The Morphology of Digital Creatures

Tim McLaughlin, Stuart S. Sumida Ph.D.

Contents

Presenters:

1. Tim McLaughlin
2. Stuart S. Sumida, Ph. D.

1 Course Description

Whether realistic or based upon novel combinations of known morphologies the articulation and animation of digital creatures is informed by understanding of human and animal anatomy. This course connects the biomechanics and environmental adaptations of living and extinct organisms to computer graphics techniques used to represent bone, muscles, and skin of digital creatures.

Three broad topics -form, articulation, and movement, are discussed from both the biological and digital recreation points of view. It is the held belief of both authors that as the art of creature design benefits from adherence to rules of biological design, so too does the craft of digital creature construction gain from knowledge of structure of biological creatures. Each topic is therefore introduced through descriptions of biological issues and concluded by discussion of how computer graphics techniques mimic their biological analogs.

One of the primary goals of the course is that the information presented be undiminished by changes in technology. With that in mind, the information communicated includes few descriptions of specific techniques. Those descriptions that are employed are only for the purposes of examples that illuminate the broader concepts at hand.

This course is not intended to be an exhaustive primer for biological studies. Nor does it purport to address the craft of digital creature creation for all media. However, it is hoped that the information communicated here will provide a basis for reflection on similarities between biological and digital creature morphologies, and serve as a springboard for deeper investigation into the topic.

2 Prerequisites

This course is designed for students and professionals who are interested in or who work in the area of digital creature design and development. For students, the course will provide exposure to the concepts of approaching digital creature development from a tool agnostic and biologically respectful perspective. For professionals the course will offer a formalized linkage between how form and function dictate the structure of both biological and digital creatures. Basic comprehension of anatomy, 3D modeling, and animation is required.

3 Introduction

Digital creatures can be realistic, fanciful, animal-based, or any combination thereof. Regardless of the combination, these creatures have certain properties: (1) they all have structure, i.e. anatomy; (2) their anatomies, whether realistic or not, are inevitably based upon combinations of anatomical structures known from actual organisms; and (3) those anatomies must function properly according to physical laws of the environments in which they are found. Correlated to these rules: (A) development of realistic creatures benefits from an understanding of structure and mechanics of those organisms they seek to imitate; (B) novel or fanciful features may generally be dissected into component parts based upon realistic creatures. In a sense, nature has started the natural experiment, providing organisms from which component parts may be picked and chosen for use in character design. Throughout all of these possibilities, basic anatomical structure remains a key. Using examples from comparative animal and human morphology, and the digital design of characters, key features of body construction may be reviewed to optimize the most natural and realistic behaviors of body elements including basic skeletal anatomy; the behavior of articulations within the skeletal system; limb orientation and body posture; locomotor step cycles; and features of aerial, aquatic, and terrestrial locomotion. Attention to these principals and successful re-creation of their synthetic equivalents results in the design and performance of digital creatures that fit and function believably within their cinematic environments.

4 Objectives

The principal goal of this course is to contribute to the body of knowledge in the area of digital creature development. The pedagogical approach taken is to formally connect aspects of the morphology of biological creatures to the morphology of digital creatures. It is likely that artists in the field of digital creature development have made these connections themselves at some level depending upon their experience and project types.

The authors are not supposing it to be a novel concept that a linkage exists between biological and digital creature morphologies. Instead, an attempt is made to deepen the understanding of the factors that drive biological design. Through that vein of knowledge we hope to reinforce the logical argument that the audience's suspension of disbelief requires a visual connection between the digital character's form and behavior and that of known organisms.

5 Meaning

Does the evolution of digital creature development techniques track with biological evolution? Over the millenia, biological evolution has progressed from simpler to more complex. This has involved two parallel progressions—increase in complexity, and the acquisition of key innovations.

Key innovations in biological creatures are comparable to breakthroughs in techniques, algorithms, and processing power for digital creatures. In both forms the result is increased complexity and "adaptive radiation" of new creatures (species) that take advantage of those innovations. These new creatures are able to expand the habitable terrain beyond the niches occupied by their predecessors. Articulated digital characters in theatrical film went from the cameo-like exposure of the Stained Glass Knight in 'Young Sherlock Holmes' (1985) to leading roles in 'Casper' and 'Toy Story' (1995) in ten short years. Twelve years later digital creatures of even greater complexity are performing on hand-held devices, game consoles, and across machine-to-machine networks.

There are key dis-connects, however, between the evolutionary track of biological creatures and the development of digital creature techniques. The biological reality of the evolution of organisms necessarily depends on populations of the organism, whereas a single digital creature may exhibit unique yet functional attributes. Also certain systems, such as the digestive system, circulatory system, and most homeostatic regulatory physiological systems have no digital analogs.

The systems that provide structure and facilitate motion have proven to be rich with analogs between biological and digital evolution and are likely to remain the primary areas of convergence. As the use of dynamic systems for muscle action, collision detection, balance, and behavior become more accessible and less computationally expensive it is supposed that the structures of digital creatures will track ever more closely in both form and function to their biological counterparts.

6 Form

6.1 Organisms Sculpted by Their Environment

Some dependable rules can address the basic issues of environmental constraints on organismal/character design. In this course, adaptations to terrestrial locomotion dominate the discussion. Those four-legged animals that live and move in the terrestrial realm tend to show a wide variety of body morphs or "bauplans", generally controlled by a combination of factors: diet (you are what you eat), plus speed and style of locomotion. Animals living in the aerial and aquatic environments, and humans with an erect posture present unique sets of biological pressures and thus particular sets of design solutions.

6.1.1 Posture, limb placement and head placement

Amongst quadrupedal mammals, and most likely dinosaurs as well, what an organism eats is critical. Carnivores consume food that is not protected by the undigestable cell walls of plant material ("roughage"), and thus have less to process in the digestive tract, resulting in a short tract and relatively leaner body. This in turn provided for a more flexible backbone that allows for dorsal- and ventral-flexion during high speed locomotion, (usually) a rotary gallop, a jaw joint in line with the teeth (like a scissors), and forward directed eyes provided depth perception due to overlapping visual fields.

On the other hand, herbivores must consume vast quantities of food to acquire adequate nutrition beyond the undigestable roughage of plant materials, resulting in a barrel-shaped body with a stiff backbone under which the mass of guts is hung. (You can generally ride an herbivore, but not a flexible-backed carnivore.) High speed locomotion is most frequently a transverse gallop, the jaw joint is out of line with the tooth row resulting in a more nut-cracker-like functional complex, and eyes face to the side for broader coverage at the expense of depth perception.

In the aerial and aquatic environments, the impact of drag on movement is a more dominant selective factor in animal shape. Thus in the viscous environment of water, or the similarly viscous environment of movement through air at high speed, body shapes converge on a fusiform or torpedo shaped body to facilitate slipping through the resistant medium through which an animal moves.

The upright posture of humans is frequently misidentified as "bipedal". Remember, birds are bipedal, as are kangaroos, and many types of dinosaurs. Post-crawling humans are more properly referred to as "orthograde" a term indicative of the backbone being perpendicular to the substrate, and the optical axis perpendicular to the body axis. This is in contrast to a pronograde posture wherein the backbone is approximately parallel to the substrate and the optical axis is parallel to both the substrate and the long axis of the body. Orthograde posture results in hands freed to use tools, a body wider from side-to-side than from back to belly, and a skull balanced on the top of the vertebral column as opposed to being cantilevered out beyond the terminus of the backbone. In humans, the most important determining factor in body shape and proportions is whether one is female or male. Females generally have longer legs, shorter torsos, more subcutaneous fat, and a fat distribution pattern that is essentially bilaterally symmetrical. On average, males tend to be taller, heavier have longer torsos, and shorter legs. Juveniles present yet another layer of complexity.

6.1.2 Mass and size related issues

Organisms of extremely large size are generally found in terrestrial or aquatic environments. The largest of animals live in the sea where water helps to buoy up body mass. Terrestrial animals like elephants, or any number of extinct, nonavian dinosaurs generally adopt what is known as a "graviportal" limb position wherein heavy limbs are held in a straight, columnar fashion in order to more easily deal with the downward drag of gravity on the body's mass.

6.2 The Digital Expression of Volume and Mass

Fundamentally, a digital model is a shell composed of surfaces. The skin of a biological creature cannot hold its form without the underlying muscles, bones, connective tissues and organs. The skin of a digital creature exists without need for support from underlying structures.

However, the form of a biological creature is determined by the expression of those underlying structures through the skin. The bulges, cavities, folds, and ridges that comprise the features of a biological creature are the skin's response to being draped and pulled across bones, muscles, connective tissues, and organs. It is important to understand how the form of the digital creature could conceivably be built up from the inside, that bone position and size, and the volume of organs and muscles must be considered for a realistic look.

In this sense the artist tasked with creating a digital creature from artwork is acting much like a paleontologist trying to infer form and function of an extinct creature from of a collection of fossilized parts. Each uses information about the morphology of known organisms as a basis composing the structure of the imagined creature.

6.2.1 Source Material

In the art of illustration sometimes a line is just a line and shading exists purely for graphic effect. More often, however, an artist draws a line or sculpts a ridge in an effort to communicate the presence of an object or a change of material. When converting a creature design from concept art to a three-dimensional digital model the process begins with evaluation of the concept design material. Dissecting the artwork in order to understand the artist's intention is key to the effort of creating a three-dimensional digital model of the creature that is faithful to the design.

Concept art, or source material, may consist of flat artwork, photographic reference, maquettes, rough digital models, or some combination of these. The challenge faced by the digital artist is to interpret the artwork correctly in terms of mass, proportions, and structure.

Orthographic artwork, once digitized and brought into the computing environment, provides views of the character design from which accurate assessments of size and position of features can be made. Perspective drawings are not as reliable in their depiction of size relationships, but are more commonly available. Photography of maquettes, though non-orthographic, may be useful assuming that the lens and position of the photographic camera can be recreated in the 3D modeling tool. Relative to other forms of reference art maquettes are the most reliable sources of information about anatomical features. Through the sculpting process the creature designer has already been faced with the task of relating forms of the creatures body in three dimensions.

An accurate recreation of two-dimensional designs into three dimensions does not always produce an aesthetically desirable result. The relationship of features, volumes, bulges, concavities, that worked in 2D, or were possibly not resolved in the design, become exposed when they are made whole in three dimensions.

Figure 1: Concept art of Saphira from *Eragon* featuring a nearly orthographic view in profile, but with perspective used to show the far legs, and feet. Body mass, limb size, and muscle structure are implied through line and shading.

6.2.2 What Do Forms Represent?

A three-dimensional model can be described in objective terms as a collection of interrelated bulges, cavities, ridges, and creases. As subjective viewers we interpret these elements as representations of anatomical features. When viewing a photograph of a horse we can, with relative confidence, identify the top of the shoulder blade (withers), the curve of the hind leg muscles, and the mass of the gut. What about the same features on an alien? Do we care? We care because fat and muscle deform differently and behave differently when in motion. A bulge may be muscle, organ, or bone. In this case of bone there will be deformation around and over it, but the bone itself should not change shape. The plausibility of the character is determined by its form in combination with its articulation and performance.

It is rare to be provided artwork of digital creatures, particularly fantastical creatures, that includes anatomical drawings identifying the locations of bones, muscles, connective tissues and organs. The responsibility for identifying these elements falls primarily to the artists tasked with creating the animation rigging and deformation systems for the creatures. These artists must make subjective decisions about the anatomical features of digital creatures in order to create systems which allow the creatures to move in believable ways.

So, what is a bulge? A bulge could represent fat, organ, muscle, cartilage, or bone. If bone, then is the bulge a connection point where bones meet? If so, then it is a sign-post for the location of animation joints. If muscle, does the bulge represent the flexed shape or the relaxed shape of the muscle?

Ridges portray the convex curvature of bulges, but with significant curvature in only one direction. A ridge is more likely to represent bone, cartilage, muscle or connective tissue -tendons and ligaments. Though ridges can also represent veins, they most often represent structural forms ridges and are therefore not likely to show appreciable bending along their length.

Bulges and ridges communicate the existence of anatomical elements under the skin. Cavities and creases convey the opposite -the absence of support for the skin. Cavities and creases often represent areas of great articulation. A cavity often exists in the motion path of appendages such as the space behind the knee or under the chin. Creases (wrinkles) identify areas of compression and/or changes in material. As with muscles, it is important to determine if a crease is the result of tension, and if so, what the neutral shape would be.

6.2.3 Neutral Poses

If a wide range of motion is expected from the performance of a digital character then a neutral pose is the most efficient form for modeling, rigging, and setting deformations. A neutral pose is generically defined as the positioning of each body element such that it is at the midpoint of its expected range of motion. For example, the motion for the lower arm ranges approximatly 160 degrees, from just a few degrees past the position of alignment with the upper arm to the other extreme of being compressed against the upper arm. Given these two extremes, a neutral position for the lower arm is a right angle to the upper arm plus about 30 degrees in the obtuse direction. When compromises must be made it is better to err on the side of opening up the joint -being closer to the in-line position with the parent joint. This is true only because the deformation systems in most 3D packages resolve extension of surfaces (stretching) more cleanly than compression.

7 Articulation

7.1 Basic skeletal anatomy

7.1.1 Joint and musculoskeletal system functions.

Although muscles drive the movement of skeletal systems, it is the skeleton that provides the raw limitations and ranges of potential movement. As an example, the number of bones in a mammalian body number in the hundreds, resulting in even more articulations, or joints. Here, the joints are the focus of examination as they provide the data for potential movement of an organism. Tables 1-3 list most of the major joints of a human body. While not exhaustive, they still enumerate more articulations than would normally be placed into a digital creature. However, the sum total of the movements described in these tables provides digital artists a summary of the range of movements to be mimicked when rigging a creature. The course here does not allow for individual description of each joint. Rather, the tables are provided as a reference data set and three examples of joints considered either as critical to proper movement or as useful case studies are presented below.

7.1.2 Skull, neck, and spine articulation

Example 1: The Atlas-Axis Joint of the Upper Neck Head are frequently designed as a ball-and-socket articulation for the skull balanced on top of the vertebral column analog. In real life, the flexion and extension of the head (“yes” movement) is separated from the rotatory movement (“no” movement) by one segment. The former takes place between the skull and cervical segment one (atlas vertebra), whereas the latter between cervical segments one and two (atlas and axis vertebrae). Separating these two movements from one another is more expensive but results in a more realistic looking movement and avoids the look of a “bobblehead doll”.

7.1.3 Fore-/Upper limb articulations

Example 2: Movement of the Scapula (Shoulder blade) In humans the shoulder blade (scapula) has only an indirect attachment to the body axis of bones via the clavicle (collar bone). In many fast moving quadupedal animals, the clavicle has been lost, leaving limb attachment via a muscular sling. In both cases the scapula is capable of a vast range of complicated movements. In humans, the posteriorly placed scapula can rotate much in the manner of a steering wheel. Additionally, it can slide up and down, as well as move medially toward its opposite mate. In all of these cases, such movements have profound effects on the more distally placed and dependant humerus and remainder of the arm. In pronograde quadrupeds, the completely free-floating scapula can move fore and aft along the side of the body in a pendular motion, adding to the excursion of the forelimb during locomotion.

7.1.4 Fore-/Upper limb articulations

Example 3: The Knee is Not a Simple Hinge Joint In humans as well as in other mammals and probably pronograde bipedal dinosaurs, the knee is far more than a simple hinge joint. As the knee flexes and extends, the distal condyles of the knee roll along the upper surface of the tibial plateau. Furthermore, contrary to common description, the knee is capable of as much as 15 degrees medial/lateral rotation. The ability to insert rotation into this joint allows for a much smoother capacity for animating this joint. Thus, a simple pinpoint hinge presents an oversimplification of a knee articulation.

7.2 Kinematic systems

The process of constructing a digital musculoskeletal system is often called rigging. The name implies the assemblage of a support structure and aptly so, though the support that is required is for articulation rather than for structural support. Rigging begins with the placement of articulation points and determination of how many points of articulation are required. Next, a system for relating the articulation points to one another and to the skin of the creature is put in place. This control system includes inputs for animation and may include the use of procedural elements for the replication of physical properties

7.2.1 Bones

Biological creatures, vertebrates at least, animate because bones move. The skeletal structure, whether driven by muscle action or external forces, articulates and carries the body with it. The articulation points in digital creatures are bone analogs. These digital bones are driven by translational and rotational input. Each software package has its own flavor, or flavors, of digital bones but they all have common features: they can be moved, rotated, scaled in 3D space and they can be connected together. In their most simple form these digital bones have a pivot point and length. Most software packages graphically represent digital bones in such a way that the pivot point and length of the bone are visually easy to identify. For the purpose of articulating digital models any object with a transform will work.

As in a biological system, a single bone on its own cannot accomplish much. A single digital bone, disconnected from other objects, is simply a transform in 3D space. Connected bones, or chains, are something more. Individual bones in chains can vary in length. With limited exceptions, the pivot, or origin, point of a child bone is coincident with the end point of its parent.

Two-bone chains are used for arms and legs. Fingers are typically three or four bones chains. Spines are rarely made from fewer than two bones, and are commonly three to six bones in length. Some rigging systems employ large numbers of bones to represent the complex bending and twisting behavior of a system like the spine.

Biological accuracy to the number of bones in a complex system such as the spine is necessary only if photorealistic representation of an actual skeleton is required. The effect of individual bones in a biological system on the articulation and deformations of skin is mitigated by the action of other parts of the system. The volume of internal organs in the torso preserve the volume of the belly despite rotation of the vertebrae. And, unless detailed representation of breathing movements is required, the same is true of the rib cage and collar bone relative to the thorax.

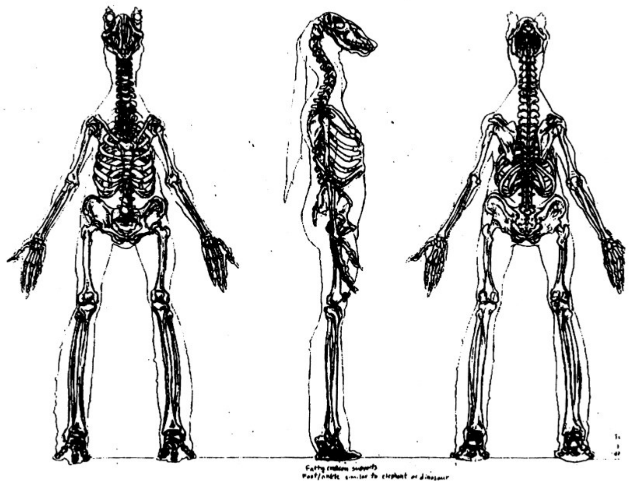

Figure 2: Jar Jar Binks' skeletal system as drawn by concept artist Ian McCaig.

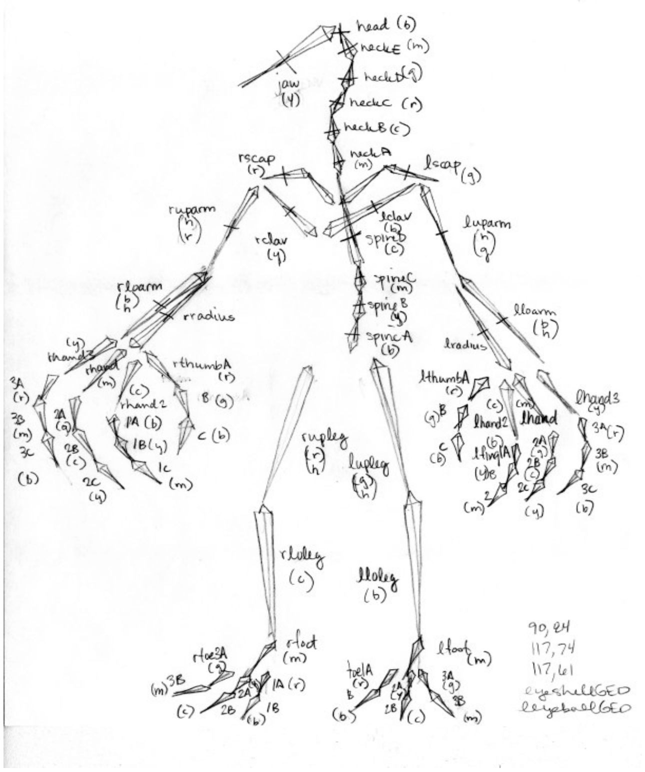

Figure 3: Jar Jar Binks' performance skeleton (not to scale) sketched and labeled prior to beginning the process of enveloping skin deformations to bone transforms.

Accuracy in the location of pivot points, the way the bones behave relative to one another in the deformation of surfaces is more important than the number of bones for digital creatures. Visible bulges on the skin of a creature provide clues to the locations of joints. Due to the implied presence of muscle mass, skin thickness, and bone thickness, however, it's often difficult to determine the exact pivot location for a bone simply from analyzing the surface contours of the model.

For human digital doubles range of motion studies, either as still images, video, or preferably motion capture data, provide excellent reference for locating pivot points. For non-human creatures and characters analogous forms must be found and referenced. Anatomy books and artist's guides provide the bulk of the necessary material.

Adherence to biological accuracy is required only if the goal is scientific visualization. In most cases, particularly those involving the entertainment industry, the goal is efficient creation of visually plausible articulation for the character. The best example of areas where the pivot points for digital creatures deviates from the pivot points for biological bones occurs along the spine of orthograde characters. In humans, for example, the bones of the spine are located just below the surface of the back of the upper torso and neck. When biological accuracy to this location is adhered to in digital creatures the front of the torso and neck compress in visually unfortunate ways when the spine or neck bend forward. In biological creatures there are other support structures such as the digestive organs, ribcage, and windpipe that prevent the skin from collapsing during a forward bend. There are various techniques that can be employed digitally to replicate the volume preserving function of the rib cage and digestive organs, but often the more efficient solution is to simply deviate from the biological placement of the spine joints. If the spine joints are moved further toward the middle of the torso and neck, though still biased toward the posterior, then the deformations will be cleaner and the range of motion will likely remain acceptable.

7.2.2 Control Systems

Control systems in digital creatures are analogous to the combination of the muscular and central nervous systems in biological creatures. Muscles provide the direct force while the central nervous system provides the intention and controls relationships between spatially disparate parts of the body. For digital creatures intention springs from the mind of the puppeteer be that an animator, motion capture actor, or programmer of behaviors. The manner in which intention is turned into action is determined by the control system.

7.2.3 Direct Connections

Control systems are defined by the types of connections employed to keep parts of the system together. The most basic form of connection is parenting. If one bone is parented to another, the parent bone will drive the position and orientation of the child bone as in the way that the rotation of the upper arm determines the position in space and rotation of the lower arm. It is easy to see the connection between the biological relationship of sequential bones, like the upper and lower arm, and the relationship of digital bones which are parented.

Simple parenting cannot account for many complex behaviors. The relationship of the upper leg to the lower leg appears to be very similar to the example given above using the upper arm and lower arm. In fact, the similarities are close enough that only the most visually demanding situations will require a more complex connection than parenting for the upper leg to lower leg connection. However, the knee joint's operation is complex enough to create a visible change in the pivot point as the lower leg swings relative to the upper leg. That complexity may need to be recreated digitally depending upon the requirements of the project.

Another complex connection between bones is the shoulder area of bipeds and the forelimbs of quadrapeds. The origin bone of the limb (upper arm on orthograde creatures, front leg of quadrapeds) is slung from the torso via connective tissues. This mechanism allows the origin point of the upper bone to slide along the torso thus creating a greater range of motion. Simple parenting obviously cannot accurately reproduce the biological form of this kind of relationship. Greater complexity is needed, and is achieved through the use of non-hierarchical connections.

7.2.4 Non-hierarchical Direct Connections

It is possible in most 3D software packages to create relationships between objects in a rig that are not in the same hierarchy or branch of a hierarchy. This is a powerful utility, as it allows for an object's action to be derived partially from its parenting, or hierarchical, relationship and partially from external sources. In digital creatures, non-hierarchical direct connections are primarily used for two reasons. First, is the unification of control of disparate elements within the rig, such as the use of position and rotation constraints to tie joint behavior to graphical icons.

The second common use of non-hierarchical direct connections is to mitigate the unwanted side-effects of mathematical operations used within the rig. For example, it is common practice to force one axis of a bone in an chain to point to, or aim at, a control object. The control object exists outside of the hierarchy of the chain and its purpose is to provide a frame of reference for rotation values within the chain. Without that reference point some systems will revert to equating a rotation value of 180 degrees to be equivalent to 0 degrees. This causes the joint to flip. The control object, when located correctly in space relative to the chain, prevents the joints from rotating into these mathematical danger zones.

A biological creature's central nervous system is the equivalent of a digital creature's control system. However, biological creatures are not puppetted, and thus don't need graphical interfaces in the form of icons for animator input. And though the motion of biological creatures is physically based, they are not bound by the limitations of numbers and equations.

7.2.5 Variable Connections

Variable connections are mathematical constructs that tie the response of one object to the behavior of another beyond simple direct inheritance of transforms. Variable connections do not require a hierarchical relationship between the parent (driver) and child (driven) objects. As the name suggests, variable connections create behaviors that are dynamic. It is through variable connections that biological behaviors of articulation are most often represented.

One example of a variable connection is the use of multiple pivot points on a digital human's foot. As the character takes a step the heel contacts the ground first, followed by the ball of the foot, and then the toes and the foot pushes off for the next stride. In the first stage of this example the ball of the foot and the toes are pivoting around the heel. As the motion continues the pivot point moves forward to the ball of the foot and now the heel and the toes rotate around it. Finally, the toes become the center about which the ball of the foot and the heel rotate. In this system the pivot point changes are dictated by the behavior of a

Threshold values are often used in variable connections to activate or speed up behavior of a driven object only after a certain point has been reached in the source object's motion. In human shoulders the upper arm joint can rotate out to a point nearly level with the line of the clavicle before the clavicle begins to rotate upward, the mass of the deltoids pivot sharply, and the trapezius compresses. If the action of the clavicle were tied linearly to the motion of the upper arm joint, or not related at all, then the form of the shoulders would be biologically incorrect at both the midway point and the fully raised point in the arm's motion.

7.2.6 Boneless Problems

Some biological creatures have no bones. Non-chordates are typically either aquatic, such as jellyfish and octopi, or very small relative to human scale, such as worms and snails found in the terrestrial world. Though boneless, non-chordates still have points of articulation. Unfortunately, from a mechanical standpoint, the lack of bones in non-chordates contributes highly flexible and amorphous bodies. Thus the points of articulation are constantly moving relative to one another sometimes compressing to lie nearly coincident and a moment later separating by great lengths. Most attempts at rigging non-chordates require a willingness to impose chordate-like structure and then employ variable connections to hide the artifice.

8 Movement

8.1 The Mechanics of Motion

Animated characters and the products of digital special effects all interact with the following four laws or issues: (1) Physical laws exist—either digital creatures can be seen to obey physical laws as we know them or obey some setoff physical laws in their depicted environment/universe. (2) Digital creatures have structure, i.e. morphology. (3) Structure has function. (4) Even fanciful creatures can be constructed of organisms known from laws (2 & 3), and interact with (1).

8.1.1 Terrestrial, aerial, and aquatic locomotion

The principal components concerning any type of locomotion are the medium through which an organism moves; if terrestrial, the substrate on which the organism moves; and the organism itself. Flight and aquatic locomotion impose particular constraints of body shape, with convergence on a fusiform body shape being the norm. Additionally, propulsion from fins, limbs (wings or arms/leg), or body undulation must be provided while maintaining that fusiform shape. In both aquatic and aerial locomotion, propulsion must also be accompanied by lift generators such as hydrofoil-like fins or wings. Piscine locomotion is somewhat more stereotyped and in many ways simpler than terrestrial locomotion, and thus is often easier to model, rig, and animate. Winged flight has proven to be derived from some extremely complex winged movements, but, impressive new discoveries based on high-speed cineradiographic analyses have provided insight about the internal architecture of avians. Conveniently, wing movement though three-dimensionally complex is stereotyped and thus can be rigged an animated with reasonable facility. Furthermore, flight feathers actually insert directly into the bones of the forearm and hand of birds. In other words, right into the analog for the internal rig. Thus, feather movement has the potential to be controlled in relation to the design of the rig.

Terrestrial locomotion depends less on pushing against a viscous environmental medium, but instead, against the substrate. This in turn interacts with body shape, diet as described above, and foot posture. Foot posture can be described as whether all or part of the hand and foot are in contact with the substrate. In general, animals adapted for greater and greater speed have relatively more and more elongate hands and feet. Plantigrade creatures place the entire hand and foot in contact with the substrate. Primitive mammals, human feet, and bears are common examples. Digitigrade creatures contact the substrate with the equivalent of the ball of the foot or hand - on the digits - in a manner familiar from cats, dogs, many other carnivores, and rodents. Hoofed animals literally contact the substrate with the modified nails of the tips of the finger(s) or toe(s). These include amongst the fleetest and most sure-footed of mammals. In real life, only quadrupeds can achieve this condition, as the minimal foot size, though it increases potential speed, also decreases stability. Digitigrade and unguligrade creatures require the inclusion of additional points of rotation for designers and riggers, and challenging limitations for animators depending on non-verbal cues and body language.

8.1.2 Step cycles and motion limiters

Both orthograde humans and pronograde bipeds, and pronograde quadrupeds all exhibit slow speed gaits (walks) and most higher speed gaits wherein more time is spent in the air than in contact with the ground. Amongst humans, the hip, knee and ankle joints are key elements in smoothing the locomotor trajectory and are thus critical to well-animated locomotion. Most damping of bounce in human walking is taken up by the hips. Three major components of hip movement—pelvic rotation, pelvic tilt, and lateral displacement—are key to human locomotion. These factors allow the hip to be analogized by the movement of a kayak paddle. On the other hand quadrupeds generally have at least two and often three limbs in contact with the substrate; thus hip movement need not be so extreme to maintain balance. However at higher speeds, trots, canters, and gallops are dependant of the dietary factor mentioned earlier.

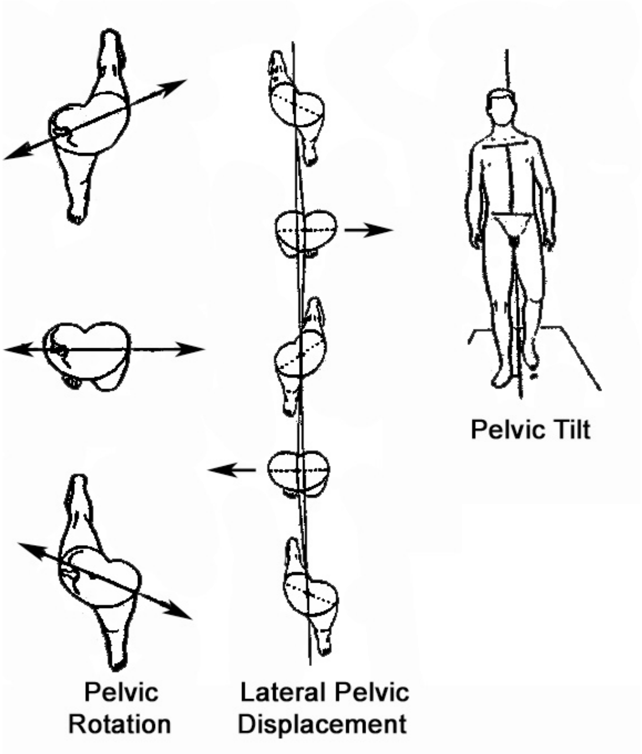

Figure 4: Hip movement during walk cycle.

8.2 Motion Generation

The motion of a digital creature is seen on the viewer's screen. Digital creatures are communicating their role in the stage play through posture, action, and reaction. In reality, digital creatures are displaying the animator's effort to communicate through a synthetic puppet. In this sense the motion of digital creatures is driven externally, rather than internally as is true of biological creatures.

The motion of biological creatures is driven by the internal action of muscles, and by the effect of the environment on the creature in response to its action. For example, contraction of the biceps muscle leads to the action of the hand lifting, and the impact of a foot hitting the substrate flattens the heel and vibrates the loose tissue of the leg. The motion of digital creatures is driven by resolving the positions in 3D space of articulated parts of the creature. For example, the joints in the spine each change rotation values by 10 degrees and the digital creature bends over.

The result is the same: visible motion that appears internally motivated or the result of internally motivated action. However, the initiation of the action for a digital creature is external, puppeted, and this significant difference resonates through the construction of digital creatures. Digital creatures are machines, are built like machines, and operated like machines. In order to be viewed as believably organic the performance of a digital creature must transcend both creature's mechanical structure and the way in which the performance is generated.

8.2.1 Key Frame, Motion Capture, and Procedural Animation

The motion of digital creatures originates in three forms: keyframes, motion capture, and procedural. These forms can be combined effectively to create performances. Of the three, key-frame motion is the most common and yet most likely to vary significantly from biological reality.

Digital characters communicate primarily through their posing, however the quality of the motion in-between the poses is the key to their physical plausibility. During key-frame animation interpolation of the motion between poses is created by the computer program rather than the artist. The artist intervenes by changing the arc of action or creating breakdown poses when the interpolation is incorrect.

Motion capture animation provides the pose-by-pose action for each captured body part as dictated by the capture frame rate, which is typically much higher than the playback rate. No in-betweening is necessary. The physical plausibility of the action is limited by capture and application of the action. The fidelity of the captured in terms of noise-to-signal ratio will affect the visual clarity of the actions as over-sampled data looses the sharp changes in direction that communicate physical contact with the environment and noisy data creates visual pops in motion. Even the cleanest motion capture data will be compromised if mapped incorrectly or re-targeted without respect for cohesion among the captured elements.

The actions of characters that feature procedural animation are determined by rule sets. These rules are often at least partially physically based, but may include behavior as well, such as avoidance or attraction. The physics may include gravity, motor driven joints, environment detection and collision avoidance or reaction. The believability of the actions in terms of biological correspondence is controlled by both the accuracy of the applied rules and their breadth in terms of capturing the conditions of the creature's environment.

8.2.2 Driving Points

The motion of a cat jumping from the floor to the seat of a chair is driven by muscles firing in the legs of the animal. This creates a force against the floor and since the floor is immovable the body of the cat springs into the air and up to the desired landing spot. The motion of a digital cat performing the same action is likely to be driven by a controller between the cat's forelimbs and a secondary controller between the cat's hind legs. The other parts of the digital cat: the head, the feet, and the tail, go along for the ride.

The position of the main controller is important to the creation of believable motion that is also easy to animate. Biological creatures do not have driving points, but they have locations on their bodies that can be viewed as the origin points for the actions of appendages. For example, the action of a biped's feet hitting the ground propels the action of the biped. The physical motion is driven to the rest of the body via the hips. The hips lock the rest of the body to what the feet are doing.

These origin points of motion in biological creature become driving points in digital creatures. Driving points in digital creatures are locations where several appendages join together. Controlling a driving point moves the origin points of appendages as a group. Orthograde creatures are driven through the hips when walking. Quadrupeds are driven through the forelegs. Avian creatures tend to be driven through a point centered between the wings. These points are simply the primary driving points and are subject to being subjugated to the control of other driving points during non-standard locomotion.

The various driving points in digital creatures must be hierarchically arranged. The goal is to allow the motion of the primary driving points to drive the position and orientation of secondary driving points, and likewise for tertiary driving points. Motion cascades through the creature such that the areas of greatest articulation are typically several steps removed from the original source of the motion. For example, the position and orientation of fingers on a human digital double are ultimately determined by the combined effect of animation on the finger joints, hand, arm, upper torso, and hips.

This cascading effect is interrupted when the secondary or tertiary driving points come in contact with other objects, either within the creature or within the environment. In the example given above, if grasping a bar or resting on the hips of the character, the fingers will cease to be driven by the secondary controls of the hand and upper torso and will instead have their spatial positions determined by the contact point. Switching the hierarchy of control in this manner mimics the role of physical laws on biological creatures. In computer graphics terms the objects are recognizing both their local (hierarchical) and global (environmental) relationships.

8.2.3 Range of Motion

In biological creatures the range of motion for an articulated part of the body is determined by many factors beyond the simple lengths of bones. Tissue such as muscles and organs create barriers to movement either by obstruction or constriction.

In digital creatures barriers to motion can also be created but they are computationally expensive if applied as collision detections. More often limitations are programmed into the rig. These limitations can take the form of mathematical limits such as specifying that the lower leg can rotate only 160 degrees back from the position of being straight relative to the upper leg. This limit, along with 15 degree medial and lateral rotational limits, would describe the lower leg's capacity to articulate as constrained by the knee cap, connective tissues, and muscle masses.

The use of motion capture typically requires that the motion capture actor move through a series of motions that are used to calibrate the skeleton of the synthetic actor to the pivot points of the live actor. These actions, or similar ones to them, can be used to define the limits of the target character or as reference for another non-motion capture character.

Range of motion limits are not necessarily hard boundaries. Visual feedback given to animators during the process of key-framing can cue that rotation limits are being approached or exceeded without limiting the artist's capacity to choose to do so. One form of feedback is to provide a visual warning such as a color change on the character or the character's controllers when a mathematically defined range has been exceeded. Another more simple form of feedback is the appearance of the digital creature's deforming surfaces. Shearing, collapsing, and interpenetrating surfaces give visual feedback that limits have been exceeded, assuming that the creature has been enveloped to an acceptable level of accuracy and detail.

8.2.4 Character Motion and Physics

Motion within a body is not only a factor of the body's muscles driving bones. A body's motion is also affected by the physics of internal and external forces. For example, walking can be described physically as repetitively interrupting a fall. The act of putting one foot in front of another for the purpose of locomotion involves moving the body's center of gravity from a position of supported balance when over two feet planted on the ground, to a position of being off-balance with the body falling forward until the fall is arrested by the forward foot's impact with the ground. In this way the primary motion of a biological body is integrally linked to the forces of physics.

The actions of key-framed digital creatures are not integrated with physics. The physics of the action is implied by the skill of the animator. Motion captured actions are physically accurate to the extent that the captured data is clean and the re-targeting to the digital character is physically accurate. Procedural animation is only physically accurate if the rules applied include the use of dynamic solvers.

The creature's mass distribution, number of articulation points, and range of motion dictate the visible effect of physical laws on the creature's actions. Beyond simply appearing balanced in posing digital creature performances must show that primary actions create secondary actions in order to be believable. Viewers apply learned expectations about the physical behaviors of objects in motion despite willingness to accept fanciful forms.

In the biological world physically-based behaviors are inseparable from the causal motion. It is impossible to separate the forces of gravity and inertia from the results of a skeletal muscle contraction. Physical properties are always "on" in the real world. In the digital world the opposite is true unless the performance is captured from live actors. Physically driven actions for digital creatures typically exist as layers of motion applied on top of the primary action. In this layered environment there must be clarity for the animator regarding how the key-framed action should contribute to the visual effect through pantomiming the dynamics of the actions.

8.2.5 Forward and Inverse Kinematics

Kinematic systems describe how chains of joints are related to one another mathematically. Forward kinematic systems describe each joint's position as solely derivative of it's parent's action. In a forward kinematic system the rotation of a parent joint drives the position of the child. An inverse kinematic system describes each joint's position relative to the action of the last joint in the chain. In inverse kinematic systems the joints between the root and the end joint must solve their positions using the first and last joints as guides. Both forward kinematic (FK) and inverse kinematic (IK) systems are useful analogs for the actions of biological creatures.

If I raise my arm and place my hand on the top of my head I am essentially employing a forward kinematic system. The rotation of the upper arm joint moves the elbow to a position from which the lower arm (child joint), can be rotated to place my hand on my head. The same two bones can behave in an inverse-kinematic way as well when I put my hand on an object such as grasping a doorknob. The end point of the lower arm (wrist) becomes locked to the position of the doorknob while at the same time the upper arm origin point (shoulder) is locked to the body. The lower and upper arms then "solve" to determine the position of the elbow.

The ability to switch between IK and FK behaviors in a digital creature rig is ideal due to the flexibility offered to animators when solving performance problems. The choice is often determined by the performance requirement for the far end of the chain. If the end of the chain must maintain a certain position or orientation in space then IK is useful since the remainder of the chain is reacting to the end's behavior. However, if the chain's behavior is reactionary to the root or the root's parent then FK is more appropriate. A creature's tail is more easily animated in FK as it follows the sway of the hips. However, if that tail is prehensile and can wrap around objects in the scene then IK is more appropriate. In this reverse situation the end of the tail is locked. The joints in the middle must resolve relative to the locked tip and the hip position.

The mode, IK or FK, has be big effect on interpolated motion. In IK mode as the foot moves from one key framed position to the next the space through which it moves can be highly variable. In FK mode as the foot moves through space from one key framed position to the next it will do so in the form of an arc of motion described by the length of the leg bones.

8.2.6 Dynamic Posing

Dynamic posing is currently not widely used but it functions in ways that are akin to the way an organic body moves and is thus worth mentioning. Dynamic posing differs significantly from IK and FK techniques. It consists of a non-hierarchical arrangement of articulation points and a dynamic solver that determines how those points relate to one another. Movement of any individual articulation point can cause movement of the surrounding articulation points in a cascading effect moving outward. For example, an animator can grab the elbow of a character and pull it sideways relative to the characters orientation. The shoulder will begin to move once the elbow's rotation limit is reached. The shoulder is not able to move very far before the upper torso begins to bend that direction. If the animator continues with the action soon the entire body will be following the elbows action. The animator could then push the shoulder back toward the torso and the elbow would follow.

The advantage of dynamic posing systems is the speed with which natural poses can be created. The body acts as an interconnected whole. Thus complex arrangements between body parts are established with minimal picking and moving. The disadvantage of dynamic posing systems is the proper form of motion between poses is not apparent. Without a central nervous system the intention of an action in digital creatures is defined by its control system. In order to properly animate a character from a sitting to a standing position a dynamic posing systems must switch from behaving non-hierarchically to imposing a hierarchy of driving points with the hips dominant. Biological creatures accomplish this both physically and mentally. Digital creature require either intuitive rules or artist management.

8.2.7 Muscles

Skeletal muscles in biological creatures provide both support for the body and drive the voluntary action of the body. In digital creatures control systems deliver the information to the bones about how to move. The surfaces of digital creatures are natively non-deforming thus there's no need for muscles as support for the model at rest. Other than occasions where digital muscles have been exposed to the camera such as in 'Hollow Man' (2000), the typical role for digital muscles is to act as secondary deformers of the skin during motion.

In the role of deformation object or collision object digital muscles must mirror the shape and action of biological muscles only as far as the effect of their motion can be seen on the rendered skin of the creature. Biological accuracy in regards to the number of muscles and insertion point are only important as they contribute to accuracy in regards to the timing, scale, and form of shape changes during motion.

The action of digital muscles can be driven by control systems or key-framed independently. Digital muscles can also be physically responsive to motion and dynamic forces. It is the muscles' relationship to the skin that determines their effectiveness visually. Can the skin slide over the muscles? Can the skin wrap tightly around a deforming muscle during flexion and return to a natural neutral state at other times?

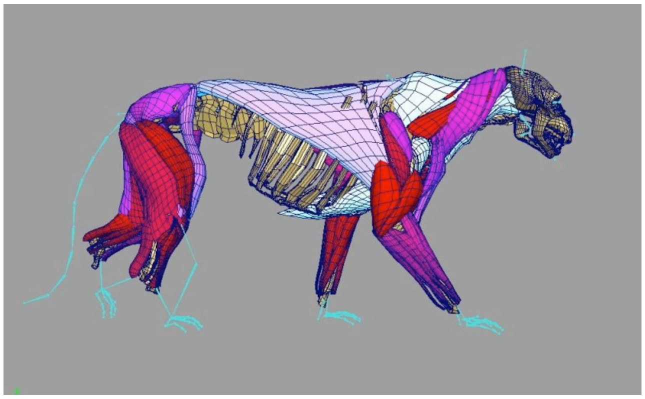

Figure 5: Digital muscles for a lion showing color change determined by level of contraction.

8.2.8 Deformations

The process of attaching renderable surfaces to rigging goes by many names including enveloping, skinning, and deformation rigging. By whatever name the process is described the desired end result is the creation of a digital analog to the effect of bones and muscles moving skin on a biological creature. In fact, the entire process of rigging creatures can be defined as the engineering of systems to deform surfaces.

The skin of most biological creatures is only loosely attached to the underlying muscles and connective tissues. This loose attachment allows the skin to slide over the underlying structure. Skin is also plastic and slightly elastic in a physical sense. It can stretch, compress, fold and wrinkle to varying degrees determined primarily by its thickness. From a 3D graphics perspective the skin's motion can be divided into two categories defining the direction of deformation and two categories describing the complexity of the deforming shape.

The direction of skin deformation is either in-plane or out-of-plane relative to the surface of the skin. Out-of-plane deformation is a shape change that creates a bulge, ridge, cavity, or crease. Out-of-plane deformations are fairly easily handled by blending the motion of the skin to the 3D transforms of a bone or other controlling object. During the animation of out-of-plane deformations the shape of the creature changes.

Out-of-plane deformations can be either planar or multi-planar in terms of the shape created. Knees, elbows, bicep bulges, and tails are examples of planar deformations. The shape change of planar deformations occurs in a single direction at any one time. Multi-planar deformations are represented by shoulders, thigh/hip connections, necks, and the gut. Multi-planar deformations are defined physically by shape changes occurring simultaneously in several directions.

Creating multi-planar deformation rigs requires the interrelationship of many moving parts each moving in a different orientation and often at different rates of speed. Dynamic and procedural systems that push the skin in or keep the skin out based upon the presence of underlying volume defining structures are typically employed in an effort to solve multi-planar deformation problems.

In-plane deformations are more complex as they involve moving skin around or across the existing bulges, ridges, cavities, and creases. In-plane deformations do not change the shape of the creature, but do change the location of superficial features such as hair, skin blemishes, and small scale wrinkles. In-plane deformations are typically accomplished via surface tension relaxation algorithms and are thus computationally expensive relative to planar out-of-plane deformations.

Highly detailed digital creature deformation systems will often employ the use of a out-of-plane deformation pass first, per given pose, followed by an in-plane deformation pass. The out-of-plane deformation pass establishes the shape of the creature in a pose as defined by bone relationship, muscle flexion, and mass movement. The in-plane deformation pass then slides the skin over the new shape to remove un-natural shears, stretches, and creases. During animated motion that is slow enough to see skin effects clearly this double action of out-of-plane and in-plane deformation creates organic forms nuanced with naturalistic details.

9 Conclusions

Artists creating digital creatures have consistently looked to nature as a guide for understanding how digital creatures should be structured and how they should move. It is thought provoking to consider how the development of techniques over time has enabled the expansion of the use of digital creatures into new digital environments. Does the evolution of digital creature technology track with the evolution of biological creatures? Will the development of techniques for digital creature rigging and motion converge ever more closely to the biomechanical laws governing form and function in the natural world?

It can only be presumed that, as with evolution, the radiation of new and novel digital creatures in the future will be part of an on-going adaptive process. The extent to which the successful adaptations for digital creatures are borne from biological analogs will depend upon continued advancement in computing technology as well as continued audience interest in natural forms and motions.

It is the opinion of the authors that the viewer's willing suspension of disbelief regarding digital creatures is enabled by the degree to which the creature adheres to understood realities of natural morphology. Thus, whether technology tracks evolution or not it is in the best interest of the creature developers and animators to understand the biological roles of form and function and how those laws translate into the digital environment.

10 Index of Images

Figure 1: Concept art of the Saphira dragon. Artist: Carlos Huante. Eragon. 2006. Warner Bros. Entertainment Inc. All rights reserved.

Figure 2: Concept art of Jar Jar's skeleton. Artist: Ian McCaig. Star Wars: Episode I The Phantom Menace. 1999. Lucasfilm Ltd. & TM. All rights reserved.

Figure 3: Rigger's sketch of Jar Jar's animation skeleton. Star Wars: Episode I The Phantom Menace. 1999. Lucasfilm Ltd. & TM. All rights reserved.

Figure 4: Hip movement during walk cycle. Stuart Sumida. All Rights Reserved.

Figure 5: Digital bones and muscles of a lion. The Chronicles of Narnia: The Lion, the Witch and the Wardrobe. 2005. Walden Media. All rights reserved.

11 Notes About the Authors

11.1 Tim McLaughlin

In January 2007 Tim McLaughlin moved from ILM to Lucasfilm Animation to take on asset creation responsibility's for Lucasfilm's first digital feature. Over the previous 12 years Tim was a Creature Developer, Creature Supervisor, and Associate Visual Effects Supervisor at Industrial Light & Magic.

His work, both at ILM and Lucasfilm Animation, revolves around the construction of digital creatures that are both visually believable/compelling and effective as tools for animators and other artists involved in shot production. He is credited on 14 feature films including 'Eragon', 'War of the Worlds', 'Van Helsing', 'Star Wars Episode I: The Phantom Menace', and 'Jumanji'.

Tim's education background includes both a Master of Science in Visualization Sciences and a Bachelor of Environmental Design degree from Texas A&M University. He is a member of the Visual Effects Society and ACM Siggraph.

11.2 Stuart S. Sumida

Stuart Sumida received his PhD in biology from UCLA and was at the University of Chicago, before moving to CSU San Bernardino. He has published three books and over sixty journal articles on the morphology of extinct animals as well as laboratory manuals on human anatomy. He is a frequent anatomical consultant to film studios, having worked on over thirty feature films including Lion King, Tarzan, Harry Potter, Chronicles of Narnia, Shrek II, Ratotouille , and many others. He also works audioanimatronic animators and creature designers, most recently with Disney Imagineering helping develop the Yeti character in Expedition Everest Disney's Animal Kingdom.

12 Acknowledgments

The authors would like to thank the following people for their assistance with preparation for this course. Jed Parsons, Jason Smith, Michael Koperwas, Akira Hiyama, Kate Shaw, and Brian Fong at Industrial Light & Magic. Ben Cheung and Virginie Michel d'Annoville at Lucasfilm Animation, Bradley Gabe at Stan Winston Studio, Kathleen Devlin at California State University San Bernardino, Bill Westenhofer at Rhythm and Hues, Chris Williams at the University of Teesside, and Stace Simmons at Louisiana State University.

13 Appendix

Table 1: Major Joints of the Axis of the Body Based on a Human Being

Major Joint	Common Name	Function(s)	Movement Range(s)	Comments
Temporo-mandibular	Jaw Joint	Abduction (opening) Lateral Displacement Medial Displacement Fore/Aft Slide	˜45° ˜0.5cm ˜0.5cm ˜±1–1.5cm	Jaw joint actually moves in three different planes to allow precise and complex occlusion of teeth
Atlanto-occipital	Head-Neck Articulation	Flexion + Extension Lateral Flexion	15° 3°	Primary joint responsible for flexion/extension movement of skull on neck.
Atlas-axis	C1–C2	Rotation Lateral Flexion	12° 5°	Primary joint responsible for rotation of head relative to neck
C2–C3 to C7–C11 each (approx.)	Cervical Intervertebral	Flexion + Extension Lateral Flexion Rotation	15–20° 5° 5° each dir.	These joints provide additive functions of flexion, extension, lateral bending and rotation. C7–T1 typical position of pivot when number neck joints limited in a rig.
T1–T2 to T11-T12	Thoracic Intervertebral	Flexion Extension Lateral Flexion Rotation	minimal minimal 1° (20° total) 0–1°	The thoracic region is region of least movement due to constraints of the presence of ribcage. However, ribcage does move for inhalation and exhalation.
T12–L1 to L5–S1		Flexion Extension Lateral Flexion Rotation	10–12° (60° total) 5–7° (35° total) 3–4° (20° total) 10–12° (60° total)	Abdominal and cervical regions are much more flexible than thoracic regions.
Rib 1–12		Elevation / Depression	2–3°	Move like bucket handles between vertebrae & sternum.

Table 2: Major Joints of the Upper/Fore- Limb Based on a Human Being

Major Joint	Common Name	Function(s)	Movement Range(s)	Comments
Sternoclavicular		Elevation / Depression	10–15°	Often an analog for attachment of shoulder blade to body axis.
Scapula-clavicle		Superior/Inferior Slide · Elevation · Depression	· 2–4cm · 1–2cm	Defines range of upwards slide of shoulder blade.
Scapula-thorax	“Muscular Sling”	Elevation Depression Rotation Medial approximation	2–4cm 1–2cm 45° 2–3cm	Technically not a joint, but a muscular sling. One of the most difficult movements to model/rig. Proper movement prevents the bobble-head effect from being translated to the upper limb. Scapula rotates like a steering wheel.
Glenohumeral	Shoulder	Ball-and-Socket · Flexion/Extension · Adduction/Abduction · Rotation · Circumduction	180° 180° 140–150° 360°	Join with greatest range and mobility of the entire body. More mobile, but less stable than the analogous ball & socket joint at the hip. Movements at shoulder joint strongly coupled to movements of scapula.
Humerus-Ulna	Elbow	Hinge · Flexion/Extension	1–160°	One of two major movements at the elbow.
Humerus-Radius	Elbow	Hinge · Flexion/Extension · Pronation/Supination	0–160° “0–180°”	Radius also moves in flextion and extension, but is the sole originator of pronation and supination which are *not* functions of the wrist

Continued on next page . . .

. . . Upper/Fore- Limb Continued

Major Joint	**Common Name**	**Function(s)**	**Movement Range(s)**	**Comments**
Radius/Ulna-Carpals	Wrist	Flexion Extension Medial Deviation Lateral Deviation	90° 45° 55° 10–15°	A saddle shaped joint that can give the appearance of rotation and circumduction. Lateral (thumbward) deviation can be much greater when accompanied by extension
Metacarpal-Phalangeal	Fingers to palm	Flexion Extension	80–90° 30–35°	The major joint between the palm of the hand and the digits. Highly variable in non-human mammals.
Digits	All five fingers	Adduction/Abduction	20–25°	Spreading and closing of fingers.
Interphalangeal Joints	Finger segments	Flexion/Extension	0–90°	Opening and closing of fingers.
Pollux-Metacarpal	Thumb	Flexion/Extension Opposition/Reposition	80–90° 30°	The opposable thumb, supposedly unique to humans (but also found in other juvenile apes).

Table 3: Major Joints of the Lower Limb Based on a Human Being

Major Joint	**Common Name**	**Function(s)**	**Movement Range(s)**	**Comments**
Acetabulum-Femur	Hip	Ball-and-Socket · Flexion · Extension · Adduction · Abduction · Medial Rotation · Lateral Rotation · Circumduction	0–120° 20° 10–15° 45° or more 30–40° 60° 360°	Joint with greatest range of movements of the lower/hind limb. Less mobile, but more stable than the analogous ball & socket joint at the shoulder.
Femur-Tibia	Knee	Ball-and-Plate · Flexion/Extension · Anterior/Posterior Medial Rotation Lateral Rotation	160° 80% tibial platfm 15° 15°	Not the typical hinge joint as typically described, the lower articular surface of femur rolls and slides on the tibial platform as the knee joint is flexed and extended.
Tibia-Talus	"High" Ankle	Flexion Extension	20–25° 30–40°	Simplified joint acts like a spool-shaped joint.
Talus/Calcaneus	Lower Ankle (Subtalar Joint)	Inversion Extension	˜50° 25-30°	Act like a "universal joint." Difficult but useful to portray for proper foot function.
Metatarsal-Phalangeal	Toes to Sole of Foot	Flexion Extension	80–90° 90°	The major joint between the palm of the hand and the digits. Highly variable in non-human mammals.
Digits	All five toes	Adduction/Abduction	5–10°	Spreading and closing of toes.
Interphalangeal Joints	Toe segments	Flexion	0–90°	Opening and closing of toes.
Hallux-Metatarsal	Big Toe	Flexion	0–90°	No opposable big toe in humans, but present in other primates and other rmammals