Internal Anatomy

Skeletal System
The skeletal system (Figure 1) is highly modified to meet the structural and energetic demands of flight. Throughout the skeleton are examples of three types of adaptive modifications: rigidity, reduction and redistribution of mass, and modifications of the limbs for flight. Rigidity is increased by modifications of the structure of bones and by fusions between them. To improve balance during flight, most of the muscle mass controlling the wings and legs are located near the center of the body, producing a compact form. Locate the following structures on the mounted pigeon skeletons and note the modifications described below.

The bones
While maintaining strength, most of the bones are pneumatic, being hollow and filled with air spaces connected to the respiratory system. Internal struts add strength to some bones such as the humerus.

Skull
The bones of the skull (Figure 2) are generally fused providing protection to the brain while being of light weight. A light, toothless beak replaces the bony, heavy toothed jaw of reptiles. Beaks, of course, can be highly modified for different types of food and feeding behavior. One important vestige of birds’ ancestral relationship to reptiles is the jaw joint articulation between the quadrate and articular bones (compare this to the squamosal-dentary joint in mammals). Note the large orbits, as sight is an important sensory mechanism for birds. Within the orbit is the sclerotic ring (this may be absent in your specimen), which helps to support the eyeball. In the posterior part of the skull is a single occipital condyle, which articulates with the first cervical vertebrae. Reptiles likewise have a single occipital condyle, while mammals have four.

Neck
The necks of birds are very important for body maintenance and eyesight. Modification for flight has rendered avian forelimbs almost useless for any task other than flight. To make up for this lack of forelimb dexterity, the beak is used for many tasks such as preening feathers. To access hard-to-reach feathers on the back and tail birds require a flexible neck. Furthermore, as birds have immobile eyes, head movement and flexibility is required to focus on objects at various distances. Heterococelous (saddle shaped) vertebrae in the cervical region facilitate the extreme neck mobility required to carry out these tasks.

Thorax and Sternum
Posterior to the cervical (neck) vertebrae are five fused thoracic vertebrae (Figure 1). Supported by these vertebrae are seven sets of...
two-pieced ribs, composed of a vertebral rib and a sternal rib. Overlying flaps projecting off the ribs called uncinate processes help to stiffen the rib cage.

The sternum is the highly modified breastbone. In flying and swimming birds the keel or carina is enlarged for flight muscle attachment (called a carinate sternum). Flightless birds in the order Struthioniformes such as Ostriches have a keelless or “ratite” sternum.

**Pectoral Girdle**

The pectoral girdle (Figure 3) is made up of the sternum, clavicle, coracoid and scapula. The clavicles come together to form the furcula, or “w Wishbone”. The furcula provides a flexible attachment site for the breast muscles and along with the coracoids act as struts that resist pressure created by the wing stroke during flight. Flight muscles running from the sternum to the relatively short and stiff humerus elevate and depress the wing. The tendon of the wing-lifting supracoracoideus muscle runs through the trioseal canal found on the dorsal end of the coracoid, where the coracoid, scapula and clavicles meet.

**Pelvic Girdle**

Again, there is an extensive fusion of bones of the pelvic region to provide stiff support for the legs in order to deal with the stress of take-off and landing. The three pelvic bones, the ilium, ischium and pubis are fused to form the innominate bone (Figure 4). Fused dorsally to the innominate bone is the synsacrum to make one complete unit of bone. The synsacrum is a fusion of the sacral (pelvic) and 6 caudal vertebrae. At the end of the spinal column is the pygostyle, a fusion of the final few caudal vertebrae. The pygostyle supports the tail feathers and musculature.

**Wing**

The avian wing contains the usual arm bones of reptiles and mammals, but in a highly modified form (Figure 5). The humerus is rather short compared to the total length of the wing, as it must withstand the pulling of the flight muscles. Note the large crests on the proximal humerus for the attachment of the flight muscles. The radius (slightly thinner than the ulna) and ulna form the support for the mid-wing. On the ulna are small bumps, the attachment sites for the secondary feathers. Two separate wrist bones, the radiale and unlnare, are immediately distal to the radius and ulna. The distal (outer) wing or “hand” bones are highly fused for strength and feather support and form the carpometacarpus. The first digit or pollex supports the alula, a small feather used to control air flow around the wing.

**Leg and Foot**

The upper leg is composed of a fairly standard femur, but the lower leg and foot are highly modified by fusion (Figure 6). Distal to the femur is an extremely reduced fibula. Next to this is the tibiotarsus, a fusion of the tibia (a lower leg bone) and some tarsals (foot bones). Of course, between the femur and the fibula and tibiotarsus is the knee, whose location in birds is often confused. Distal to the tibiotarsus and fibula is the tarsometatarsus, an extended fusion of the foot bones. This lengthening adds extra leverage for running, landing and take-off. Note that birds walk on their toes (as opposed to foot and toes, as seen in humans) and are thus digitgrade.

**Musculature**

The dominant muscles are of course the flight muscles, which can account for 40% of the body weight of a bird. The mass of muscles, as in the skeleton, is concentrated ventrally, in the center of gravity, for aerodynamic stability. Little back musculature is required for support, as the thoracic, sacral and lumber spinal regions are fused and consequently very stiff.

The two primary flight muscles are the pectoralis major (largest muscle in the birds body) and the supracoracoideus (Figure 7).
The pectoralis major acts to depress the wing in the downstroke. It originates on the carina of the sternum, furcula and sternal ribs and inserts (where the muscle acts) on the proximal ventral surface of the humerus. The supracoracoideus is the primary elevator of the wing in the upstroke and is most important for take-off. The supracoracoideus lies internal to or beneath the pectoralis major. It also originates on the carina of the sternum, the furcula and sternal ribs. Insertion on the proximal dorsal surface of the humerus is by way of a tendon that travels through the trioseal canal and acts as a pulley to lift the wing. With this design the large supracoracoideus can remain in the ventral (below the wing) center of gravity while still being able to raise the wing.

Muscles are composed of both red and white fibers. Red fibers provide a continuous supply of aerobic power for sustained flight, fueled by the metabolism of fat and sugar. White fibers are powered by products of anaerobic respiration and are capable of providing only short burst of energy for powerful, rapid flight.

**Circulatory System**

Sustained flight is metabolically demanding and requires an efficient circulatory system to provide oxygen and fuel to the body while removing toxic metabolites for excretion. Like mammals, birds have a double circulatory system with a separation of the pulmonary (to lungs) and systemic (to body) systems to prevent mixing of oxygenated and deoxygenated blood. In birds and reptiles however, blood passes to the lungs via the left systemic arch, whereas in mammals blood travels to the lungs via the right systemic arch. Like mammals, birds have a four-chambered heart, compared to the ancestral reptilian three-chambered heart. The four-chambered heart is probably necessary to meet the greater aerobic demands of endothermy. Bird hearts are proportionately up to 40% larger than mammals while they beat only half as fast as a similarly sized mammal. The larger avian heart therefore provides a greater stroke volume of blood to achieve a similar cardiac output.

**Respiratory System**

The avian respiratory system is extremely efficient in order to meet the enormous energetic demands of sustained flight. Truly unique structures and air flow pathway help to distinguish the avian respiratory system from that of reptiles and mammals. The air-flow of reptiles and mammals is two-way, as air passes in and out of the lungs along the same pathway. Birds, in contrast, have an efficient one-way air flow system that allows a continuous flow of air to pass through the lungs. A complete respiratory cycle takes two sets of inhalation and exhalation (Figure 8). Air sacs (Figure 9) are auxiliary structures that help to deliver air through the respiratory tract but are not directly involved in O2 and CO2 exchange. Oxygen and CO2 exchange only occurs in the lungs. Air sacs are fairly large and take up about 15% of the volume of the thorax and the abdomen. Air sacs also help to dissipate heat, as air passing through the air sacs absorbs heat and is then expelled from the body. Birds also lack a diaphragm thus breathing is thus powered by the intercostal muscles. Finally, instead of using a larynx to produce sound (as in most mammals), birds use an analogous syrinx (located in the trachea) for sound production.

**Digestive System**

The avian digestive system follows the general vertebrate plan of mouth, esophagus, stomach, small intestine and large intestine.
(Figure 10). Of course there are many modifications from this general plan, due in part to diet and the lack of true teeth and chewing. In many birds a part of the esophagus is expanded into a crop. The crop stores and softens food and regulates its flow through the digestive tract. The stomach of birds is divided into two chambers, the proventriculus (glandular stomach) and the gizzard (muscular stomach). Food first flows through the proventriculus where it receives digestive enzymes. Food then enters the gizzard, which essentially functions as teeth, where it is mechanically broken down to maximize surface area contact for the digestive enzymes. The stomach and crop can vary considerably between species with different diets. Granivores, for example have a well-developed crop, proventriculus and gizzard. Birds that primarily consume easily assimilated fruits, berries, and nectar have a very reduced gizzard. In many birds, particularly herbivores, the small intestine ends with blind pouches called caeca. Caeca contain bacteria that aid in the digestion of cellulose plant material. At the end of the digestive tract is the cloaca, a holding area for wastes and products from the digestive and urogenital systems. The cloaca opens to the outside by means of the vent.

Figure 8. Schematic diagram of the pattern of air flow through the avian lung.
Figure 9. The distribution of air sacs and the functioning of the avian lung.
Figure 10. Thoracic and abdominal organs.