Kovacs and Meyers 2000), originating on the supraspinous ligament of the thoracic spine to insert on the proximal surface of the humerus, adducting and flexing the wing, moving it backward and dorsally.

MUSCLES OF THE PECTORAL LIMB: BRACHIUM

Although the avian wing bones are extensively fused and reduced, the wing muscles are numerous and complex (Figure 2.4).

Figure 2.4: The musculature involved in avian flight.

Avian muscles are remote from the joints, producing tendons that are often very long, many of which cross two or more joints. This creates muscles that are small and lightweight while, at the same time, are able to control distal movements of the wing (Biewener 2011). Muscles of the arm and forearm act primarily as joint stabilizers and shape modifiers during flapping flight. It was crucial for me to

understand the origin, insertion, and function of each of these muscles in order to accurately model and animate them for this project.

The Patagialis longus originates on the distal coracoid and Pectoralis muscle, inserting on the dorsal surface of the carpal bones. This muscle flexes the elbow, extends the manus, and tenses the patagium of the wing. The Biceps brachii originates near the glenoid fossa and proximal head of the humerus, inserting on the anterior surface of the radius, serving to flex the elbow, extend the manus, and tense the patagium of the wing. The Triceps brachii has long and short heads originating on the neck of the scapula and proximal humerus, to insert on the olecranon process of the proximal ulna. This muscle flexes the shoulder and extends the elbow. (Proctor and Lynch 1993)

MUSCLES OF THE PECTORAL LIMB: ANTEBRACHIUM & MANUS

The avian antebrachium, or forewing, and manus are controlled by a number of small muscles (Figure 2.5).
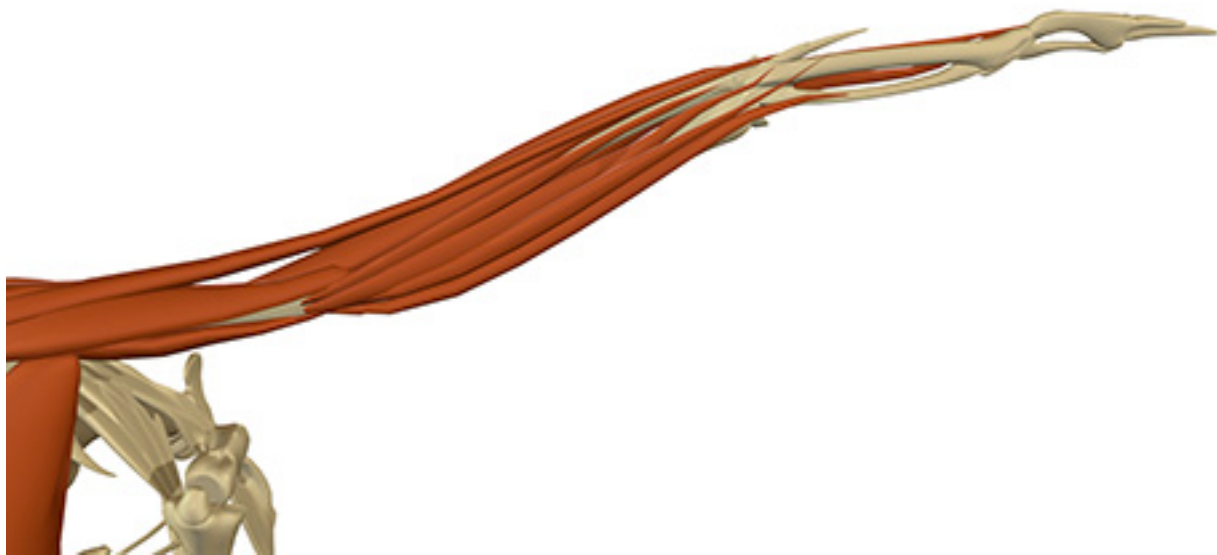

Figure 2.5: The musculature of the avian antebrachium and manus.

The Extensor carpi radialis originates on the lateral condyle of the humerus, and inserts on the dorsal surface of the carpometacarpus. It functions to flex the elbow and extend the manus. The Extensor digitorum communis, or common digital extensor muscle, originates on the lateral epicondyle of the humerus, inserts on the first phalanx of digit 2, and serves to extend the manus, metacarpus, and alula.

11

The Ulnaris lateralis originates on the lateral epicondyle of the humerus, and inserts on the carpometacarpus, flexing the metacarpus and helping to coordinate flexion of the manus. The Pronator's longus and brevis both originate on the medial epicondyle of the distal humerus and insert on the medial surface of the radius. These muscles pronate the manus and the outer wing. The Extensor carpi obliquus originates on the ventral surface of the medial ulna, inserts on the dorsal surface of the 2nd metacarpal, and functions to extend and rotate the wing inward. The Flexor carpi radialis originates on the medial epicondyle of the distal humerus, inserts on the carpometacarpus, and serves to supinate the manus, flex the elbow, and helps erect the secondary feathers. The Flexor carpi ulnaris originates on the medial epicondyle of the distal humerus, inserting on the ventral surface of the carpometacarpus, serving to flex the manus and the outer wing. The Interosseous ventralis is a small muscle of the manus that originates on the ventral surface of the carpometacarpus, inserts on the 1st and 2nd phalanges of digits two to flex digit two. (Proctor and Lynch 1993)

THE AVIAN RESPIRATORY SYSTEM

The avian respiratory system is the most efficient in the animal kingdom and in both its large and small details it is surprisingly unlike that of most other land vertebrates (Proctor and Lynch 1993). When first learning about the complexities of avian flight, I failed to recognize the vital importance of the respiratory system, and have since learned that flight would essentially be impossible if it wasn't for the unique respiratory anatomy that birds posses. It was important for me to include this aspect of avian specialization to ensure that my thesis would represent a complete overview of the anatomy necessary for flight.

The primary function of the respiratory system is to supply oxygen to the body tissue and carry away carbon dioxide produced by high levels of metabolic activity. In birds, this process of gas exchange is crucial because the demand for oxygen during flight is enormous. The flight muscles must receive a large and constant supply of oxygen to maintain flight, and metabolic wastes must be removed quickly (Proctor and Lynch 1993). Unlike mammals, birds lack a muscular diaphragm to power respiration, and instead rely upon expansion of the ribcage to draw in air. When a bird inhales, air actually leaves the lungs. Fresh, oxygenated air enters the lungs as the bird exhales (Proctor and Lynch 1993).

The avian respiratory system is composed of the trachea, relatively small lungs, bronchi, pneumatic bones, and usually 9 large air sacs (Podulka, et al. 2004) (Figure 3.1).
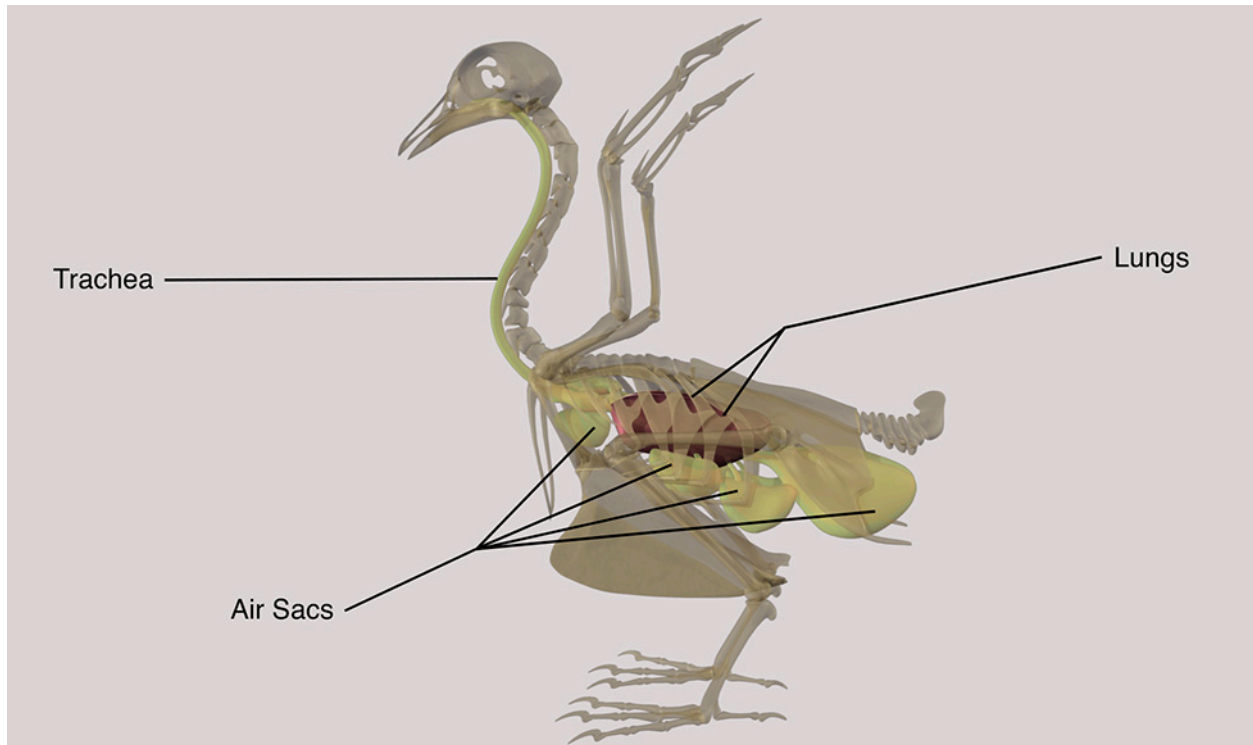
Figure 3.1: The anatomical components of the avian respiratory system.

These air sacs are extremely thin-walled and do not play a direct role is gas exchange. Instead, they serve as bellows to bring air into the bird and store it until expiration. They allow a continuous stream of air to pass through the lungs in a one-way flow, thus producing the most efficient respiratory system of any vertebrate. They are also connected to certain pneumatized bones, aiding the bird in shedding excess heat from its body as it breathes, which would be fatal if not removed.

The cervical air sac is located between the clavicles and surrounds the bifurcation of the trachea (Figure 3.2).
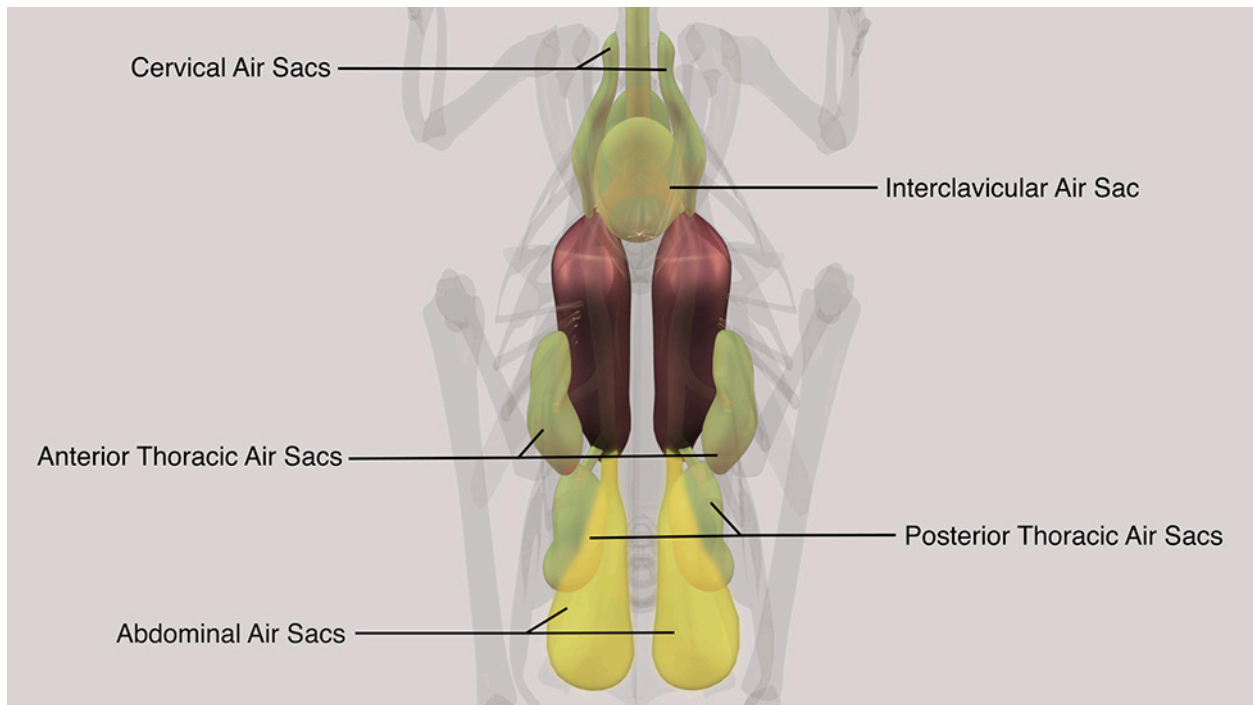
Figure 3.2: The avian air sacs.

This air sac has extensions that lie near the shoulder joint and connect through a hole in the humerus, the pneumatic foramen, to the pneumatic space within the wing bones. The interclavicular air sac is a single, unpaired sac that lies ventral to the trachea in a notch between the furcula. The anterior and posterior thoracic air sacs are paired sacs within the thorax, lateral to the heart and ventral to the lungs. The abdominal sacs are typically the largest and are paired sacs that lie lateral and ventral to the abdominal viscera, generally between the intestines and the abdominal wall. All of the air sacs participate to some extent in the respiratory process: all of the posterior air sacs expand on inspiration, while all of the anterior air sacs contract on expiration. (Proctor and Lynch 1993)

The path of a breath through the system can be summarized in four steps. During the first inhalation (cycle 1 inspiration), the breath travels down the trachea, into the left or right bronchus, through the lung, and into the posterior thoracic and abdominal air sacs (Figure 3.3).
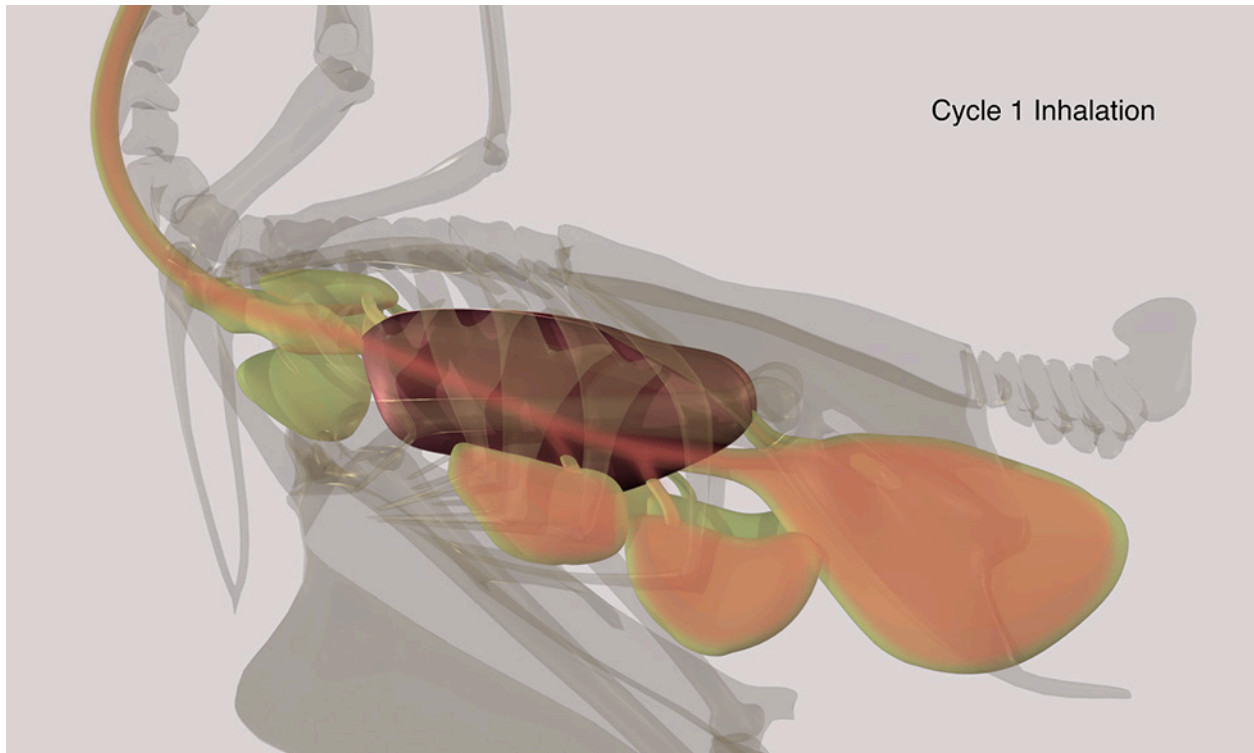
Figure 3.3: The path of a breath through the avian respiratory system during the first inhalation.

As the bird exhales (cycle 1 expiration) the abdomen contracts, and the air is forced out of the posterior air sacs and into the lungs. Within the lungs, the air passes through a progressively smaller filter of tiny air passages, called parabronchi. The smallest air passages within the lung are called the air capillaries, and it is along the walls of these blind-ended air capillaries that the exchange of carbon dioxide for oxygen occurs (Figure 3.4).
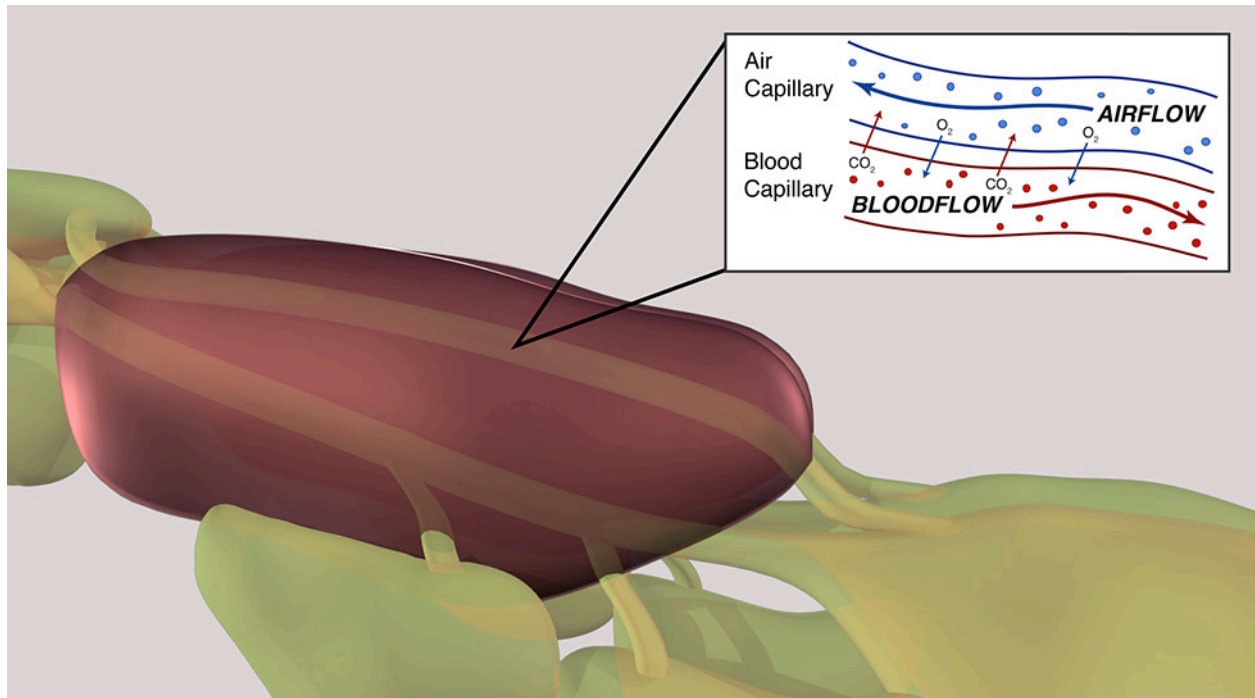
Figure 3.4: The process of gas exchange within the avian lung.

The blood capillaries channel blood in through the lung tissue along the all of the air capillaries, and this countercurrent flow of blood produces the maximum efficiency of gas exchange. During the second inhalation (cycle 2 inspiration) the air within the lungs is driven out. The now stale air passes into the interclavicular, cervical, and anterior thoracic air sacs. During the second exhalation (cycle 2 expiration) the anterior sacs contract; the air is then driven out into the trachea, where it passes up and out of the nostrils. This specialization of the avian respiratory system is one of the greatest factors in flight. Without this unique anatomy, the act of flight would likely be impossible. (Proctor and Lynch 1993)

FLAPPING FLIGHT AND RESPIRATION

Ornithologists have long speculated about the relationship between upstroke and downstroke and the avian respiratory cycle that occurs during flapping flight. The compression and expansion of the thorax in flight complements the respiratory cycle of inhaling and exhaling, i.e., birds use some of the power of their flight muscles to help them breathe while flying (Proctor and Lynch 1993). It has been found that the furcula plays an important role in breathing, acting like a leaf-spring in the pectoral girdle, expanding as the wings are pulled downward and snapping back as they are raised again. This spring-like movement of the furcula stores some of the energy of the breast muscles as they contract in downstroke, expanding the shoulders laterally. In upstroke the furcula releases this stored energy as it snaps back into

normal position, drawing the shoulders in toward the body midline. This furcular "spring" may facilitate the movement of air between the lungs and air sacs independent of breathing. This is especially important when remembering that birds lack a muscular diaphragm to power their respiration (Podulka, et al. 2004).

PRODUCTION DECISIONS

DIGITAL VS. TRADITIONAL

When embarking on this project, one of the most fundamental choices I had to make was what medium would be used to produce the artwork. The first step in making this choice was comparing and contrasting digital and traditional media.

Since I knew very early in my thesis that I wanted to produce animations as a final product, the choice between digital and traditional media was relatively easy to make. Though both rendering techniques have their pros and cons, there are many reasons why digital medium was a more logical route to take for this project. I based my decision to work digitally on the following advantages. 1) Artwork can be created at a much faster rate; 2) once work is created it can be used over and over again; 3) work can be created at nearly any size and, in most cases, can be easily increased or decreased in size; 4) the product can be easily formatted for viewing on the web; and most importantly, 5) it is much easier to animate artwork that is created digitally.

Choosing to work digitally ultimately saved me a lot of time and energy, and also produced higher-quality, more realistic images. It would have been nearly impossible to create my final animations using traditional methods, considering I would have had to render literally thousands of separate illustrations per movie. Clearly this would not have been a wise choice when working under a strict timeline. The viewer won't know how much time was spent creating particular images, so it is best to choose a rendering method that will produce the highest quality images in the most reasonable amount of time.

Another advantage of using digital medium is that there are multiple methods of back-up storage, and files can be saved in many different locations. Works created with traditional media, however, are relatively difficult to preserve and keep safe, very likely losing quality (fading, smudging, etc.) with time. These traditional works are extremely vulnerable since they only exist in a single form, with no real form of back up. Since this project was so valuable to me, it was very important that it be kept safe and saved in multiple locations. Working digitally prevented any work from being lost and ensured that multiple forms of the file existed, providing insurance against that inevitable software crash.

3D VS. 2D ANIMATING

One of the greatest difficulties in grasping the biomechanical aspects of avian flight is visualizing the movement and interaction of the various anatomical components. Although a series of static images might aid in this understanding to some extent, an animated sequence of images is usually much more effective. This was the main reason I chose to create animations as opposed to static illustrations. I also chose to produce animations because it was a form of delivery that I had not yet seen used with this subject matter. Most of the artwork I had seen of avian anatomy consisted of static illustrations that sometimes lacked a sense of cohesion. It is much easier to comprehend avian anatomy if you can see how it moves and how all of the separate elements relate to each other, working together to produce various forms of motion.

After making the decision to work digitally and through animation, I next had to choose between 2D or 3D rendering techniques. I ultimately chose to render my images out in a 3D rather than a 2D environment based on a number of different considerations. To start, images that are created using 3D software are much easier to animate, producing a cleaner, more realistic product. It was important to me that the final product of this project to be as realistic-looking as possible, anticipating that the model of the bird anatomy would closely resemble the anatomy of a living bird. I wanted the avian skeleton, muscles, and respiratory anatomy to appear very life-like and move in a very natural way, allowing the viewer to observe the images and then picture the anatomy within any real bird. It was clear to me that creating 3D models for this project would be the best way to create these images and animations that I envisioned. This was going to be the most logical method of rendering and animating my ideas for this project, allowing them to be more easily "brought to life".

The use of 3D software has many other advantages that were influential in my decision. The ability to re-use any models in different animations, or even for different projects at a later date is an appealing advantage, saving both time and hard work. Another rather obvious advantage of 3D software, as opposed to a 2D method, is the production of a more striking, or "slick", product. It helps in making subject matter that may initially be seen as boring, more interesting and engaging. Though 3D modeling and animating produces a good-looking product, it is by no means easy, and requires a lot of education and practice to perfect. Because of these requirements, the production and use of 3D images may highlight a certain skill set that might not be very common. Producing a high quality product using 3D software demonstrates that one has spent a significant amount of time learning the software and put a great deal of effort into the final product.

Throughout this project it was important for me to remain consistent with the different animations, applying the same rendering and animating techniques to each. This was relatively easy since the "main characters" in each movie were all able to be rendered in 3D, ensuring that each animation had a similar feel and look to it. Before starting the rendering process of this project, I believed that I would illustrate the musculature in a 2D environment as opposed to a 3D one. I planned on this only because I wasn't initially confident in my ability to model and rig the muscles in 3D, since I had never done anything like that before. However, I did a lot of research on creating and rigging 3D muscle and decided that I should at least try it out. After testing this technique, I found that it was actually not that difficult, and that rendering the muscles in 3D would produce a much better product than if I had tried to render them in 2D. This would have created an inconsistent product; with a 3D skeleton model and 2D musculature, the muscles would have looked very out of place. The ability to model and animate the muscles in the same environment as the rest of the work allowed the animation to flow much better. The muscles turned out to look very natural when applied to the skeleton, in both appearance and movement.

It was very important for me to incorporate the anatomy of the respiratory system as a 3D component in this project. This was because I had never viewed the respiratory anatomy in such a way, and to my knowledge, it had not yet been created in a 3D environment to be used as an educational resource. Any previous images I had seen (both illustrations and animations) of the avian respiratory system were only in 2D and were difficult to understand. I wanted to create this unique anatomy in a way that would easily relate to the skeletal anatomy of the bird and would straightforwardly demonstrate its specialization. I also wanted to be able to show the respiratory system from a number of different angles, providing the viewer with a comprehensive overview of the anatomy and how it functions as a whole. The only logical way to achieve this sort of product was to create the anatomy in a 3D environment.

I wanted the final product of this thesis to be an educational movie in order to make the scientific material more interesting and engaging to the viewer. Animations, in general, seem to be more interesting learning tools then static illustrations or images. Another advantage of animation is that the viewers are able to control what they are viewing. The ability to move forward, pause, and go backward in the timeline provides the viewer with a sense of control and a way to learn the material at their own pace, possibly providing a better learning experience overall.

I also wanted to provide narration to the movie, instead of static text images, producing a final movie that engages the viewer with the 3D animations, narration, and labels (text). This stimulates the viewer in more ways than a static image would, and may promote a more effective and enjoyable learning experience. It was important for me to create an animation that was not only visually striking, but highly educational and informative as well. I wanted the images to enhance the information and make the viewer interested in learning more about the topic. The project would have failed if the final animation looked

nice, but failed to educate the viewer. As a Medical Illustrator, it is my job to find the perfect balance between educational content and image quality. Sometimes the quality of an image must be sacrificed in order to portray the proper information within the image, and vice versa. This project represents an informative tool that has a very good balance of image quality and educational content.

It is also useful that 3D images can be rendered at just about any size. For my animations, I chose to render by images at a very large scale, 1920x1800 pixels at a resolution of 300 pixels-per-inch. This produced a high quality, high-resolution animation as the final product. An animation at such a large size maintains the same quality when viewed on monitors of various sizes: from the large 27 inch computer screen to the small 4 inch screen of a smart phone. It was important that the final product of this thesis be easily viewed in the various technological platforms that are common these days. Smaller animations, such as ones intended for web viewing, were easily rendered at a much smaller size. The ability to choose the exact size of the final image, but still be able to go back and increase or decrease the size of that image is a useful feature of 3D software.

PRODUCTION PROCESS

THESIS WEBSITE

Prior to the creating any artwork for this project, I developed a website that would be dedicated to the process of the production of this thesis. I intended for this website to document the progress of the project, from the first preliminary sketches through the final animation.

Designing a website that recorded the entire production process provides a more comprehensive method of delivery and shows how my thought progress evolved, as well as how the artwork improved over time. It helps to document the entire process instead of focusing on the final result. To develop this website, I created an address on Rochester Institute of Technology's server using my student account, naming it http://cias.rit.edu/~kmk1417/thesis/home.html. To create the actual website, I used a combination of scripting in HTML, CSS, and JavaScript. These techniques were used to develop a comprehensive website that contained a number of different pages; each dedicated to a different aspect of the thesis and its production.

The layout was intended to be clean and simple, focusing the viewer on the artwork rather than the design. The first page of the website, "Overview", was intended to provide the viewer with the general idea of the thesis and the reasons for creating the website (Figure 4.1).

Figure 4.1. The first page of the thesis website, "Overview".

It also served as a "welcome" page for the website. The second page, named "Development", was dedicated to my brainstorming process and was further divided into three pages: "Concept", "Story", and "Sketches" (Figure 4.2).

Figure 4.2. The second page of the thesis website, "Development".

Instead of merely showing the finished artwork and animation, these pages were all intended to document my preliminary ideas early in the project and to portray my reasons for choosing this particular topic to study. The next page, "Pre-production", was dedicated to the actual process of the producing the artwork. It was further divided into three pages: "Modeling", "Rigging", and "Storyboards" (Figure 4.3).

Figure 4.3. The third page of the thesis website, "Pre-Production".

These pages were intended to show the viewer what the production process actually looked like, and how the artwork evolved over time. It was also intended to educate the viewer as to the type of software and rendering techniques that were used to create the artwork. The next page, "Production", was dedicated to the placement of each individual animation once completed (Figure 4.4).

Figure 4.4. The fourth page of the thesis website, "Production".

Here, the viewer was able to choose which animation they would like to view. The final page of the website, "Final Animation", was where the viewer would find the completed animation, the compilation of all of the individual movies.

All animations were embedded within the web pages using the website www.vimeo.com. After uploading each movie to this website, they were embedded in my thesis website by copying an HTML code (provided by Vimeo) and pasting this code into my corresponding HTML code for my web pages. To create the actual website pages, HTML, CSS, and JavaScript documents were edited in TextWrangler (Mac) or Notepad++ (PC). These documents were then uploaded to the World Wide Web through the R.I.T. server using File Transfer Protocol (FTP) software Fetch (Mac) or FileZilla (PC). Both Mac and PC software was used for this process because I worked on both a Mac desktop computer and a PC laptop computer.

After researching the necessary scientific material for each movie in depth, general notes were made for each movie. These notes included a broad range of information that might be included in each movie. From here, the information was narrowed down to what was crucial information for each animation. This included the minimal amount of material that would still provide a great deal of education to the viewer. It was necessary to condense the material to a realistic amount to allow each movie to be a reasonable length and to ensure that I would have enough time to complete each animation. The condensed information was then used to create a rough narration script for each of the three movies. The narration was recorded by myself and was created and edited using Audacity, exporting each file in AIFF format. Each narration script was edited and perfected several times before the final narration was recorded.

Storyboards were created for each of the three movies using Adobe Illustrator. Each of these storyboards included images, camera directions, timing, and the anticipated narration for each individual movie (Figure 5.1).

Figure 5.1. An example of a portion of the storyboard created for movie 1.

The storyboards were intended to provide the viewer with an overall concept of each of the three movies, in terms of how much and what type of material would be covered, what the images might look

like, and the approximate length of each movie. The use of storyboards simulated how the anticipated project would be presented to an actual client, instead of just a viewer. If the client was unhappy with the storyboards in any way, they could very easily be adjusted before major work for the project began. This would ensure that the client had a good idea what they were getting before the project is completed, and helps prevent any confusion or disagreements down the line.

3D MODELING: SKELETON

The majority of the artwork created for this project was rendered in 3D using Autodesk Maya 2013. The first step of the modeling process was to create an accurate 3D model of an avian skeleton. For reference, I purchased a mounted and articulated skeleton of a pigeon (rock dove). This skeleton was sketched and photographed at various angles to provide reference images in Maya. A pigeon was the best available reference because it is a common bird that has been well studied, and includes the general skeletal adaptations that are found in all flying birds. Chicken skeletons are also readily available but since chickens do not fly very often, they have different skeletal anatomy than birds that spend a significant amount of time in flight.

To begin the modeling process, reference images (such as sketches) were imported into Maya as image planes. Each individual skeletal element first began as a simple polygon cube. Various techniques were used to model each element to accurately represent the skeletal elements of the pigeon. Since the bird's skeleton is symmetrical, all of the elements could be first modeled on the left side of the body. Once the elements were accurately (though roughly) modeled, they could each be duplicated and mirrored to the right side of the body. This method ensured that the final model was symmetrical and accurate, and also saved a significant amount of time. Repeated skeletal elements, such as the ribs and cervical vertebrae, were easily duplicated to create the proper number of each element. Each duplicated element was then individually modified for anatomical accuracy. This way, the element maintained a similar overall shape, and saved time from having to create each rib and vertebra from scratch.

Once the entire skeleton was modeled, all of the skeletal elements were brought together to accurately "build" the bird. All of the models were first kept relatively rough with a small number of faces, and were only smoothed when the entire model was complete. Each individual element was also assigned a simple UV map to ensure that any shaders applied would appear uniform over the entire model. During the modeling process, only a default shader was used on the entire surface of the model. Only after the entire model was complete and smoothed was a bone textured shader applied to entire surface. This layered bone shader was adjusted in various ways in terms of color and bump map to give the skeleton the appearance of actual bone (Figures 6.1 - 6.3).
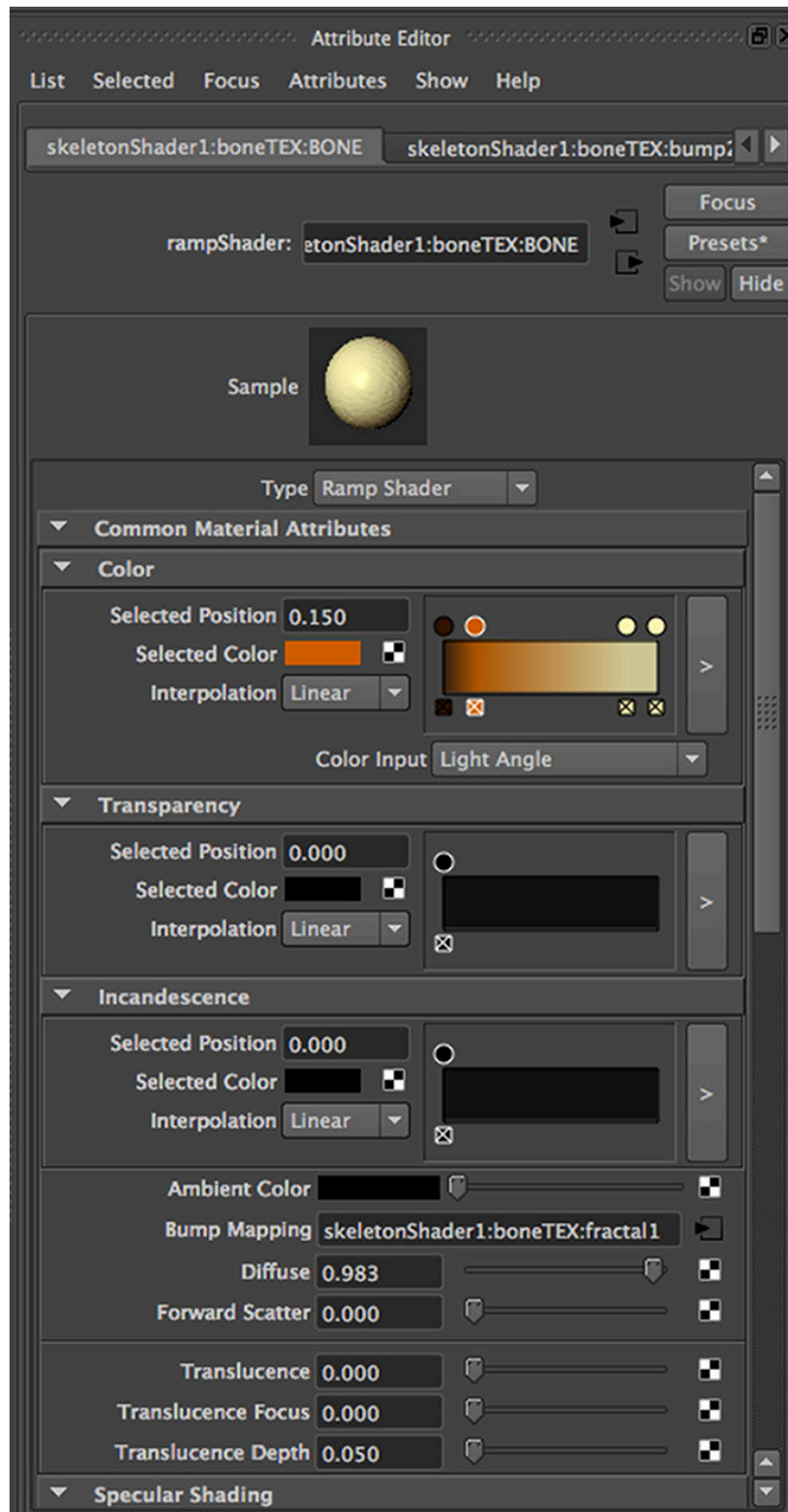
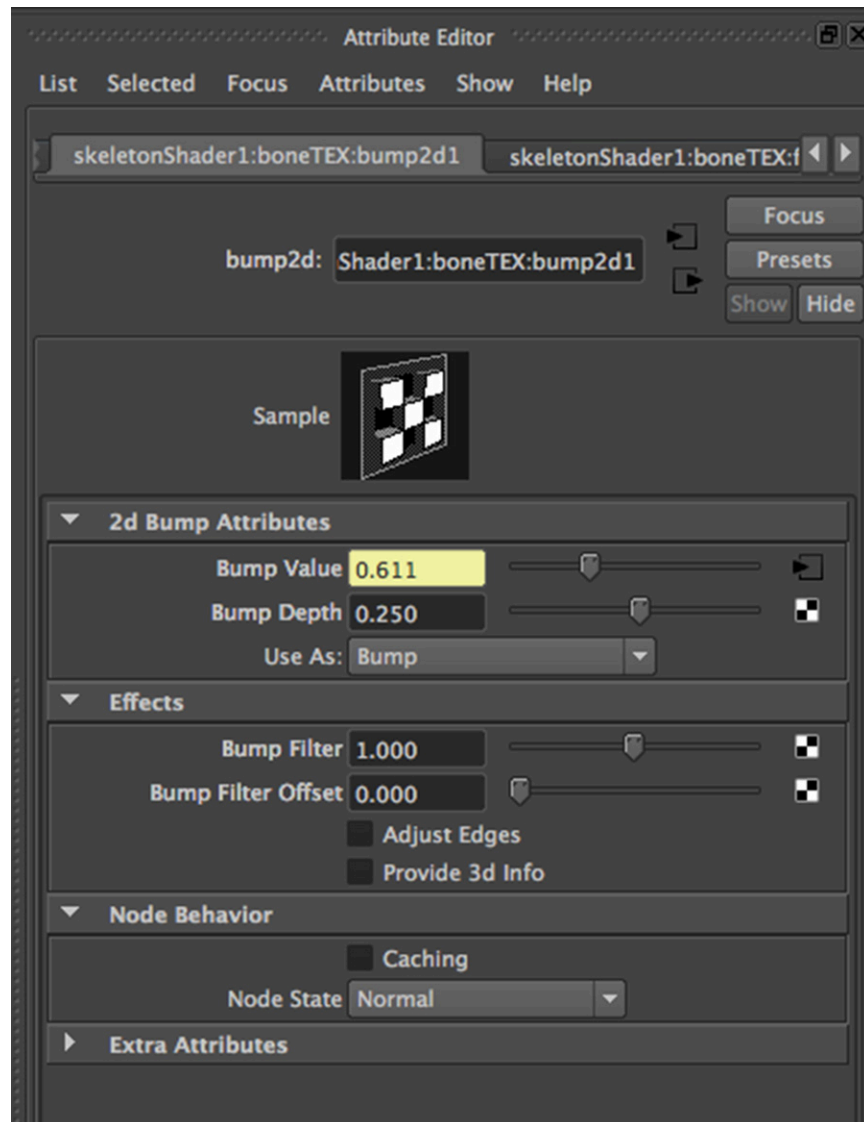**Figure 6.1**. The adjustments of the bone shader in Maya's attribute editor

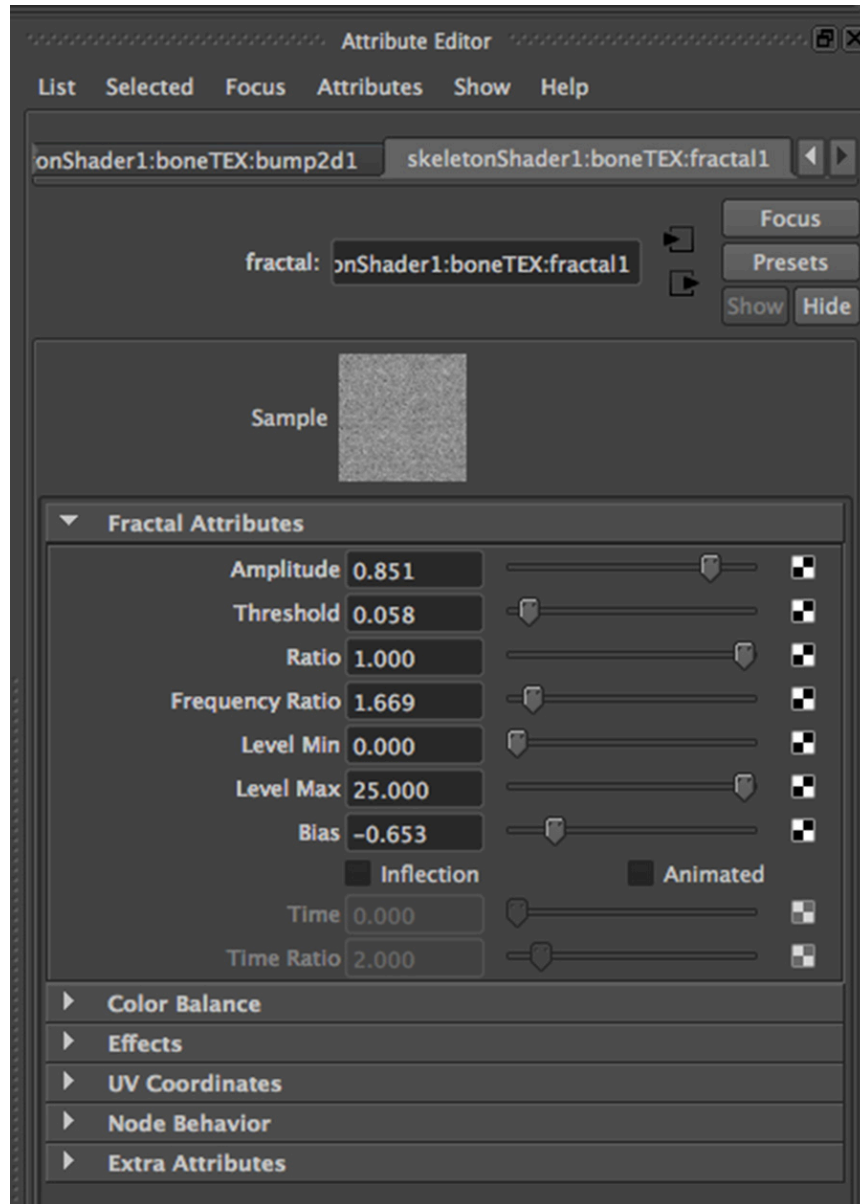**Figure 6.2**. The adjustments of the bump map for the bone shader in Maya's attribute editor.

Figure 6.3. The adjustments of the textured bone shader in Maya's attribute editor.

Throughout the modeling process the Maya Outliner was crucial is keeping track of each of the individual polygon models (Figure 6.4). Each model was assigned an appropriate name (such as Tibiotarsus_left) and was then further grouped into different categories. For example, bone models of the left hindlimb (femur, tibiotarsus, tarsometatarsus, and feet) were all put into a group named "Hindlimb_left"; models of the left forearm (humerus, radius, ulna, carpometacarpus, digits) were grouped into "Forelimb_left", and so on. This helped to organize all of the elements of the pigeon skeleton model and made the different parts of the body easy to locate and/or select. The entire skeleton was then combined into one large group, "Pigeon_skeleton", allowing the whole skeleton to be easily

selected. Without utilizing this organizational tool in Maya, the scene would have become very complicated and disorganized. It was important to keep track of every model that was made, and their ease of accessibility saved time in the modeling process.

Figure 6.4. The skeletal model in Maya emphasizing use of the Outliner.

After the 3D model of the pigeon skeleton was complete, the modeling of the anatomy of the avian respiratory system could begin. The opacity of the shader on the skeleton model was first reduced in order to see "inside" the model and be able to build the respiratory system in its anatomically correct position. Unlike the skeleton model, the respiratory system was created using NURBS curves. NURBS circles were first created in a way that represented the outer "circumference" of the intended anatomy. For example, a number of small NURBS circles were created to correspond to the length of the trachea, adjusting each to accurately represent the width of the trachea. Once these circles were of the correct size and were in the correct location relative to the skeletal anatomy, they were selected and sequentially lofted. This created a surface built around the circles; essentially creating a "tube" that represented the bird's trachea (Figure 7.1). This same technique was used to create the lungs, bronchi, parabronchi, and all of the air sacs.

Figure 7.1. The early modeling process of the respiratory anatomy in Maya.

Since the air sacs are very thin-walled and delicate, they were assigned a yellow shader with an opacity adjusted to make them appear thin and transparent (Figure 7.2).

Figure 7.2. Models of the avian respiratory anatomy with shaders applied.

The lungs were assigned a dark purple shader that was also semi-transparent, but this was only to allow the bronchi and parabronchi to be visible within the lungs (Figure 7.3).
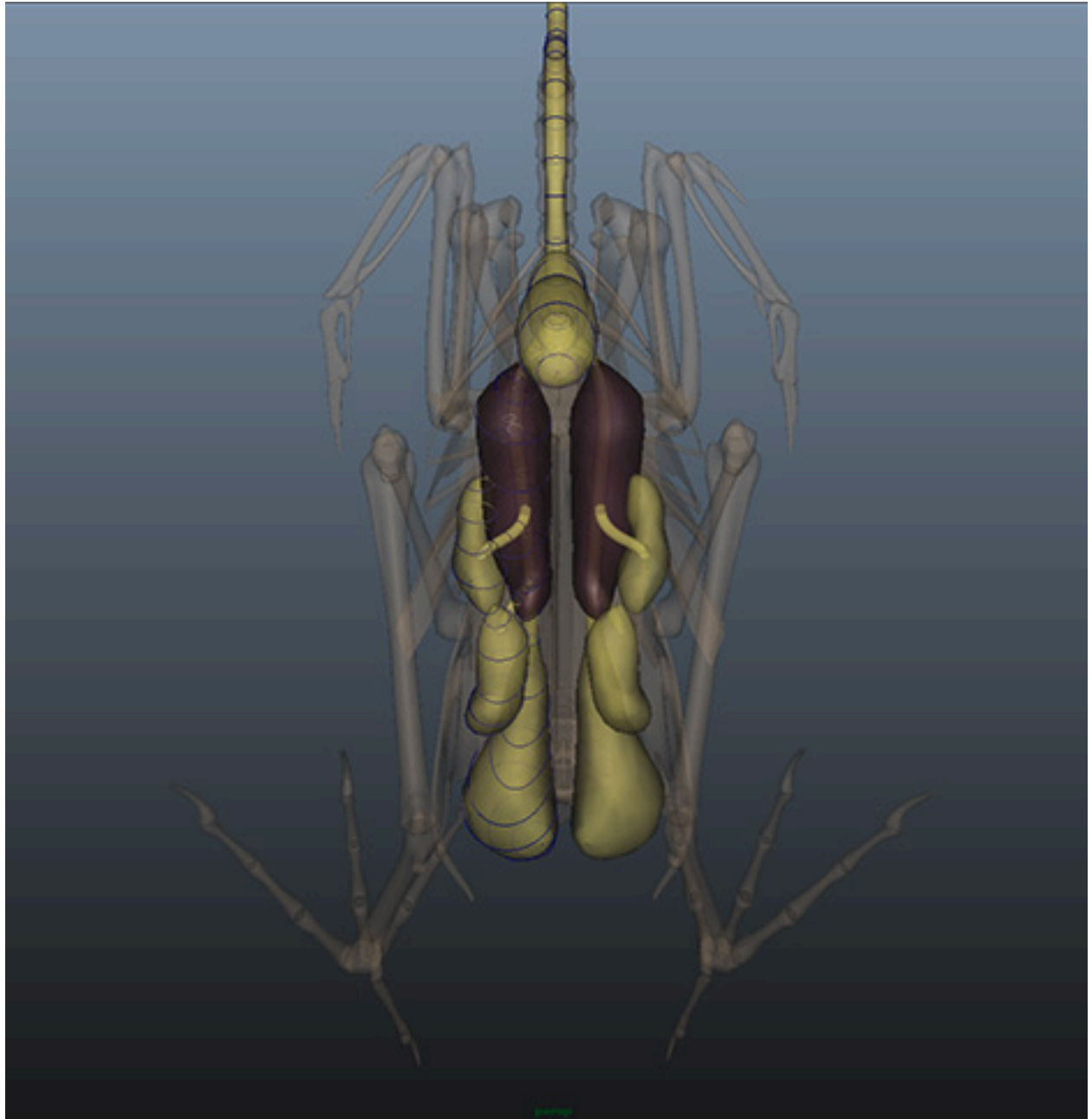
Figure 7.3. The completed models of the avian respiratory anatomy.

When the 3D models of the pigeon skeleton and respiratory system were complete, the next step was to rig the skeleton. This rig provided controls for the movement of the skeleton and its joints, producing a "skeleton within the skeleton".

To begin, the joint tool in Maya was used to create appropriate joints throughout the model. These joints are meant to act as pivot points or general points where movement will occur in the model. In general, joints were made in places where actual joints would be located within the bird. For example, joints were created in the hindlimb at the hip joint, the "knee" joint, "ankle" joint, and "toe" joints (Figure 8.1).

Figure 8.1. Joints created to fit the avian skeletal model in Maya.

This allowed the hindlimb to be moved and animated in a way that would be natural in a living bird. After all of the necessary joints were made within the model, the Inverse Kinetics (IK) Handle tool was used to inversely control the joint rotation. These IK handles allowed particular joints to be selected and rotated, having the selected joint affect a chosen hierarchy of joints. The IK handle typically spans three joints, creating an inverse control that allows the distal joint to control the rotation of the middle joint (Figure 8.2).

Figure 8.2. IK handles created to control the skeletal model in Maya.

Certain IK handles were then supplied with constraints that limited the axis and degree of joint rotation. This ensured that the joint would only rotate in a direction that would appear natural, and prevented it from being moved or rotated in a direction that would be anatomically incorrect or impossible. For example, the "knee" joint was constrained such that it was only able to bend in the Y-axis, since the knee can only bend in one axis and cannot be extended beyond 180°. Constraints such as these ensured that the rig, once bound to the 3D model, would rotate naturally and accurately.

Once the joints were distributed and constrained accurately throughout the skeleton model, the model was then bound, or "skinned", to the rig using a smooth bind and selected joints option. Doing this actually applies the rig to the 3D model, now supplying the model with an internal skeleton that allows it to be moved and animated. In order to more easily select certain IK handles of the model, simple controls were created using NURBS circles. This was done by creating a NURBS circle, snapping its pivot point to register with the IK handle, deleting its history, freezing its transformation, and then parenting the IK handle to the NURBS circle. This now meant that the NURBS circle was able to control the rotation of the IK handle (Figure 8.3).

Figure 8.3. NURBS curves created to control rotation of the IK handles.

This was done to various IK handles because locating and selecting these handles can become quite difficult once the model becomes complicated. Since the NURBS circles are arbitrary and can be made to any size that you want, they are much easier to see and select and are an overall simpler way to control the handles. In addition, the simple geometry of the NURB circle makes it easier for the software to calculate the rotation of the joint in response to the controls movement. It was also useful to parent different NURBS circles to other, larger circles, therefore creating a hierarchy of controls to choose from. Since Maya does not render NURBS curves, they were essentially invisible and did not show up as part of the image when the scene was rendered.

RIGGING & MODELING: MUSCULATURE

The avian flight muscles were created and rigged in Maya using the Simple Muscle Builder. To begin, objects called capsules were created at each joint or region where a muscle was anticipated to originate or insert (Figure 9.1).

Figure 9.1. The capsules created in Maya to begin the process of modeling the muscles.

These were necessary to create starting and ending points for the muscles and to have them connect and move accordingly to the appropriate joints. These capsules were created in the sternum, shoulder, scapula, "elbow", "wrist", and "hand" on each side of the model.

After the capsules were created, the individual muscles could then be modeled. In the simple muscle builder, the capsule where the muscle originated was selected as the "input", while the capsule where the muscle inserted was selected as the "output". When created, a muscle was built between these two capsules, rigged appropriately to the connected joints (Figure 9.2).

Figure 9.2. The Simple Muscle Builder in Maya used to model the flight musculature.

The individual muscle could then be modified and shaped to portray a correct representation of the actual muscle using CV's that were created in the process. Once the muscle was the correct shape and size, it was also necessary to make sure that the muscle moved properly and corresponded to the bones of

the wings when the joints were moved. This process was then repeated for all of the necessary flight musculature.

It was originally intended that once the musculature for the left side of the bird was created that these muscles could be copied and mirrored for the right side of the body. This would have ensured symmetry and consistency with the appearance of the muscle. However, a reliable method of performing this task was not found within Maya. All of the musculature for the right side of the body, therefore, had to be modeled from scratch in the same method that the muscles of the left side of the body were created. Since the left side was already complete, it was relatively simple to use those muscles as reference to create the muscles on the opposite side of the body (Figure 9.3).

Figure 9.3. The completed models of the flight musculature in Maya.

ANIMATING: MAYA

Once all of the necessary 3D components were completed in Maya, the process of animating could then begin. To start, the render settings in Maya were set to a size of 1920x1080 (1080 HD) at a resolution of 300 pixels-per-inch (PPI). This ensured that a high quality animation would be produced. The file format was set to PNG, allowing the background of each image to be rendered as transparent. This was important because the actual background color of the animations was best determined while completing the final animations. If at some point I decided to change the background color of the animation, I didn't have to go back and re-render every frame out of Maya.

For each of the three movies, a different scene in Maya was used. This prevented too much history from building up on the models and allowed each animation to have its own settings. Prior to animating, it was crucial that any unnecessary history on the model was deleted and all transformations were frozen. This helped to prevent any errors while rendering the animation sequences, since any unwanted history on the model could have added unwanted information to the already complex animations; it is important to start with a "clean slate" when animating. For each of the three animations, a separate camera for rendering was created; the "Render Camera" was the camera that was used when rendering all of the image sequences. This allowed changes to be made to the model through a separate camera (such as the perspective or front camera), and prevented any work on the animation from being lost or altered.

For the first animation, General Flight Adaptations, 800 frames were used in Maya. Animating was achieved by altering the Render Camera, moving IK handles, rotating joints, and setting keyframes (Figures 10.1 - 10.2).

Figure 10.1. The completed model of the avian skeleton rendered out of Maya and posed for animation.

Figure 10.2. The completed model of the avian skeleton rendered out of Maya.

After the skeleton and camera were both animated as desired, the rendering was broken up into a number of different segments. For example, I would choose to render frames 001-120 and then frames 120-200. This allowed the animation to be broken up into smaller sections that would better correspond to the previously recorded narration. This worked out better than simply rendering the entire animation (all 800 frames) in a single shot. This technique was used for each of the three animations. This would later allow a still image to be inserted between two animation sequences, causing a "pause" in the animation to allow for more time for corresponding narration.

Animation number two, The Avian Pectoral Limb, was the most complicated of the three movies to animate, and consisted of 1700 frames in Maya. The most difficult aspect of this animation was controlling the animation of the muscles. Each individual muscle had three different controls, each of which needed to be taken into consideration when animating movement of the wing. It was quite complicated to make each muscle behave correctly when animating even a small movement of the wing. Each muscle needed to be moved and keyed at nearly every frame of the wing movement to ensure that the movement appeared natural and that the muscle appeared to be doing its proper job. Though I had originally intended to animate the wing muscles functioning in the actual process of flight, it became

quite difficult to animate the entire skeleton in unison with the muscles to accurately portray the flight process. I chose instead to animate only movements of the wing that simulated what the wing might do and/or look like during flight. This was achieved by animating the wings in a variety of different movements while the bird was essentially standing still (instead of actually flying). I believe this method was successful and portrays how the muscles work together to control the wing. I find it to be a good educational tool when trying to learn the avian flight anatomy, emphasizing the muscles that are present in the wing, and how they relate to the skeletal anatomy of the wing (Figure 10.3).

Figure 10.3. The completed model of the avian skeleton and flight musculature rendered out of Maya.

The third animation, the Avian Respiratory System, was made up of 700 frames in Maya. The majority this animation involved camera movements, and only included slight movements of the bird's head as well as inflation of the air sacs. The air sacs were animated "expanding" and "contracting" by simply increasing or decreasing the size of the air sacs and setting keys. The most difficult aspect of the animating was controlling the different transparencies of the skeleton and respiratory system. These transparencies were achieved by altering the opacity of the shaders assigned to the models (Figure 10.4).

Figure 10.4. The completed avian skeleton and respiratory anatomy rendered out of Maya.

I chose to render a particular sequence of frames at one transparency and then re-render that same sequence at a different transparency. This allowed the sequence to later be animated to appear as though the images were fading from one transparency to another. Altering the transparency of the shaders also drastically increased the amount of time required to render each frame.

During the animation process, it was crucial to consider the lighting used in Maya. I created four directional lights that best illuminated the bird and produced quality-looking images. White lights at 50% intensity were placed in front and in back of the bird, while pale yellow lights at 50% intensity were placed to the right and to the left of the bird (Figure 10.5).

Figure 10.5. The avian skeleton and muscles in Maya with the four lights created for each animation.

These four lights were saved and exported from the hypershade window to each animation, ensuring that all of the models had the same appearance and that the bird was lit consistently in all of the movies.

47

After the animation sequences were rendered out of Maya, the PNG sequences were then brought into Adobe AfterEffects to produce the final movies. The AfterEffects composition for each of the three animations was set to a size of 1080 HD; the same settings that were used to render out of Maya. This was important to ensure that the images out of Maya would fit correctly within the composition size in AfterEffects and maintain their quality as well (Figures 11.1 – 11.2).

Figure 11.1. Movie 1 Animation, bird landing.

Figure 11.2. Movie 1 Animation, bird posed.

After the PNG sequences were imported into AfterEffects, the narration AIFF files were also imported. These were important in determining how much "pause" time was needed between each PNG sequence. To do this, the last image of each sequence that needed to be "paused" was again imported into AfterEffects, but not as a sequence. This allowed the end of the sequence to stay on that still image for as long as was necessary (Figure 11.3).

Figure 11.3. Movie One Animation, a section of pneumatic bone created in Photoshop and text elements created within AfterEffects.

Typically the length of the corresponding narration determined the amount of time this still image was used.

Throughout the three animations there were regions where a portion of the model needed to be "highlighted" in order to identify and label it. To do this, the frame (PNG file) in the animation where the highlight was to occur was brought into Adobe Photoshop. A path was then created around the anatomical element to be highlighted. This path was then selected, feathered 2-5 pixels, and then filled with a bright yellow color. The opacity of this layer was then decreased to about 80%, still ensuring that the color would be obvious, but that the anatomical element would be slightly visible. This image was then saved as a PNG file, imported into the AfterEffects file, and then placed at the appropriate section of the animation where the highlight was meant to occur (Figures 11.4 – 11.7).

Figure 11.4. Movie One Animation, emphasizing the tarsometatarsus with a yellow highlight created in Photoshop and a label created in AfterEffects.

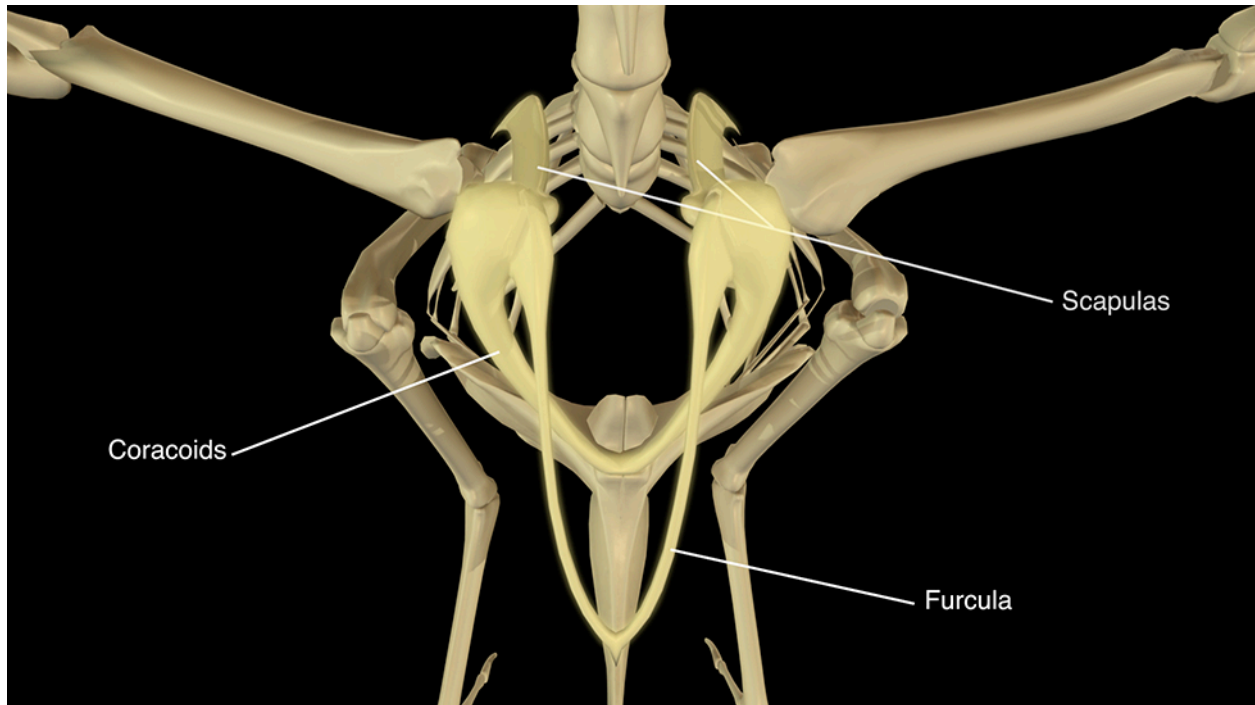**Figure 11.5**. Movie One Animation, emphasizing the large, keeled sternum.

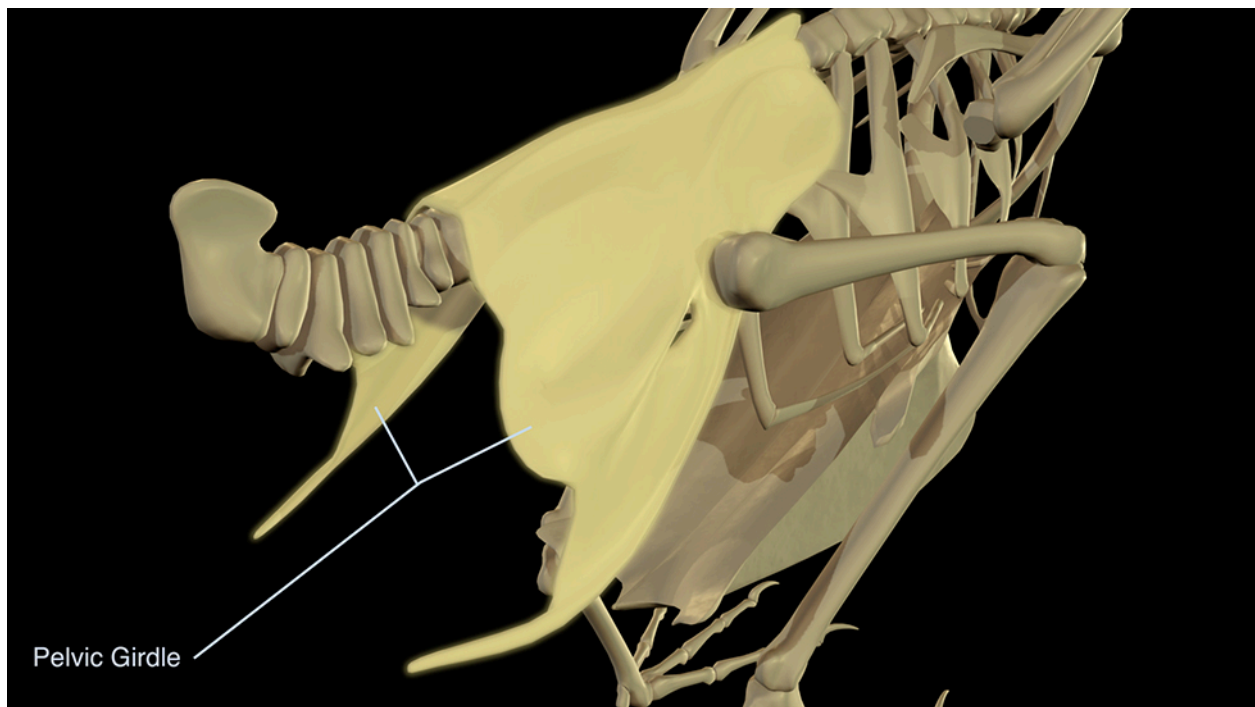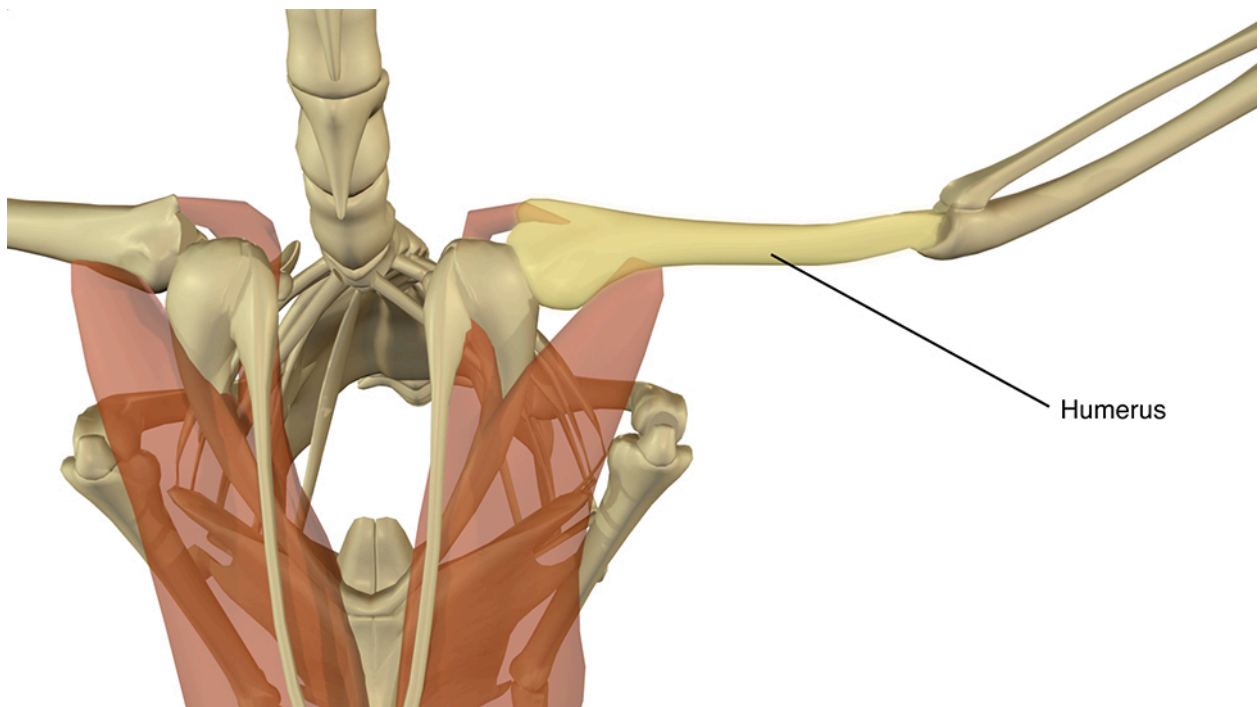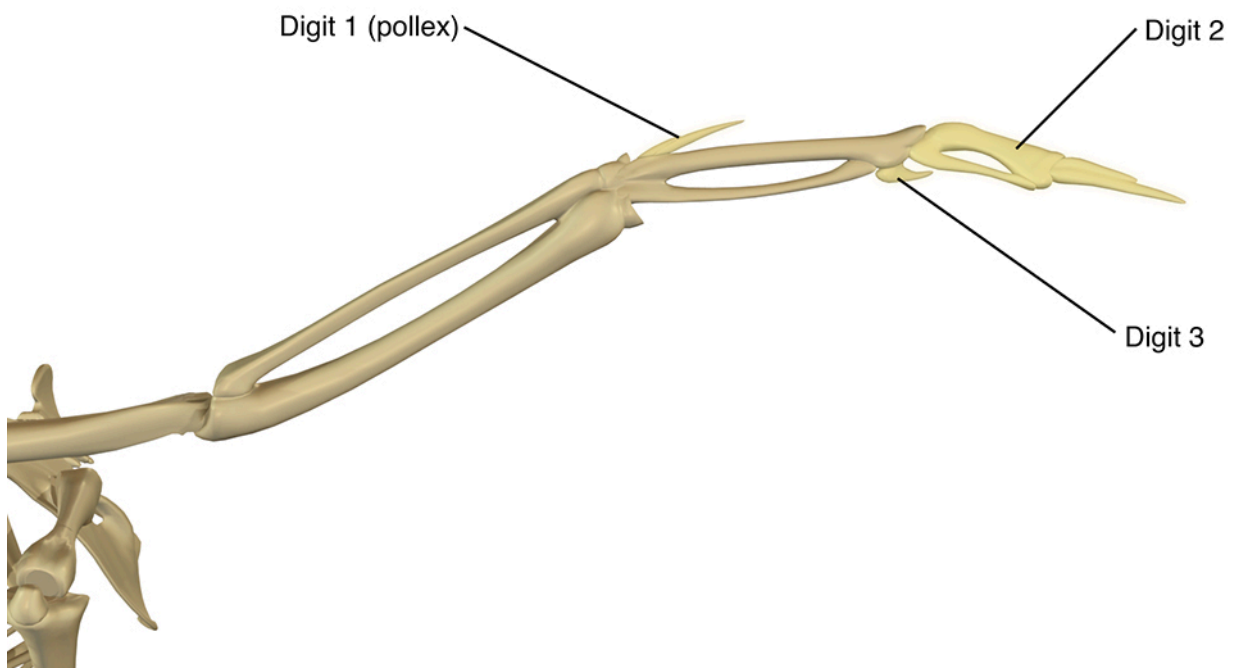**Figure 11.6**. Movie One Animation, emphasizing the bones of the pectoral girdle.

Figure 11.7. Movie One Animation, emphasizing the pelvic girdle.

This process was then repeated for each element that was highlighted and identified in each of the movies. The opacity of this PNG file was then animated to give it the illusion of fading in and out of the scene. All text elements and labels were produced and animated in AfterEffects, as well as the background color of each of the animations (Figures 11.8 – 11.22).

Figure 11.8. Introduction to Movie Two animation, The Avian Pectoral Limb.

Figure 11.9. Movie Two animation, emphasizing the humerus with a yellow highlight created in Photoshop and a label created in AfterEffects.

Figure 11.10. Movie Two animation, emphasizing the digits of the avian wing model.

Figure 11.11. Movie Two animation, emphasizing the flexion of the Pectoralis major muscles.
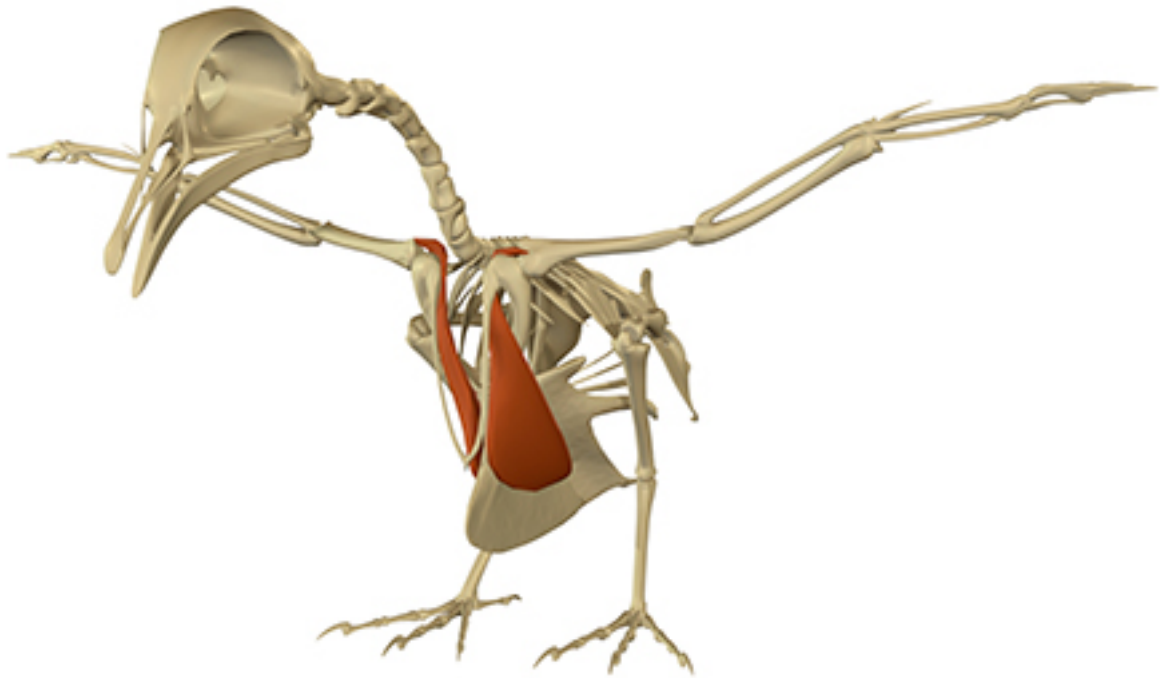
Figure 11.12. Movie Two animation, emphasizing the Supracoracoideus muscles.
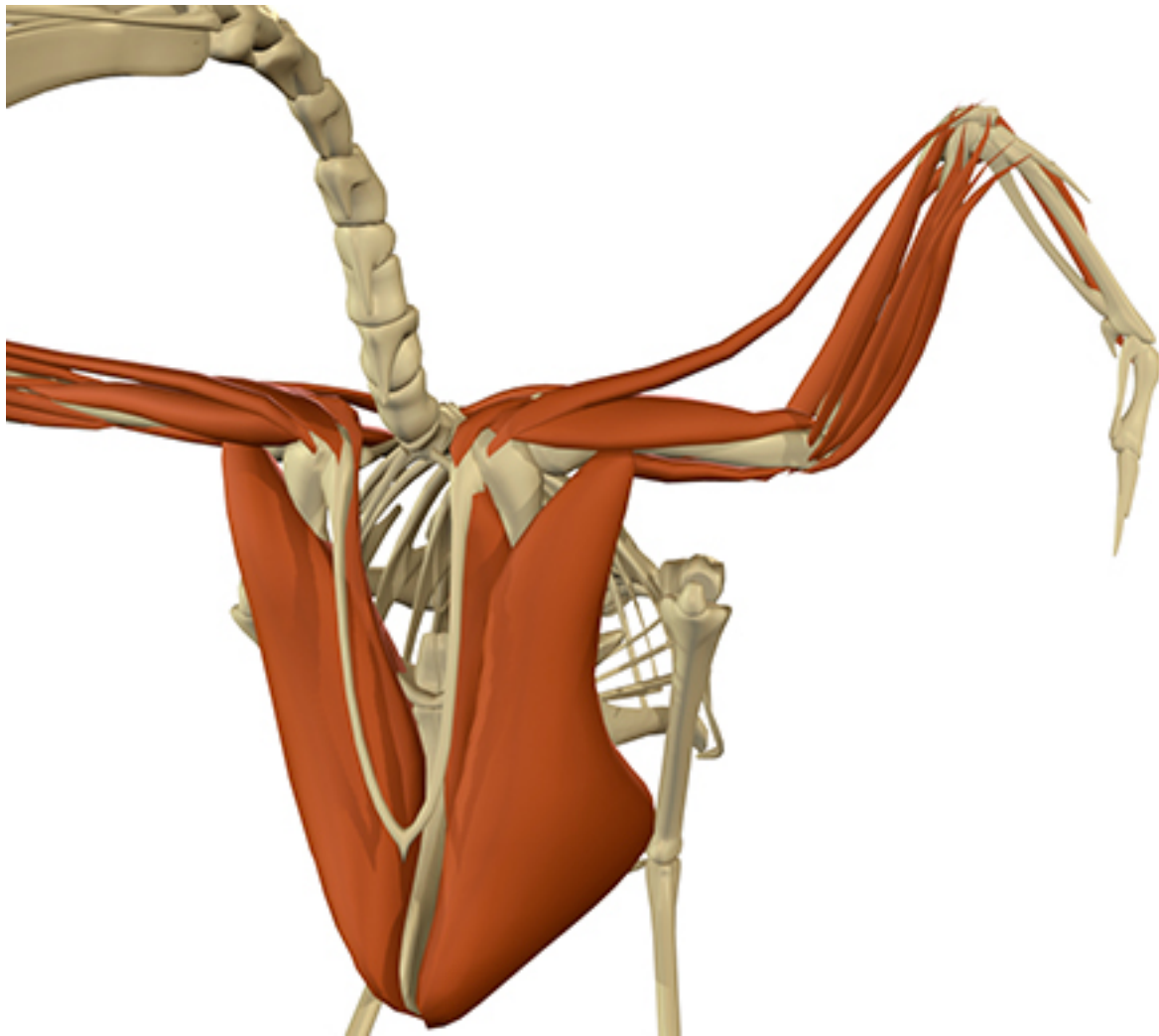
Figure 11.13. Movie Two animation, focusing on the musculature involved in flexion of the wing.
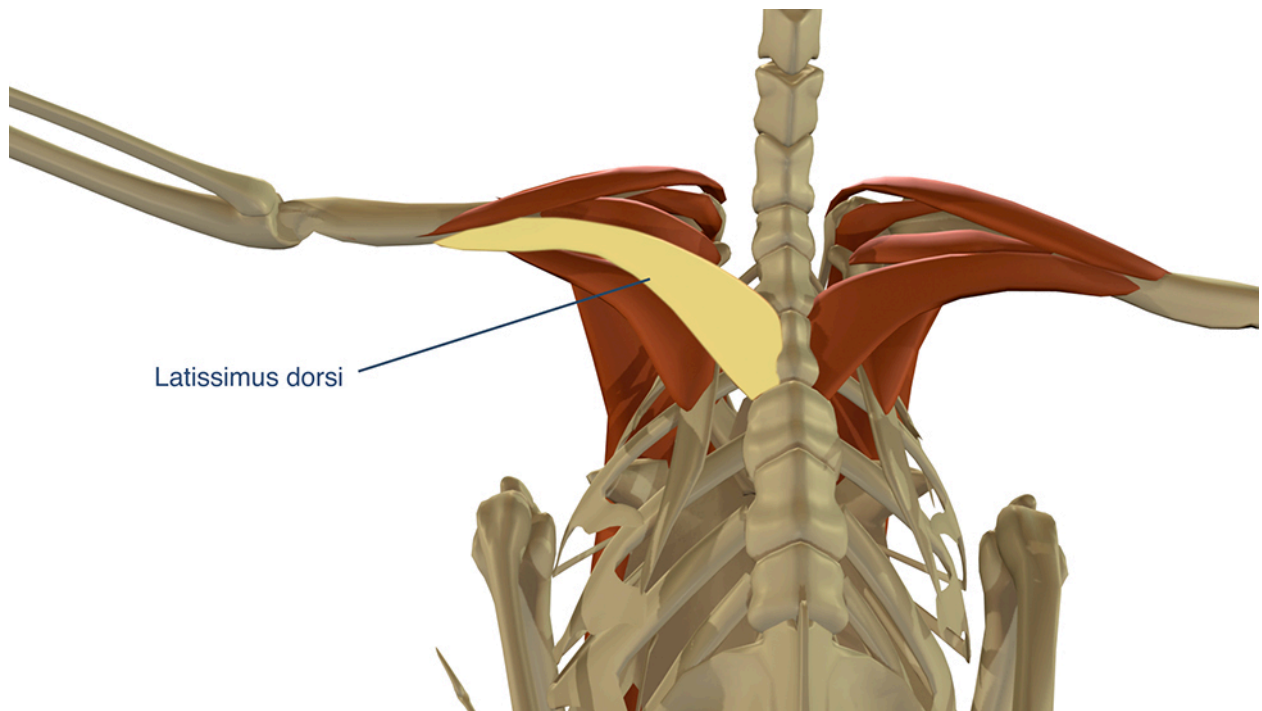
Figure 11.14. Movie Two animation, emphasizing the Latissimus dorsi muscle.
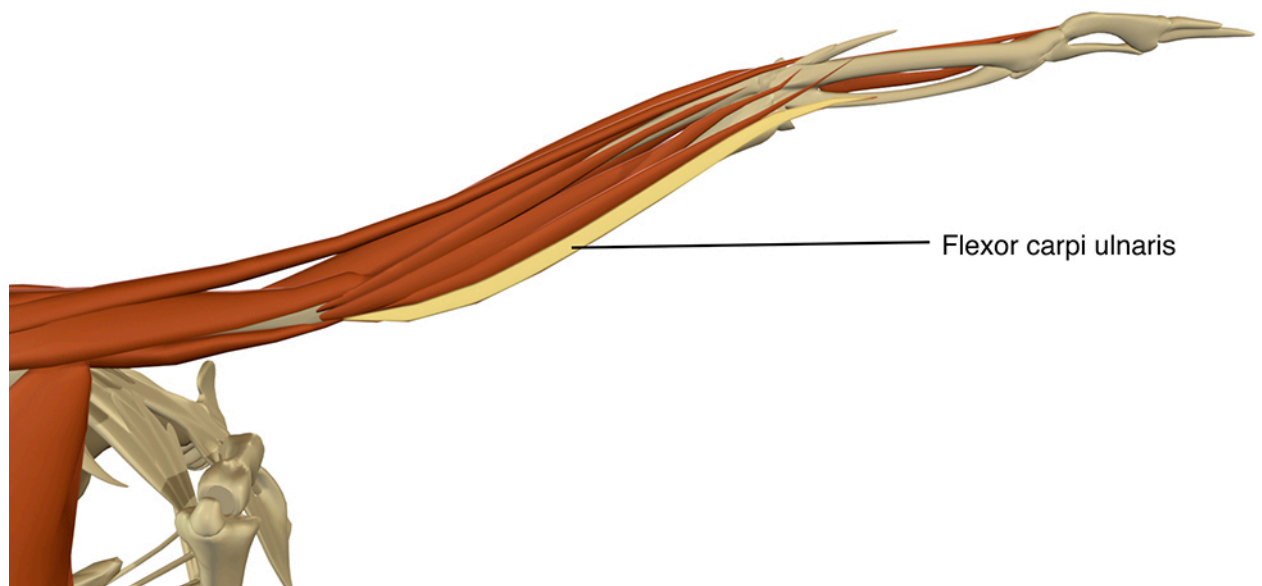

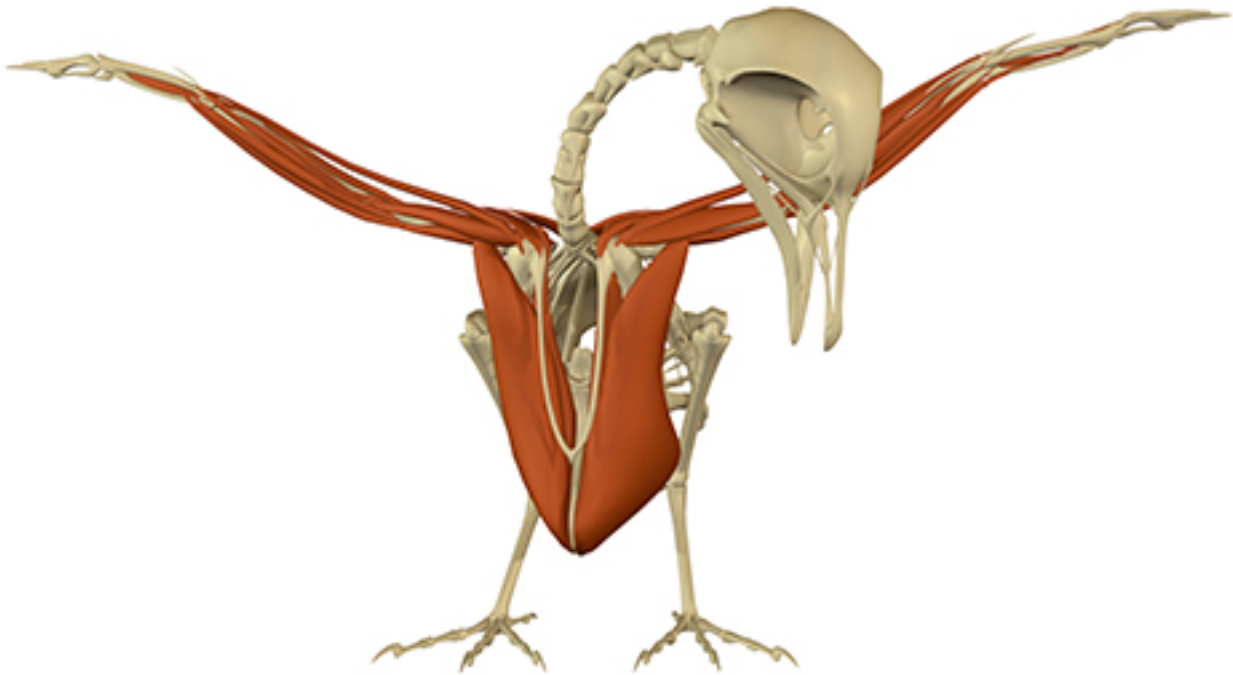**Figure 11.15**. Movie Two animation, emphasizing the Flexor carpi ulnaris muscle.

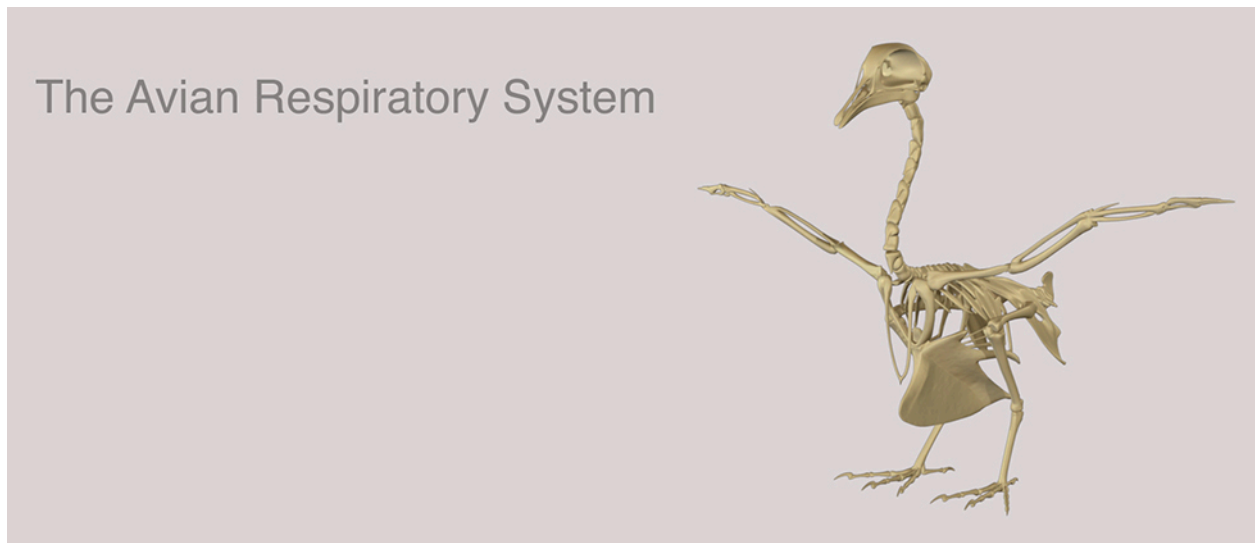**Figure 11.16**. Movie Two animation, the bird raising each wing.

Figure 11.17. Introduction to Movie Three animation, The Avian Respiratory System.
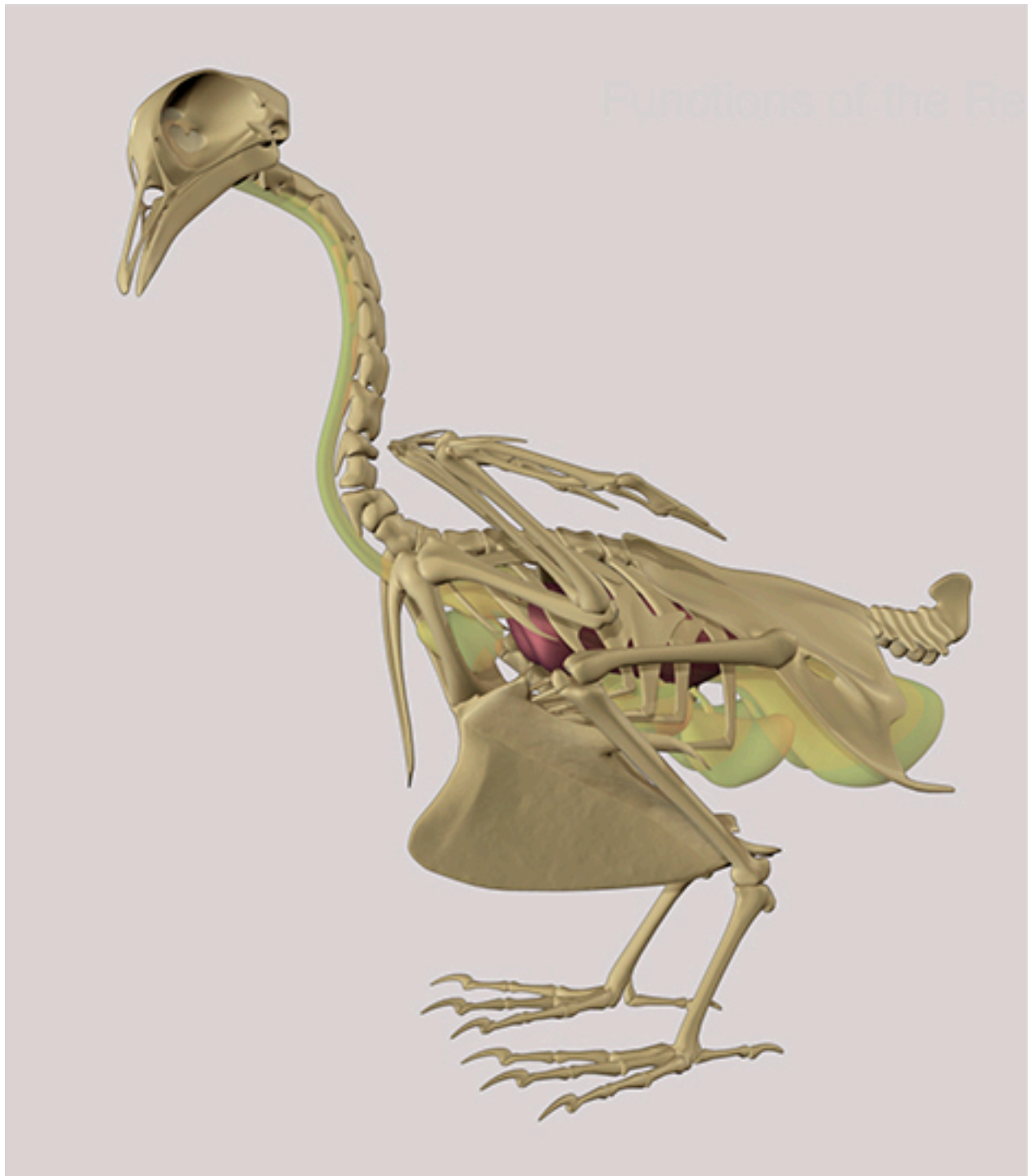
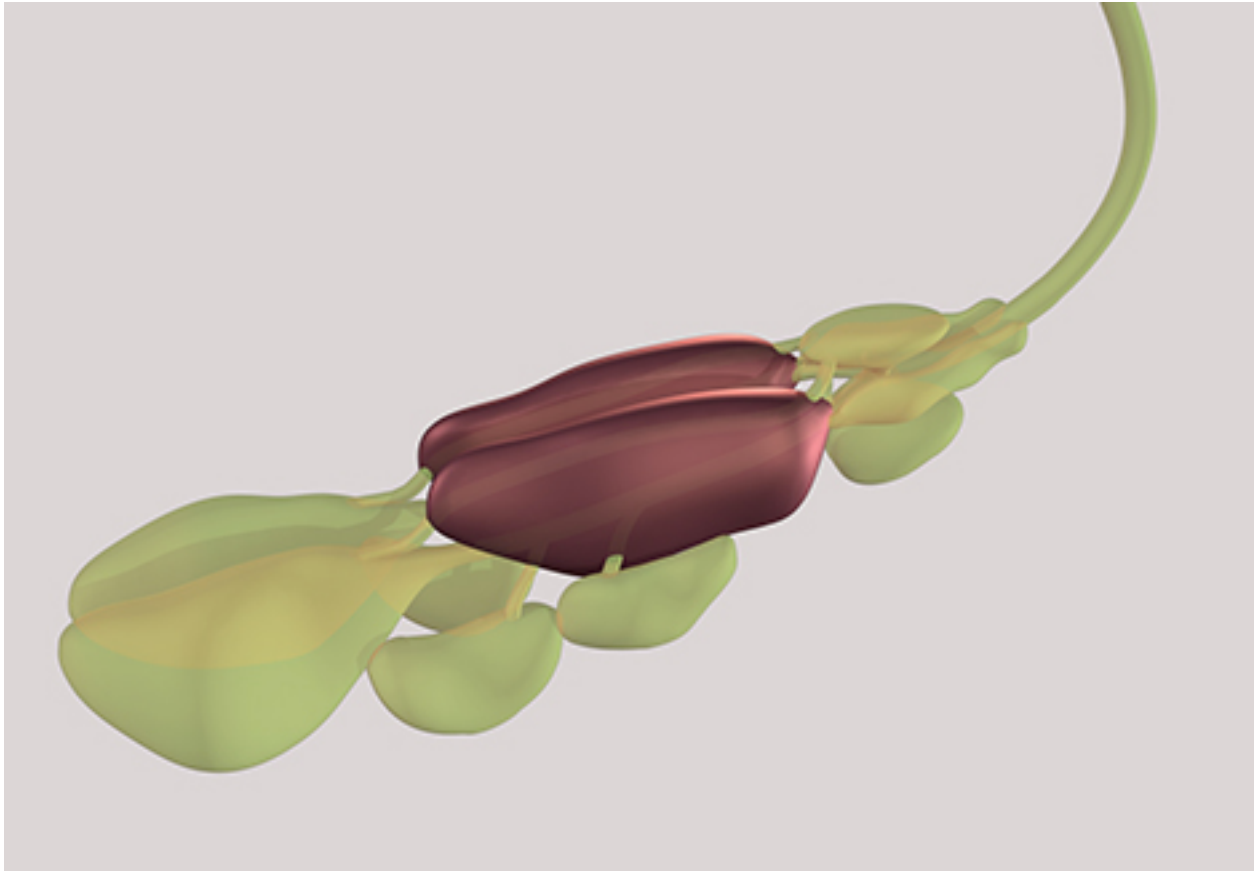**Figure 11.18**. Movie Three animation, the respiratory models within the skeleton model.

Figure 11.19. Movie Three animation, the isolated models of the respiratory anatomy.
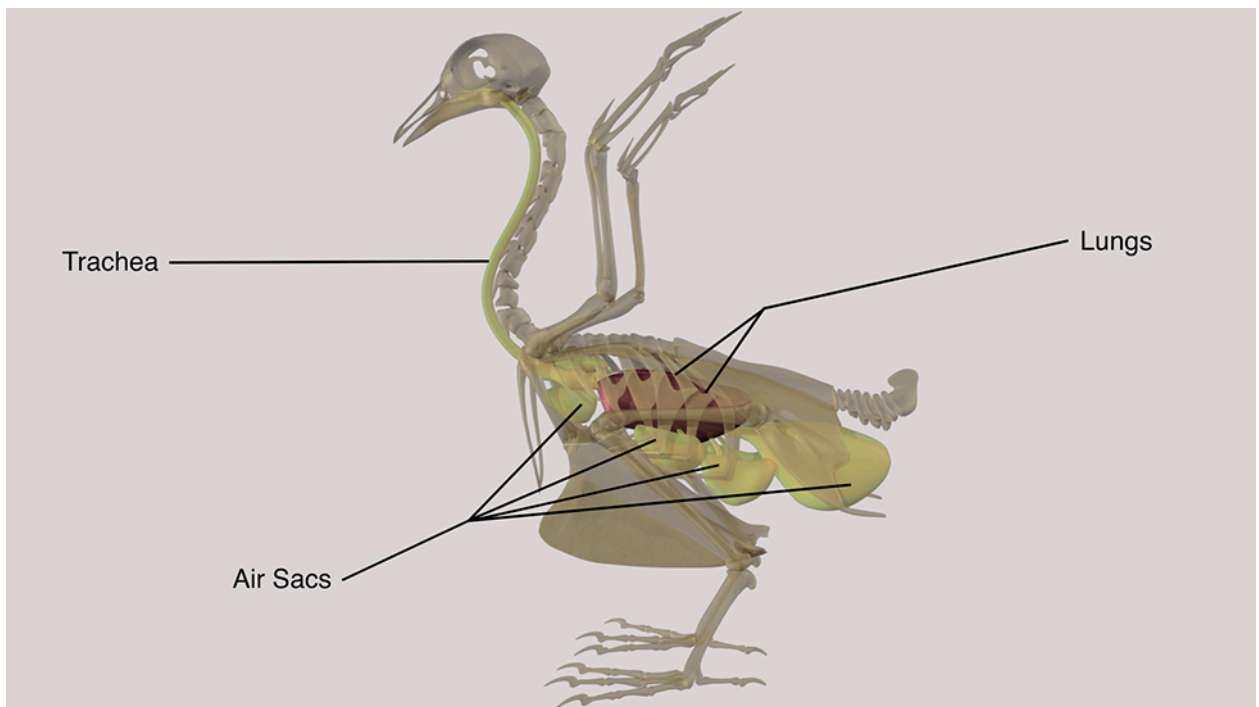

Figure 11.20. Movie Three animation with labels created in AfterEffects.
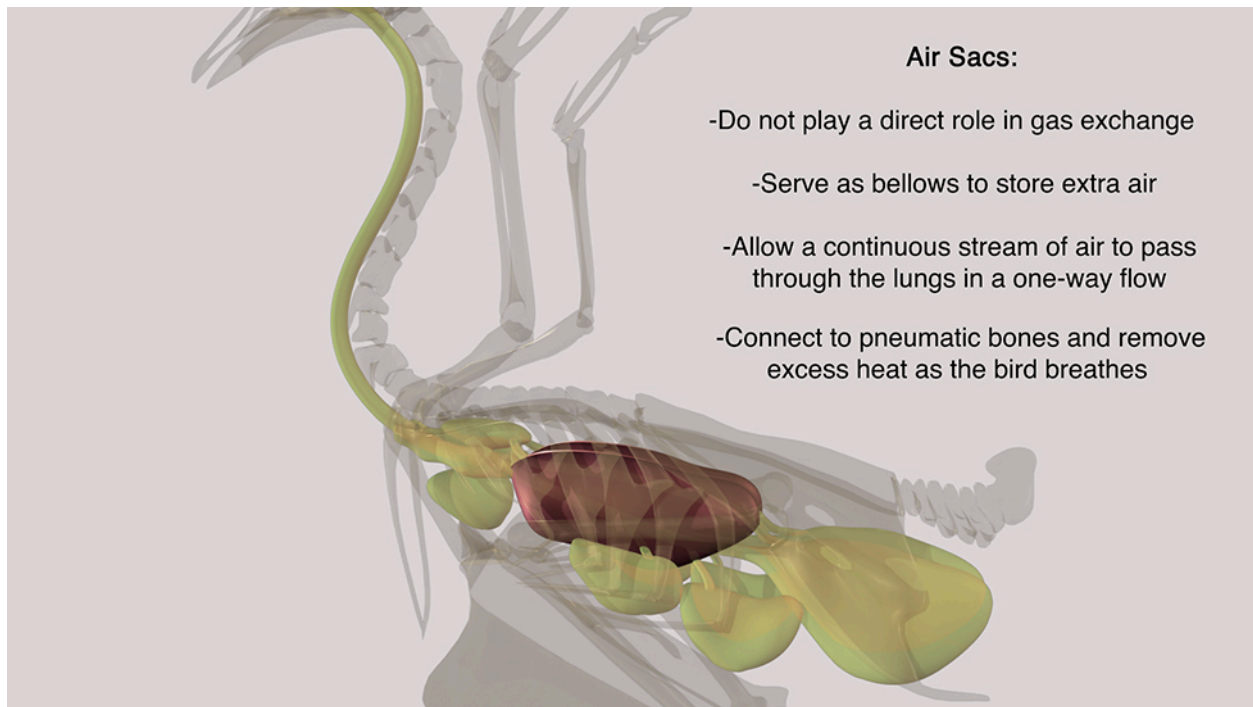
Figure 11.21. Movie Three animation, text elements created in AfterEffects.
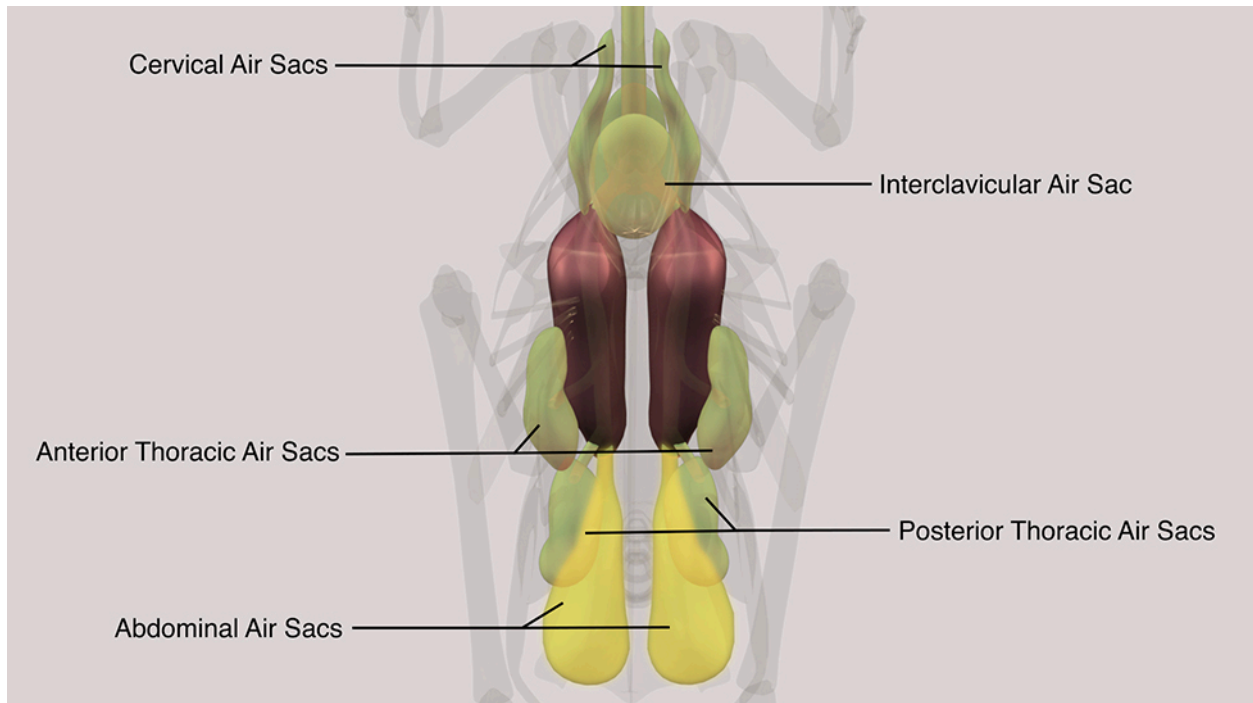

Figure 11.22. Movie Three animation, emphasizing the air sacs with yellow highlights created in Photoshop and labels created in AfterEffects.

There were a few sections of the Respiratory System animation that required the use of a mask, which was necessary when illustrating the movement of air through the respiratory system. This was completed by importing a PNG image of the colored air into the AfterEffects file, adding a mask to this PNG, and animating this mask to slowly reveal the PNG of colored air (Figures 11.23 – 11.24).
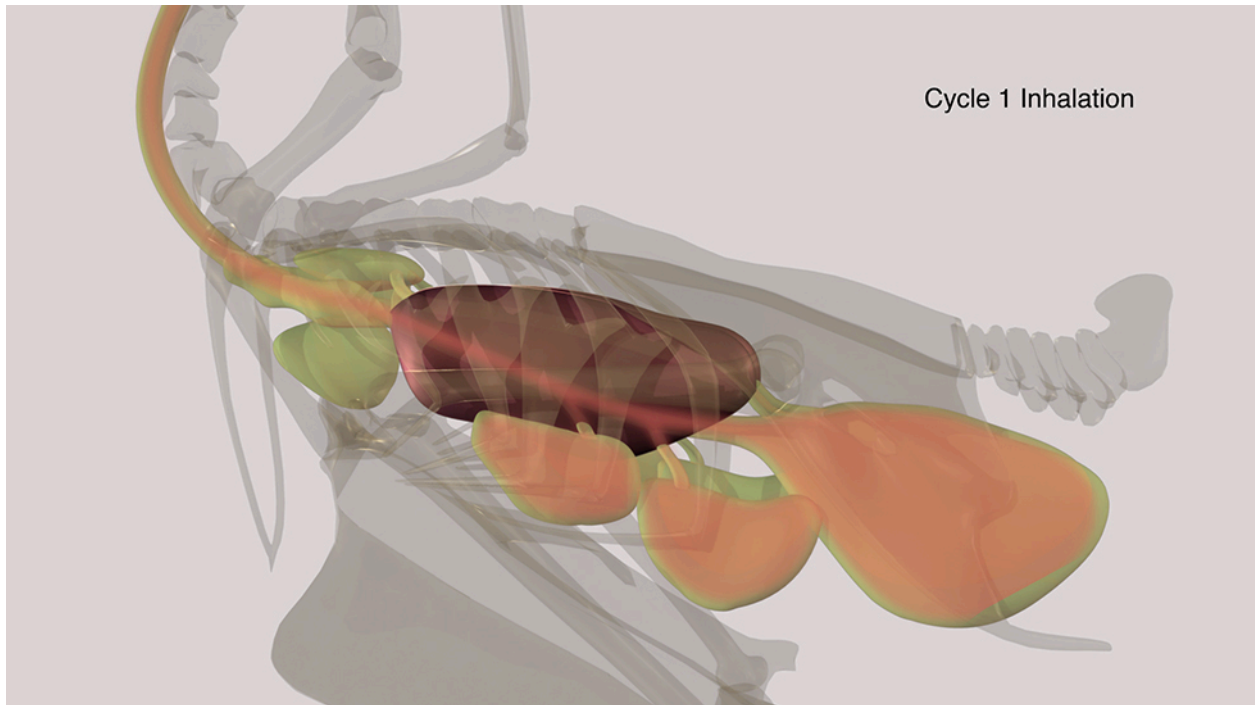

Figure 11.23. Movie Three animation, focusing on the flow of air into the avian respiratory system using a red color created in Photoshop and revealed in AfterEffects using a mask.
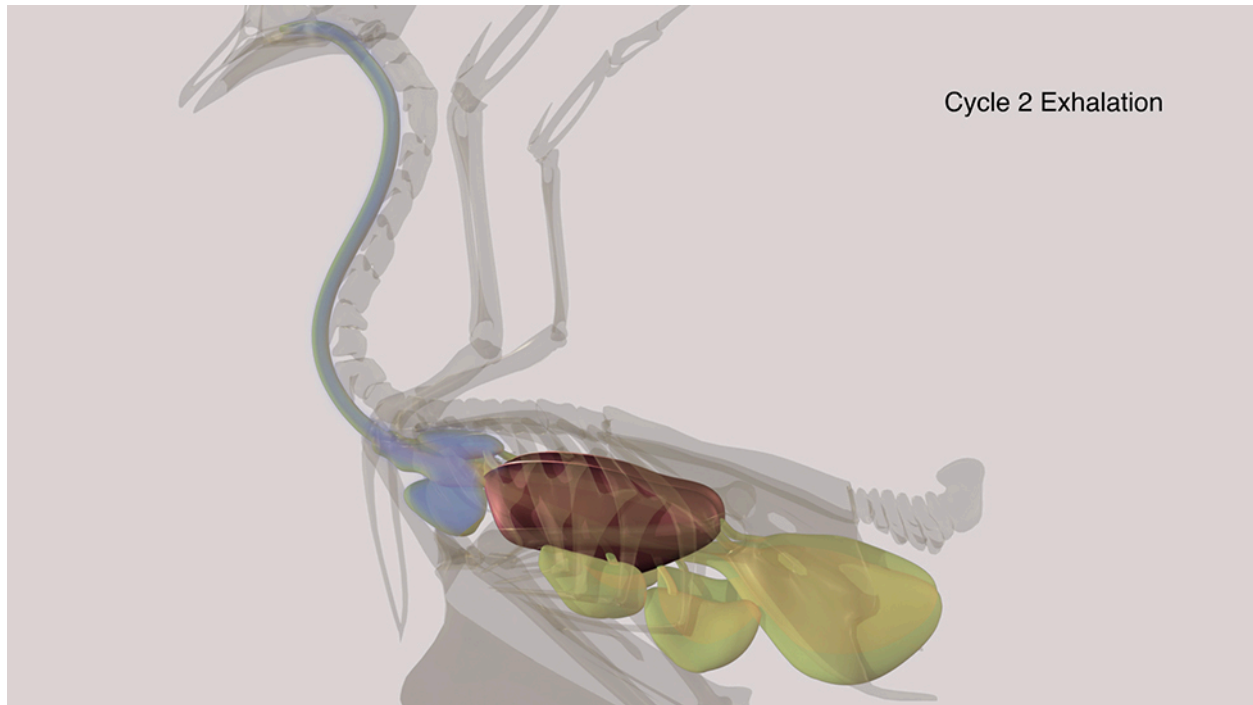
Figure 11.24. Movie Three animation, focusing on the flow of air out of the avian respiratory system.

This same method was applied to simulate air traveling through and leaving the respiratory system. To make the text and labels appear more subtle and natural, the transparency of each text element was animated so that they appeared to fade in and out, instead of abruptly appearing and disappearing.

At various points of each movie, I found that some of the animated PNG sequences had a pace that was a little too fast. Instead of going back into Maya and re-rendering these sequences with more frames, I utilized the stretch tool available in AfterEffects. This was useful in stretching the sequence to about 150-200% and made the sequence last longer, therefore decreasing the amount of time where no movement was occurring in the animation. This made for animations that flowed more smoothly to produce an overall more interesting product.

Once each animation was completed in AfterEffects, they were rendered separately as .mov files (QuickTime movies). This file format produced the highest quality product, though it made for a very large file size. An .mov file was chosen for the final product since it would be compatible with any computer operating system, playing automatically in QuickTime player on a Macintosh and Windows Media Player on a PC. It was important that this educational animation maintained the same quality and appearance no matter what computer it was viewed on. It was originally intended that these .mov files would be burned to DVD for the final form of delivery, but I chose not to do this for a number of reasons. First, DVD's (as well as CD's, and virtually any other sort of discs) have become relatively obsolete. Many people now watch movies or stream data through the Internet or the "Cloud". Physical discs have

become so out of date that new Macintosh computers are not even being built with disc drives anymore. If you want to be able to watch a DVD or install software through a disc onto a new Mac computer, you must purchase an external hard drive, or "super drive", to do so. I did not want to assume that everyone who viewed my animation would be in possession of a computer with a disc drive. If the viewer was in possession of the physical DVD, but had no means of viewing the animation on his/her computer, than the DVD would be completely useless. Therefore, creating the movie as only a .mov file ensured that anyone would be able to view the movie on any platform.

Another reason I chose not to burn the final animation to DVD was the fact that it rendered in very poor quality (as I found out after attempting to burn a few sample animations). DVD's can only be created at a size of 720x480 pixels, while my animation was rendered at 1920x1080 pixels. Since these sizes and aspect ratios were so different, the quality of the animation would be reduced by more than 50% in order to burn it to a DVD. Since reducing the quality of my images would have ruined the point of my high quality animation, I naturally chose not to do this. As I mentioned earlier, though, using a DVD as the form of final delivery was not the best route to take anyway. In order to create files that were small enough for web viewing, the AfterEffects composition was reduced in size to 800x450 pixels. This produced a smaller product at the same aspect ratio as the large movies. The animations were then rendered as condensed .mp4 files (h.264), and were then small enough to be uploaded on Vimeo for viewing on the web.

CONCLUSION

The art of avian flight is so unique and complex that it will certainly continue to be the subject of in-depth study for many years to come. The animations that I have created have made an important contribution to the ornithological field, and will hopefully provide others with a greater understanding of avian flight. I believe that the three animations, whether viewed separately or as a group, present the viewer with a broad range of educational material focusing on the biomechanical requirements for flight. After viewing movie one, General Flight Adaptations, the learner will be able to list the skeletal adaptations that enable birds to fly. After viewing movie two, The Avian Pectoral Limb, the learner will be able to describe the importance and specialization of the avian wing, and explain the muscular adaptations of the wing and how these elements function during flight. After viewing the third movie, The Avian Respiratory System, the learner will be able to describe the importance of avian respiratory anatomy, list the importance anatomical structures, as well as describe the steps of respiration and the path of a breath through the system. Together, all three movies provide a relatively complete overview of general avian anatomy and the specializations that have evolved to make birds so unique.

I hope to continue to work on this project in the future, and would like to add at least two more animations to the completed movie. In order to provide the viewer with a more comprehensive overview of avian flight, I believe it is important to also understand the physics of flight as well as the act of landing. A fourth animation focusing on the physics and aerodynamics of flight would explain important topics such as the angle of attack, the generation of lift and forward thrust, the cambered wing, and the importance of overall wing shape. A fifth animation concentrating on the act of landing would explain various toe arrangements seen among birds and would describe how these differences are adapted for different life and landing styles. These two new animations, when combined with the previous three animations, would provide the viewer with a greater educational experience regarding the complexities of avian flight.

Throughout the production process of this thesis, I learned a great deal about new modeling and animating techniques as well as where my own limits and strengths lie. I hope to continue my pursuit of ornithological understanding and will continue to explore various aspects of avian flight. In the future I plan to expand my areas of study to include avian social and sexual interactions, migration patterns, and the ever so interesting path of avian evolution from predatory saurischian dinosaurs. This thesis has been greatly rewarding and I hope that my efforts will help to spark an ornithological interest in the hearts and minds of others.

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