Digital Paleoart:

Reconstruction and Restoration from Laser-Scanned Fossils

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Bernie and Wendy

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ABSTRACT

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For over two centuries, the science of paleontology has used imagery in order to help convey its ideas. This "paleoart" struggled at first to be accepted as a legitimate tool in science due to fears over scientific accuracy of reconstructions and restorations. At first, many restorations were made on the basis of poor fossil evidence. This was a result of the combination of the vastly incomplete nature of the fossil record compounded by the fact that too many artistic and scientific speculations became integrated into the artwork. With the 20th Century came the general acceptance of paleoart. Throughout the century it co-evolved with paleontology as new discoveries and ideas were founded. In the digital age, new technologies are being used not only for reconstructions and restorations, but for research purposes themselves. Digital technologies, including three-dimensional digitizers and computer animation, can now be used to create more accurate restorations than ever before, based directly on extremely detailed three-dimensional digitized fossils. In order to capitalize on this technology, and push the limits of what is possible in 21st Century paleoart, a restoration of the extinct crocodylian, *Thoracosaurus neocesariensis*, was created, by starting with a relatively complete digitized fossil source. The rest of the animal's skeleton, its muscles, and outer skin were then restored, using techniques of computer animation, guided by the scientific literature and principles of comparative anatomy. Motion was then used to depict the behavior and habits of the animal, influenced by the biology of the restoration and observations of the animal’s closest living relatives. The goal was to restore an animal with an unprecedented amount of scientific accuracy by blending the techniques of rigorous scientific research with state-of-the-art computer generated imagery.

I. INTRODUCTION AND THESIS OVERVIEW

Particularly in the 20th century, paleontologists have relied on collaborations with creative artists to help bring life to their discoveries, as well as to help give their work meaning to the public. The field of paleoart has a long history of trial and error, reconstructing and revising images of creatures from prehistory. Many of the reasons for inaccuracies in the history of paleoart simply come from the vastly incomplete nature of the fossil record. The majority of fossil specimens discovered are largely incomplete. While there are species named that are known quite well from numerous specimens and rather complete skeletons, the majority of fossilized material consists of very fragmented remains. There are entire species that are sometimes named on the basis of only a couple bones [8].

New research arises and challenges previously conceived ideas. This is because science is a self-correcting process. Science is based on observable phenomena that are able to withstand repeated testing. If more evidence is found to support one theory over another, then ideas change [12]. This is particularly present in the realm of paleontology, where there will always be at least some amount of speculation. A lot goes into the reconstruction of an extinct animal, including comparative anatomy and morphology, evolutionary theory, and biomechanics. Although there is a lot of research that goes into consideration, there are some things that are simply unknown, and will probably never be known due to the scarcity of the fossil record. Soft tissue is rarely preserved, and behaviors can only be inferred from morphology, trace fossils, and modern analogues [23].

How, then, can an artist accurately reconstruct an animal if all he or she has to work with is scarcely preserved, fragmented hard parts? Most of the time, speculation and artistic vision come in to play. Some of the more "imagined" reconstructions in paleoart history have been extremely influential in demonstrating the self-correcting nature of science, as well as producing some incredibly beautiful artwork.

Now, in the 21st century, new tools can be used to ease the process of creating more accurate paleoimagery. Not only can actual fossil data be digitized to use as a starting point, but the increasing availability of tools that display motion over time can be used to help reconstruct possible locomotion and behaviors of extinct animals. Seeing fossilized bones and traditional paintings and sculptures only goes so far toward the public understanding of how these organisms lived. Seeing a reconstructed animal alive, breathing, and moving can really help the public understand scientific ideas more intuitively, while also allowing scientists to predict and test their own hypotheses [8]. Digital paleoart creates digital assets that can always be revised and modified to be congruent with new research. These highly modular assets can then be used to answer a multitude of scientific questions, such as those involving postures, gaits, and locomotion.

The central purpose of this thesis was to use a variety of these established and emerging digital techniques, combined with rigorous scientific research to accurately bring a creature from prehistory to life. These state of the art tools were used to attempt to reach a level of paleo-authenticity previously unattainable by traditional paleoart methods. Much of the credibility of the project would come from using digitized fossil data as a starting point. The central concept was by using the actual shapes of the bones, opposed to artist created approximations, a much more accurate restoration could be created from the start. The main factors in the thesis problem were ultimately discovering ways to restore a complete animal from an incomplete fossil source, and finding ways throughout the process to keep the restoration as accurate as possible at every step of the process.

II. REVIEW OF RELEVANT RESEARCH AND THEORY

1. The Fossil Record

It is always a great challenge to reconstruct the life of prehistory, not only because of the fact that the animals being reconstructed do not *exist* anymore, but because of the incomplete nature of the fossil record. Fossilization in itself is quite a phenomenon, and it is a wonder that any remains have been recovered at all. Although there are detailed documented lineages for many organisms, the entire record of life on earth is extremely incomplete [12]. It is quite rare to uncover one hundred percent of any organism's skeleton, for instance. Many species are known from one specimen, and sometimes those specimens consist of only a few bones [8][12]. Of all of the dinosaur species described by man, for example, about half of them are only known from one specimen [23].

One may wonder exactly why a complete record of life on earth is so difficult to document. Many organisms simply do not fossilize. If an animal is small and fragile, or lives in an area with rapid decay, such as a tropical rain forest, it is very unlikely to become part of the fossil record. An animal with large robust bones is much more likely to fossilize than small organisms with little to no hard body parts [12]. Before burial, there are a number of factors an organism's remains must survive through to make it to the fossilization process. If not buried quickly, wind, water, and scavenging animals can easily tear a body apart and spread its remains over vast distances [23].

In the chance that an organism dies and is buried quickly enough to prevent its remains from decaying or being dispersed, there are still invertebrates in the ground to worry about. If an animal is able to survive this, it must then undergo the process of permineralization, where groundwater carrying minerals makes its way into the bones. This is often coupled with replacing the organic matter altogether with another mineral [23]. Another method of fossilization, which is more common for smaller plants and animals, is carbonization. Carbonization is the process where an organism is usually flattened, and a carbon film is left as other elements are lost. This usually results in the preservation of full organisms, including outlines silhouettes, muscles, and even feathers along with the skeletal structure.

Once fossilization occurs, the mineral remains are sturdier than when they were made of organic matter, but it is still not definite that the remains will make it into the present [23]. The actions of plate tectonics and erosion can easily destroy a fossil, especially when it has been in the ground unprotected over the course of *millions* of years [12].

There is yet another major factor that limits the amount of organisms preserved as fossils. This is the fact that paleontologists have to be able to *get* to the fossils in order to describe them. Good fossil sites are relatively rare on the planet. There are three major criteria for promising fossil sites. A site has to contain sedimentary rocks from the correct time period, and these rocks have to be on the surface of the ground. Igneous and metamorphic rocks are not likely to have fossils because of the extreme heat and pressure that goes into creating them. Sedimentary rocks are ideal because they are a result of fine grain particles in environments such as bodies of water, where organisms live. Such particles can quickly settle and bury the remains of an organism [35].

These sedimentary rocks from the right time period then must be at the surface so they are accessible to people [35]. Usually when hunting for fossils, paleontologists look for “float,” or bits of fossil that are either protruding from the ground or resting on top of it. The scientists then follow the shape of the protruding fossil to find more of what is hidden in the ground. If one were to aimlessly dig holes in the ground around the world, he or she would not have a successful career in paleontology. Also, even if one were to know *where* there were fossils, digging random holes with a pickaxe, without any knowledge of how a skeleton is laid out underneath is bound to damage and even destroy fossil material. It is also important to note that in a developed world, there may very well be, and most likely are, a plethora of fossils hidden under the towns, cities, and even remote jungles of the world, but since they are buried and so difficult to access, scientists may never reach them [35].

This is why fossils are so precious. Each and every specimen contains invaluable information that could have easily been lost during the millions of years it spent in the earth. It is hard to comprehend the fact that many fossils have been in the ground for far longer than the entire existence of the genus *Homo* [23]. When examining the processes that it takes for the earth to create a fossil, and then for humans to find and excavate that fossil, it makes sense why the fossil record is so incomplete. It is amazing that there are *any* fossilized specimens, which allow us to begin to speculate, imagine, and reconstruct prehistory.

2. A Historical Progression of Paleoart

Humans have been interpreting and restoring images from fossils throughout human history. Many ancient mythical creatures, such as the Cyclops, dragons, and griffins are considered to be the result of early interpretations of fossilized remains (Fig. 1) [24]. As incredibly visual beings, it is important for humankind to be able to visualize the animals of prehistory in order to help better understand them [8]. As a result, paleontology and "paleoart" have evolved side by side over the course of the past two centuries [23].

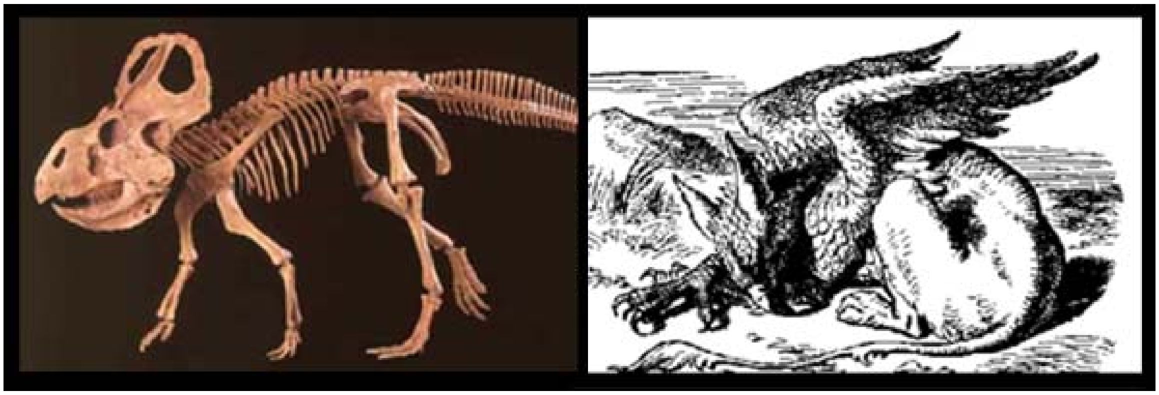


Figure 1 Fossils of *Protoceratops* (left) are a likely explanation for the invention of the Griffin (right)

Paleontology is an extremely visual science, and owes a lot of its popularity to its symbiotic partnership with paleoart. Paleoart takes scientific ideas and combines them with some degree of speculation in order to bring these creatures of the past to life through reconstructions and restorations. A paleo-reconstruction involves reconstructing skeletons in the form of drawings, paintings, models, or even display mounts. It also includes casting models of missing skeletal pieces. A restoration, on the other hand, displays how deceased organisms appeared in life by portraying them with muscles, skin, fur, feathers, etc. It is not uncommon to combine the two types of paleoart, such as displaying a reconstructed skeleton with a body outline to give context to the reconstruction. These techniques can help depict the ideas expressed in the science in a more “tangible” form. It is often easier for people to grasp and accept paleontological ideas when they have an image to use as a frame of reference [8].

The goal of paleoart is to be as scientifically accurate as possible, based on the fossil evidence. Because of the nature of the fossil record, however, it is difficult to achieve absolute accuracy without introducing some form of speculation. Some level of speculation is almost always used, since there is information that simply will most likely never be found, such as skin colors. It is not uncommon to surmise the look of missing skeletal parts based on an organism’s phylogeny. Each time something is inferred, however, it introduces yet another chance for error. As new specimens are found, and new research becomes available, paleoartists change their perspectives to adapt to the science and correct the inconsistencies between the art and the literature. The successful paleoartists also work closely in conjunction with the scientists researching the organisms being reconstructed [8]. It is actually extremely common for paleontologists to be paleoartists themselves [23]. The progression of both paleontology and paleoart are constant works in progress, revising information, and reworking ideas as new data is found [8].

Despite the interconnected relationship science and art has in the realm of paleontology today, scientists were very wary about using visualizations for hard science until the end of the Paleoart Reformation period, which spanned from about 1900-1910. It took nearly a century for paleoart to establish itself as a legitimate part of science [8].

Decades before Sir Richard Owen described *Dinosauria* in 1842, French anatomist George Cuvier was carefully and accurately sketching and describing animals. He thought of organisms as a sum of functional parts, and claimed that he could construct the entirety of any organism if given a single piece [20]. He described a number of fossil species, and worked on two-dimensional reconstructions, first posing and placing them in simple environments. He then moved toward restoration by sketching in the muscles and other important body structures on top of his reconstructions. He never actually published any of these sketches in conjunction with his research, however. He was aware of the liberties he took when theorizing structures not found in the fossil record, and did not want to be criticized by fellow scientists [8].

Gideon Mantell, known for describing *Iguanodon*, was another early paleontologist who took the time to delve into fossil illustration. He is credited with the first dinosaur reconstruction, of *Iguanodon*, completed in 1832. Despite the fact that the thumb claw of the dinosaur was misplaced as a nose horn, such work is still an early example of paleoart, and stands as a symbol for the self evaluating and correcting nature of science. Mantell also commissioned restorations of his prized *Iguanodon* to be depicted in full environments, complete with other prehistoric fauna. He used these illustrations to accompany geology lectures he presented, and was one of the first people to use paleoart in such a way [8].

Another notable player in the beginnings of paleoart was the English sculptor, Benjamin Waterhouse Hawkins. Hawkins was a student of natural history as well as a sculptor who assisted many important scientists throughout his career, including Sir

Richard Owen, Edward Drinker Cope, and Joseph Leidy. He created a number of lifelike restorations, despite many of them being extremely inaccurate from what is known now. These restorations represent an early attempt at bringing scientific ideas to the general public [8].

In 1852, Prince Albert wanted to bring the ancient world to life in the park grounds outside the Crystal Palace at Sydenham, England. Hawkins, with the oversight by Richard Owen, was commissioned to create life sized sculptures of prehistoric animals. The duo decided to depict the animals in the flesh, despite lacking the proper fossil remains to base them. The thirty five concrete sculptures (many of which still exist today) include *Megalosaurus*, *Hylaeosaurus*, and *Iguanodon*, depicted as bulky lumbering monsters (Fig. 2) [8].

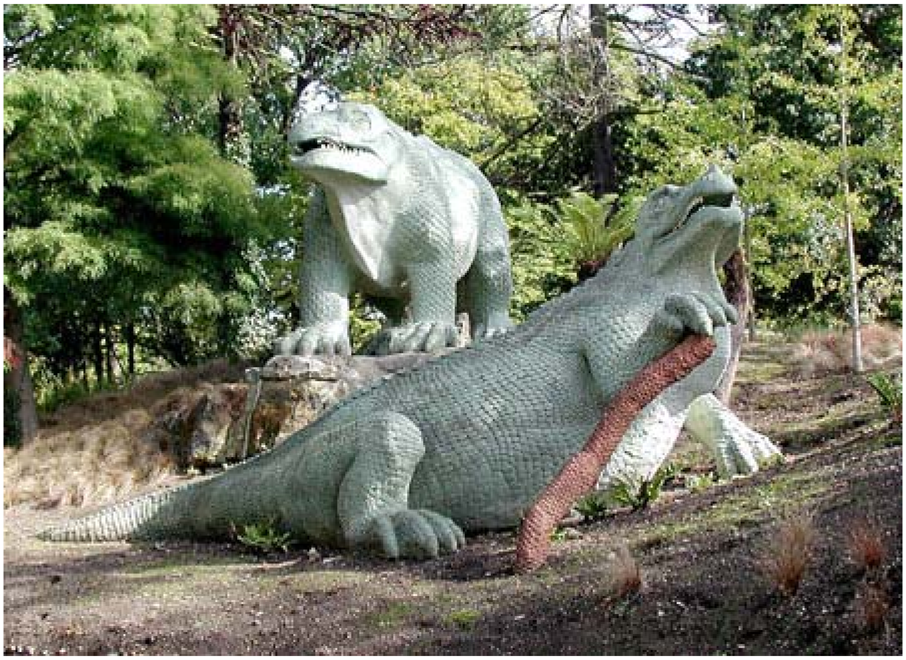


Figure 2 A couple of Hawkins' *Iguanodon* at the Crystal Palace Park

After success in England, Hawkins came to Philadelphia where his work was noticed, and he was approached about a massive project to be called the "Paleozoic Museum." This museum was going to be constructed in New York City's Central Park, and was to house sculptures of a number of extinct American animals. Hawkins studied American fossils under Edward Drinker Cope and Joseph Leidy at the Academy of Natural Sciences in Philadelphia to prepare for such a large scale project. Unfortunately, to Hawkins' disappointment, this museum was never actually constructed due to many factors, such as financial and political battles, as well as disapproval for the spread of evolutionary ideas by the general public [8].

Although there were a number of notable people establishing the realm of paleoart as a legitimate part of science, in the later 1800's many scientists were still extremely reluctant. Even as late as the 1870's, American science as a whole was desperately trying to live up to the standards of the Europeans. Scientists had to be extremely careful when taking risks and making speculations. This was a driving factor on the delayed general acceptance of paleoart [8].

One scientist who completely avoided restoration was Othniel Charles Marsh. Marsh was the arch rival of E.D. Cope and did not even come around to accepting skeletal reconstructions of any type until the 1880's. Life restorations were completely out of the question for Marsh, due to the chance for error. He never shifted his stance on this, despite having uncovered plenty of fossil material from the American west that was more than adequate for restoration. Cope on the other hand opposed Marsh's view, and saw merit in both reconstructions and restorations [8].

With the mixed feelings on paleoart and the state of American science, it is surprising that it was the *Americans* who finally drove paleoart to become an accepted part of paleontology by the 1920's. Probably the most influential player in this reformation was the painter and sculptor, Charles R. Knight whose work spanned from 1900 through the 1960's. Knight was a skilled wildlife artist who started his career in paleoart with the restoration of an extinct pig-like mammal for the American Museum in New York City. He worked closely with E.D. Cope until Cope's death in 1897. Knight found it incredibly important to study the bones of the specimens he was restoring directly, while also consulting with scientists. His "slices of life" from prehistory rapidly made him recognizable among artists and paleontologists alike. His most famous piece is a mural created for the Field Museum of Natural History in Chicago that depicts a face-off between the Cretaceous dinosaurs, *Tyrannosaurus* and *Triceratops.* This piece has become an iconic image to dinosaur enthusiasts everywhere [8].

Knight was greatly endorsed by a paleontologist at the American Museum by the name of Henry Fairfield Osborn. Osborn loved the idea of accurate restoration attempts by talented artists for scientific purposes. He claimed that restorations were like scientific hypotheses, documenting the contemporary knowledge of the science. As more and better preserved specimens were being excavated from the American West, it became popular to accurately mount skeletons in life-like poses in the halls of American museums. The plethora of American fossils led to the common practice of reconstructions and restorations, and paleoart eventually became accepted. It became understood that the steps involved in restoring an animal was not based on wild guesses, but on actual scientific ideas. Images of prehistory then spread overseas and saturated pop-culture and the media [8].

After the "Reformation" period, the next influential movement in paleoart history marked a major change in thinking of paleontology as well. This era is known as the Dinosaur Renaissance, with paleontologist and paleoartist Robert Bakker at the forefront [23]. When the carnivorous dinosaur *Deinonychus antirrhopus* was discovered in 1964, ideas about dinosaurs changed dramatically. Before *Deinonychus,* dinosaurs were typically depicted as giant, slow, sluggish lizard-like reptiles. The morphology of this *new* animal, however, was one that looked very much like a fast moving predator. This carnivore was much smaller than a *Tyrannosaurus* or *Allosaurus,* and with its long arms and famous toe-claw, *Deinonychus* appeared to be an active hunter [8]. This led to the thought that at least some dinosaurs were warm-blooded like birds and mammals, and boasted energetic lifestyles [8].

During the Dinosaur Renaissance, the evolutionary connection between birds and dinosaurs was also becoming stronger due to the discovery of more birdlike dromaeosaurs, as well as the findings of feathers preserved in many similar dinosaurs such as *Sinosauropteryx, Caudipteryx,* and eventually the four winged *Microraptor* [12]. Depictions emerged showing gregarious dinosaurs along with dynamic, active, running, and galloping dinosaurs. It also became very common to depict imagery of fully feathered theropods (the bipedal carnivorous dinosaurs). Paleontology was booming and so was paleoart by the end of the 20th century [8].

We are still in the midst of the Dinosaur Renaissance in paleoart, although now new tools are being used to portray the latest science. With the release of Steven Spielberg's blockbuster film adaptation of Michael Crichton's *Jurassic Park* in 1993, dinosaur imagery became more popular than ever before. The film generated a lot of public interest in dinosaurs with its use of computer graphics to depict living breathing animals from prehistory. Although not a scientific restoration piece, it led the way for the use of new digital tools to create more believably rendered paleoimagery [8].

Piggy-backing on the success of the technology behind the *Jurassic Park* franchise, BBC released its *Walking with Dinosaurs* series to show living breathing animals in the form of a nature "mockumentary." *Walking with Dinosaurs* was a creative and popular attempt to bring paleoart to the public to inform about real paleontology. The series spawned many spin-offs depicting other prehistoric life as well [34]. The episodes were based off of the fossil evidence and proposed scientific ideas, with intercut sequences featuring experts talking about the scientific influences of the show. There was still quite a bit of speculation, artistic input, and the heavy use of modern analogies, however, and as a result, inaccuracies resulted. Nevertheless, the television program was quite successful with the public [34].

With evolving technology, paleoimagery is now being used in other ways than simple entertainment. Today, paleontologists rely a lot on paleoart to make their discoveries more accessible. Modern paleoart is typically used as a final culmination of all the research and conclusions made by scientists on a project. Today in the digital world, it has even come to the point where scientists are using new forms of accurate paleoimagery in order to *test* their own hypotheses. The relationship between paleontology and paleoart has come full circle. Traditionally, artists would illustrate the finds of scientists, but now scientists are looking to digital imagery in order to help *discover* the finds [8].

Newer technologies such as three-dimensional laser scanners, physics simulations, and animations have been able to help research scientific ideas through imagery. A number of such projects have focused on biomechanics and movement of extinct animals. In 2000, the Smithsonian National Museum of Natural History undertook a project to digitally preserve their *Triceratops* skeleton. The dinosaur had been on display since 1905. After roughly a century of sitting mounted in the museum hall, the fossils were starting to weaken due to natural wear and tear. It was decided that the beloved fossils should undergo digital preservation (Fig .3). Using a variety of types of laser scanners, point-cloud data for the entire skeleton was generated after about three weeks of scanning. Many pieces were too heavy to be moved and had to be scanned in parts to later be stitched together. Since the Smithsonian's *Triceratops* was a composite of several individuals, some of its proportions were very inaccurate. These facts were known and some scanned bones were duplicated and mirrored as well as resized in order to get a much more accurate dinosaur from the inaccurate mount [10].

Casts of the *Triceratops* bones were made in order to keep the original fossils in a safer display area. Some of the inaccurate bones were corrected by creating casts of the computer generated models made from the corrected digital scans. The digital scans were then used to investigate the gait and posture of the animal, and *Triceratops* was animated to a ceratopsian trackway. Unfortunately the animation on this digital dinosaur is incredibly crude, and does not appear to have any real sense of weight. This being said, the project was very successful in its attempt at preserving the *Triceratops* fossils, and creating digital assets for future research. It is also notable as an early attempt at using digital tools to create motion for the purpose of scientific research in biomechanics [10].

Figure 3 The digital skull of the Smithsonian Institute's *Triceratops*

Dr. John Hutchinson, a biologist at the Royal Veterinary College at the University of London, conducts a lot of research in the realm of animal locomotion. Recently, he and his colleagues undertook a project to attempt to determine the gait and stance of an all-time favorite theropod, *Tyrannosaurus rex*. Focusing strictly on the leg bones, Hutchinson and his team determined that, mathematically, there were around 67 million possible stances for this animal. Luckily, with more and more readily available and affordable animation and simulation packages, Hutchinson was able to test a number of possibilities very quickly. Using laws of biomechanics, geometry, and modern analogues to extant animals, the team was able to set up a number of constraints on the range of motion in order to narrow down possibilities [14].

Hutchinson was still cautious throughout this whole process, placing the results of the research in the framework of a proposed hypothesis rather than a definite conclusion.

According to Hutchinson, the biomechanical constraints of modern animals "are often not well enough understood to apply them to extinct animals" [14]. These sorts of projects help scientists to understand what sorts of biomechanical issues to research, however. In Hutchinson's view, instead of pinpointing exactly how an animal stood and moved, progress will come from discovering how it *did not* move, which in turn narrows down the possibilities [14].

Digital paleontology has arrived in full force, and has taken many forms. Entertaining stories help educate and engage the public, while digital tools can also be used for data collection and hypothesizing. Now, museum displays are even taking advantage of augmented reality to combine the real and the digital, in order to visualize projected soft tissues on top of the bones themselves [27]. Despite the abilities to achieve more accurate data via digital technology, when bringing any prehistoric creature back from the dead there is always the dangerous possibility of speculative inaccuracy.

3. Speculation: The Balance Between Science and Art

Through further scientific research and study, many of the early restorations in paleoart were very inaccurate. Most of the time, this was a result of foolishly attempting to recreate an entire animal from very scanty remains. Cuvier's Laws of Associated Anatomy and claims of the ability to restore an entire animal from one bone were not the best for the early credibility of paleoart. Genera such as *Megalosaurus, Iguanodon, Dryptosaurus*, and even *Hadrosaurus*, the first "nearly complete" dinosaur, had too little fossil evidence at the time to be restored adequately. A lot of speculation went into such creations. For example, when Benjamin Waterhouse Hawkins was working on *Hadrosaurus*, the lack of the skull and pelvic bones resulted in Hawkins scaling up an iguana skull and referencing a human pelvis to complete the animal, creating an extremely inaccurate composited beast [8].

Scientific accuracy is crucial to the success of paleoart. Although they may be fun, there are dangers that arise when taking too many creative liberties. There is a big responsibility that comes with the recreation of extinct species. When one creates a work with the label of *scientific accuracy* the average person usually associates it as factual or real, opposed to a proposed solution, or possible idea [18]. Viewers create this preconceived idea in their heads of how they think something should act and move, using popular fictional stories as a frame of reference. In fact, it even shapes a viewer's conception of how history itself worked. This is how powerful a visual media meme can be. The media allows a viewer to see something he or she has never seen before, and then makes that person unable to see it in any other way. Fictional proposed realities become realities to the average viewer [34]. A perfect example of this is the mural by Charles R. Knight at the Field Museum of Natural History in Chicago depicting the showdown between *Triceratops* and *Tyrannosaurus* (Fig. 4). This painting is the reason why these two dinosaurs are arch enemies in popular culture. It was not painted with this idea in mind, but the image became a cultural icon over time [23]. Even with aspects of restorations that are obviously invented, such as the color of a creature in a particular painting, if it is the first time someone has seen a depiction of that animal in the flesh, he or she will often associate those colors with that animal for most of their life [8].

Figure 4 *Tyrannosaurus* and *Triceratops* depicted as mortal enemies by Charles R. Knight

Popular fictional movies like *Jurassic Park* and *King Kong*, which depict extinct animals as living breathing creatures, profoundly affect how average people think of actual extinct species. To many, the *Jurassic Park* franchise shows how dinosaurs moved. It is true that Jack Horner was a paleontologist who was consulted to help the films feel more authentic, but the film is still fiction, and a lot of liberties were taken for the sake of storytelling, drama, and art direction. There are fairly substantial inaccuracies in Spielberg's film, most apparent in the portrayal of *Velociraptor mongoliensis*. The animals in the film more accurately represent *Deinonychus antirrhopus* considering *Velociraptor* was actually only about three feet tall [8]. The makers of the film probably made it bigger for dramatic purposes in order to suit the story they were trying to tell.

The filmmakers, however, still claim to be aiming for scientific accuracy. They tried to update their "science" for the third iteration of the franchise by adding feathers to

Velociraptor [16]. This was a strange half-move toward science. The film portrayed the dinosaurs with small quill-like feathers restricted to their heads opposed to the full plumage that the animals most likely had [1]. It also didn't resize them correctly. At this point, the attempt to move toward science not only hurt the film's attempt at accurate reconstruction, but it took away from the storytelling of the film itself. It created a strange continuity error with the previous two films in which the raptors did not have any feathers at all [15]. It took viewers out of the story, while also not achieving scientific accuracy.

The less speculation that is involved usually means higher accuracy. This being said, speculation can be helpful to science when used in the right way. Most of the time, hypothesizing and experimenting is necessary to brainstorm and suggest new ideas. Obviously, restorations of specimens known from little material should be avoided until more data can be produced for them, or unless such a restoration is coated with disclaimers. Speculation and creative input can lead to hypotheses, though, which can drive research and even lead to scientific discovery. Looking at phylogenetic relationships, scientists can predict intermediate evolutionary forms by combining derived and basal characteristics. For example, the Cretaceous ant, *Sphecomyrma freyi* is an intermediate species that shows a combination of basal characteristics of primitive wasps and derived characteristics of modern ants. Just about the entire body structure of this animal was hypothesized by scientists before they discovered it. This hypothesis is what led them to look for the invertebrate to begin with. This species helped support the evolutionary relationship between wasps and ants, and was found because of scientific speculation on the appearance of such an intermediate form [12].

Half the appeal of paleoart through the ages is the fact that it documents quite well the evolution of scientific thought over the past two centuries. In fact, the great animator, Ray Harryhausen enjoyed animating dinosaurs in particular since nobody knows exactly how they moved. It gave him more artistic freedom to experiment without criticism [14].

Even if a specimen is well represented, it does not guarantee an accurate restoration. It is important to note that some inaccuracies of early paleoart actually come from differences in interpretations of characteristics, opposed to limited source material. A long debate on the dorsal plate layout of *Stegosaurus* persisted throughout paleoart history. Many interpretations came through, including a proposed single row of plates, a symmetrical double row of plates, and a staggered double row of plates. This was not necessarily a result of poor fossil material, but rather the result of the layout of the fossils when found in the ground. Even if all of the fossils are there, the physical processes that take place just after death can easily jumble the remains into a near-impossible puzzle. This is particularly true for structures like plates and osteoderms, which are embedded in the skin opposed to having a definite visible connection to an adjacent bone [8].

Even with sauropods, the long necked largest of dinosaurs, debates still rage over posture, despite plenty of fossil material being available. In the early days, sauropods were thought to be aquatic animals with sprawled postures in order to support their weight. The elevated nares (nostrils) were also interpreted as an adaptation to an aquatic lifestyle [8]. Today they are known to be terrestrial with a more erect stance, but aspects like neck posture and orientation continue to be argued, and the use of digital imagery has been used to help make arguments for different hypotheses [36].

The line between scientific integrity and fanciful artistic restorations is often very fine. Simply portraying an animal in a dramatic pose can suddenly introduce too much speculation. On the other hand, tamed speculation can be harnessed to help theorize and promote research and scientific discovery. More than anything else, reconstructions and restorations need to remain as true to the source materials and related scientific literature as possible. The use of digital technologies in collaboration with the knowledge and guidance of working experts can help achieve this balance between science and speculation to create a credible and accurate result [8].

III. APPROACH

1. Project Planning

1.1. Workflow Overview

In order to improve upon digital paleoart, a project had to be designed. For this thesis, that project was to culminate in an animation depicting an extinct organism behaving as it did in life. The animation would use both reconstruction and restoration strategies to visualize the process of paleoartistic rendering, as well as show a connection between the original fossil source and the final restored animal. The level of paleo-authenticity of the project would also have to position it as a legitimate material for the teaching of paleontological ideas. Because of this, the final animation would ideally be displayed on a monitor mounted next to the actual fossils of the specimen it was depicting. This would help make the connection between the displayed fossils, and the living animal. It is important that the final piece does not overshadow the original fossil material itself, but rather augments the viewing experience and inspires spectators, while giving them the chance to make a connection with the animal whose remains sit before them.

The thought behind this project was to take the concepts of traditional paleoart and combine them with the techniques of digital paleoart in order to create an accurate restoration based on more accurate source material: the fossils themselves. While the traditional paleoartists started by studying, sketching, and hand-modeling the fossils they were referencing, three-dimensional laser scanning technology of today would be used to obtain accurate digital copies of a skeleton to use as the source. Instead of approximating the shapes of the skeleton based on visual insight, a Konica Minolta 910 digitizer would allow for extremely detailed data capture, while virtually eliminating the risk of human error.

After compiling the scanned data, any skeletal material that was missing or incomplete would have to be modeled or appended by hand. This modeling would be based on information about the missing pieces found in the scientific literature. For any part of the organism not described in the literature, closely related species within the animal's wider phylogeny would be used to approximate these parts.

After a complete skeleton was assembled, a control rig (the equivalent of a digital armature) would then be created in order to help pose and animate the creature. This rig would also incorporate a dynamic, anatomically accurate muscle system. Limits to the motion of the animal would be applied to the control rig based on constraints such as minimum and maximum angles achievable by the bones without interpenetration, as well as other limits based on estimated muscle mass. The muscle system would be constructed based on related species and principles of comparative anatomy; paying special attention to origin, insertion, and action of the individual muscles. The point of the muscle system would be to achieve heightened accuracy of motion, which was not easily achievable before the digital age. The entertainment industry uses muscle systems to make more believable creature animation by depicting skin sliding over muscle, as well as by simulating fat and muscle jiggle. These are approximated visible muscles, however, opposed to complete and accurate muscle systems.

After the underlying structure of the animal is setup, the outer skin of the creature would be modeled, sculpted, and textured. The skin would be conformed to the combined skeleton and muscle systems to maintain an accurate body shape. The look of this skin would be largely extrapolated from the animal’s morphology and the appearances of modern analogues, as well as some amount of aesthetic creative decisions. This process would complete the restoration by illustrating how the creature probably looked in life.

The final animation would have to portray the animal performing a number of natural motions. These visuals would also need to depict the science behind the animation by showing how the creature was built up from the fossil source. This final animation would start with imagery of the original skeletal material in motion. Slowly the other pieces would fade in. First the parts of the skeleton that were hand modeled would appear, and then the muscles would fade in on top of that. There would be a color coded distinction between the actual scanned bones and the approximated hand modeled pieces that were added, in order to maintain the visual connection to the original fossils. Finally the skin and final restoration of the animal would be revealed. It is important to show this buildup so that the process from fossil to living animal would be apparent. It is important that the animation be about the fossils and their scientific significance above all else.

After this “schematic” presentation of the fossils and restoration is shown, a more narrative sequence would then be portrayed, to show the depicted organism in its restored paleo-environment. The purpose of this section would be to transport viewers of the fossils to another time, and show how the animal likely behaved in life, based on behavioral characteristics derived from the morphology of the fossils as well as from modern analogues.

1.2. Thoracosaurus neocesariensis

An important concern when undergoing such a project is what specimen to use as a starting point. As previously discussed, a primary issue in reconstruction and restoration is incompleteness of the fossil record. In order to get more accurate depictions, more complete fossil material must be used. The source of this project was a local species of prehistoric crocodylian, *Thoracosaurus neocesariensis*, which was excavated by students from both Drexel University and the University of Delaware, under the supervision of paleontologist and associate professor at Drexel, Dr. Kenneth Lacovara (Fig. 5). It was found in the latest Cretaceous deposits of Gloucester County, New Jersey, which was a mangrove swamp at the time. There were a number of advantages to using this *Thoracosaurus* as the source material for the project.

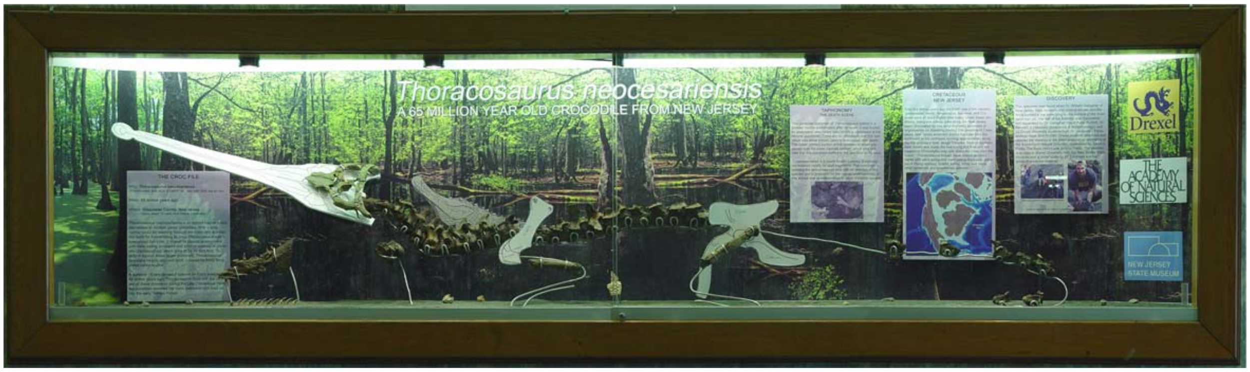


Figure 5 The nearly complete *Thoracosaurus neocesariensis* on display in Stratton Hall, Drexel University

The specimen of *Thoracosaurus* is a part of the collections of the New Jersey State Museum (NJSM NH 2005.2). This specimen is from an animal that was approximately sixteen feet long, and the skeleton is considered to be nearly complete. Normally when *Thoracosaurus* material is found, there is very little post-cranial (body) material [33]. This specimen, however, has most of its vertebrae and even pieces of the skull and limbs. This animal was a good place to start this venture into digital paleoart since the bodies of most crocodylian species are generally very similar [5]. Because of this, all skeletal material that was not represented in the specimen and not described in the literature could be safely approximated based on descriptions of related fossil crocodylians, as well as modern gharials, crocodiles, and alligators. This would minimize the amount of speculation involved when working with incomplete fossil material, since the modern analogues are considered to be very similar.

Crocodylian muscle structures and locomotion are also very well documented, which would be helpful throughout the project. Well documented literature would be used to provide a great reference for the shapes of missing skeletal material, as well as for the musculature. For the motion of the animal, the animation would pay particular attention to the major motions of large crocodylians, such as the high-walk, the belly-crawl, and swimming motions [31]. The goal for the final animation would be to put it on display as an augmentation to the *Thoracosaurus* display at Drexel University. This would keep viewers of the animation connected to the original fossil material while providing more insight on the fossil specimen.

Restoring *Thoracosaurus* also opened the opportunity to use many local resources, since the specimen was excavated by Drexel students. It allowed for working directly with local paleontologists in order to guide investigations and productions in the appropriate directions. For this project, the major paleontological experts were also to be members of the thesis committee. These experts were:

1. Dr. Kenneth Lacovara Ph. D. – A professor at Drexel University, Dr. Lacovara was crucial for setting up the project, considering he supervised the excavation of the *Thoracosaurus*. Aside from general knowledge about the animal, his paleoecology expertise would be central to guiding the creation of the environment, the animal's behavior, and the overall narrative of the final animation.

2. Jason Poole –A working paleoartist, and the manager of the Fossil Preparation Lab at the Academy of Natural Sciences in Philadelphia, Jason's expertise on crocodylian osteology would be pivotal to the reconstruction of the full

Thoracosaurus skeleton. He would also be an impeccable resource for research on phylogeny, motion, and general crocodylian biology.

3. Dr. Peter Dodson Ph. D. – As a Professor of Anatomy and Paleontology at the School of Veterinary Medicine at the University of Pennsylvania, Dr. Dodson would prove to be the best possible resource for the muscle restoration. His insight would also be vital to the skeletal reconstruction, the motion, and to research in general crocodylian biology.

Although they each had their areas of expertise, each committee member would also provide informative insight to all aspects of the project. The constant dialogue between art and science, and the critiques from a paleontological perspective would prove to be critical in the success of the project.

Because of all of these factors, *Thoracosaurus neocesariensis* was an ideal starting point for research in accurate digital paleoart. The product of this project would not only provide an animation to the public, but in the process it would create a modular digital asset that could be used to safely study and test other questions about the animal. The restoration could even be updated in the future as new research and discoveries about *Thoracosaurus* are unveiled. Newly discovered, more complete specimens, for example, could be scanned and integrated into the existing rig in order to adjust the restoration, making it more and more accurate and up-to-date over time. Because of this, the project is able to combine the ideas of paleoart as scientific results with paleoart *for* scientific results. The work on this project would also establish a pipeline and provide a solid foundation for the restorations of other prehistoric animals in the future, many of which have more speculative and theoretical constructs, such as the crocodile's fellow archosaur cousins, the dinosaurs.

2. Working with Scan Data

2.1. Background of the Scanning Process

Over the course of 2009, the scanning of the *Thoracosaurus neocesariensis* was completed. There were two attempts at this lengthy process. The first was in March 2009. At that time, Drexel digital media students Mark Petrovich and the author worked together under the supervision of Ph. D. students from the paleontology program to scan the fossils. Two nightly scanning sessions took place, resulting in successful scans of most of the spinal column. Each fossil required about twelve scans from different angles, to be later stitched together in the scanning program to create a single scanned fossil. The program used for scanning at the time, PET (Polygon Editing Tool), was very cumbersome and would tend to constantly crash, losing work and causing constant frustration when trying to stitch scans together.

Figure 6 Evan Boucher (left) works PET as Mark Petrovich (right) prepares vertebrae for scanning

Because of this, new scanning software was purchased, Geomagic Studio, which was intended to simplify the workflow. It was also supposed to be able to link up to a turntable to automate the process of stitching the different scans together into a single piece. No headway had been made on this automated workflow, however, as the process came with no documentation. After many failed attempts to get the turntable working, and many months of waiting, scanning with Geomagic Studio went ahead over the summer of 2009. This was run by two digital media STAR students, Girish Balakrishnan and David Myers, as part of their various scanning duties for that summer. They worked, once again, under supervision of Ph. D. paleontology students as well as with the author. This scanning took place over the course of two three or four hour sessions a week for about a month. At the end of the scanning, the files were stored, and backed up in multiple places for later use. Shortly after the second round of scanning is when this project commenced. Everything was in place for the reconstruction of *Thoracosaurus neocesariensis* to begin.

Figure 7 Girish Balakrishnan prepares the dentary for scanning with Geomagic Studio

2.2. Scan Stitching

With all of the fossils scanned, there were still a number of steps that had to be taken for each of the fossils before they were ready to be used in the reconstruction. Most of this process required taking sets of raw point cloud data from the scanning session, and combining them together to create a complete object. It then required taking that solid object and polygonalizing it; that is, turning it into a surface made up of polygons so that it could be used later in the pipeline. The basic process required the following.

1) Before stitching any scans together, extraneous points that the scanner picked up had to be deleted by hand. Since the scanner simply runs a laser over the surface of what is being scanned, there is no way for it to determine what is wanted scan data and what is extraneous data from the surroundings of the scanned subject. What it picks up is simply a matter of depth from the lens. Because of this, the scanner often picked up the tarp that the fossils were placed on while scanning. For more complex objects that could not support their weight on their own in certain positions, prop objects were used in the scanning process to prevent the fossils from toppling over and breaking. As a result, parts of many of these prop objects were picked up in the point cloud data, including objects such as rolls of tape, the lens cover of the scanner, and even fingers when someone from the scanning team had to hold the fossil in place as a last resort.

Because of this, the first step to combining scans was to remove any surrounding points that were not part of the subject. This process required the user to inspect each of the 8-20 scans (per object), and then hand select and delete any extraneous points. At first, worries arose about deleting an extra point or two in areas where the fossil subjects met the surrounding surfaces, but this really was not a significant issue since piecing the scans together involved finding matching points on multiple scans, resulting in many overlapping scans at these edges, which therefore filled in those possible missing points.

2) After removing extraneous points on all the scanned data for each bone, the next step was the registration process. To complete the registration process, the user had to first find two scans with matching features. After selecting those two pieces, and using the “manual registration” option, a new workspace displayed a viewport for the first scan, a viewport for the second scan, and a third viewport showing how the two scans matched up after the registration. The user had to click a point that matched in both individual scan viewports, and see how they lined up in the third viewport. For more accurate results it was best to use at least three points of registration, so the software could properly triangulate the positions and move the scans to line up with one another. The process could be completed by selecting only one point, but most of the time this produced less than favorable results. With only one point, the algorithm could match the position of that shared point, but not the orientation of the object.

3) After the manual registration of two scans was complete, a “global registration” option was used, which tries to automate what the manual registration does. It was best to do this only *after* the manual registration process, because otherwise the scans would not be close enough to one another for the program to know how to accurately match them together. The global registration basically looks at the topology of the points between the two scans and tries to match every overlapping point together the best it can. This was helpful after manual registration so that one could rely on human intuition to line up the scans as best as possible, and then use the automated global registration to have the overlapping scans adjust and literally slide into place, with the precision of a computer.

After two sides of a scanned object were successfully matched together, the result was a slightly more complete scan, which was essentially a group of two scans that were properly oriented to one another. No detail was missing, and the scans, although lined up, were not actually combined into one piece just yet. The registration process then had to be repeated, finding another piece to match to that correctly oriented group, and going through both manual and global registration processes until all 8-20 pieces were matched up, or until a completed object was assembled.

Once an object was completely stitched together, there were a few more steps that had to take place before the object was ready to export to a format that animation applications could use. First, the multiple, correctly oriented sides had to be combined into one, non overlapping polygonal mesh object. This process is automated, by simply using the “merge” tool. After an object was merged into a polygonal mesh, the original data was still in the file, but hidden. This was so the program could run with real-time feedback, since it no longer had to display so much data in the viewport.

The last step in stitching scans together required cleaning up poor geometry and filling holes, where needed. This was done through the “mesh doctor” option, which cleans up extraneous points, softens areas where the averaging of points created strange spikes and intersections in the geometry, and fills holes in the mesh. Where there were large holes, or holes that were filled in unacceptable ways, there was the option of going in manually and “bridging” areas together to create the proper contours when filling in holes. This became quite common in complex objects like vertebrae, since there are deep areas, such as inside the neural canals (where the spinal cord passes through) where the digitizer was unable to collect data. Long bones, like those from the limbs, scanned much more completely than irregular bones like vertebrae, where the "fill-holes" tool had to be used a bit more extensively.

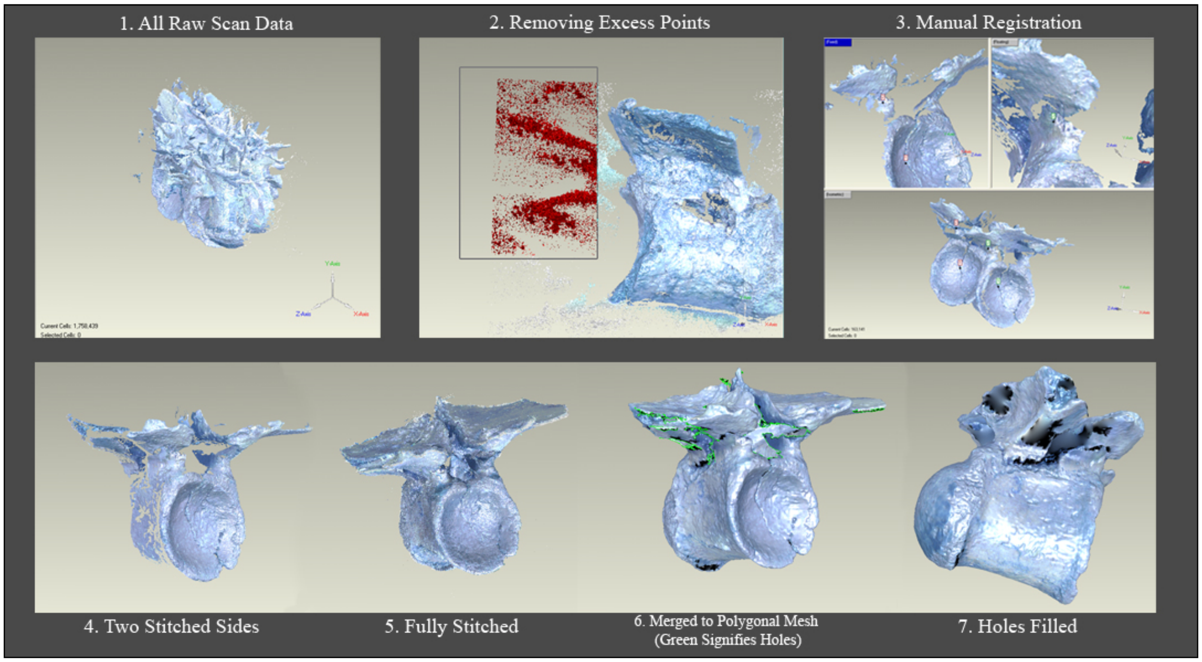


Figure 8 A digitally scanned fossil undergoing the stitching process

Once all of this was completed for a single bone, the combined object could then be saved as an ".OBJ" file for other 3D packages to work with. Stitching scans together quickly became a much larger task than originally expected, as this process had to be completed for 40 scanned fossils. It was the first step to be completed, and one of the most time consuming tasks of the project. After experience with both processes, there are many advantages to piecing fossils together in the physical world with glue over piecing in the digital world. This is mostly because of how slow the computer became due to the tremendous amount of data that Geomagic Studio had to handle. It slowed down considerably when trying to register the last couple scans of each object together. This was because one had to work with all of the scanned data at the end of the process, since the data did not combine into a polygonal mesh until after the registration process was complete. Also, when gluing fossils together in the physical world, one can feel where matching parts click into place, confirming exactly where they go. In the digital realm it is a strictly visual process, with no tactile confirmation.

Being a strictly visual process, there were other challenges in piecing scans together besides viewport slowdown. With the digital scans, the points of the original point cloud data that were further away from the focal point of the scanner's lens became rougher and less precise due to the focal distance of the lens. This meant that using points closer to the edges of the scans as registration points became increasingly difficult. Also, there was the issue of the complexity of the fossils. With many crevices and irregular shaped bones, it was difficult to gather all the sufficient data with the scanner. Geomagic has its method of filling holes, by averaging the distance between points of the scan data, and although it mostly worked pretty well, it also naturally introduced a degree of inaccuracy. Some of the more complex objects also had larger holes, which required more manual guidance when filling them, further increasing the probability of human error.

Certain fossils were undoubtedly more challenging to stitch than others. Pieces such as the limb bones, most vertebrae, and scutes (i.e. osteoderms – armored plating in the skin) were relatively simple to put together, while other vertebrae and the pieces of the cranium were particularly difficult to complete. In the case of the skull pieces, (particularly the parietal, frontal, and squamosal bones; although there was sufficient scan data) there was not always sufficient overlapping scan data, resulting in more manual registration. These cranial bones, in particular, were all very flat and thin, so, although the top and bottom sides were relatively easy to scan, the connective edges between the top and bottom were difficult to capture (Fig. 9). This resulted in a lot more effort spent lining everything up properly. These fossils are particularly fragile. They are heavily broken and eroded, with some parts being held on by a single thin layer of Paleo-Bond^{TM} brand glue.

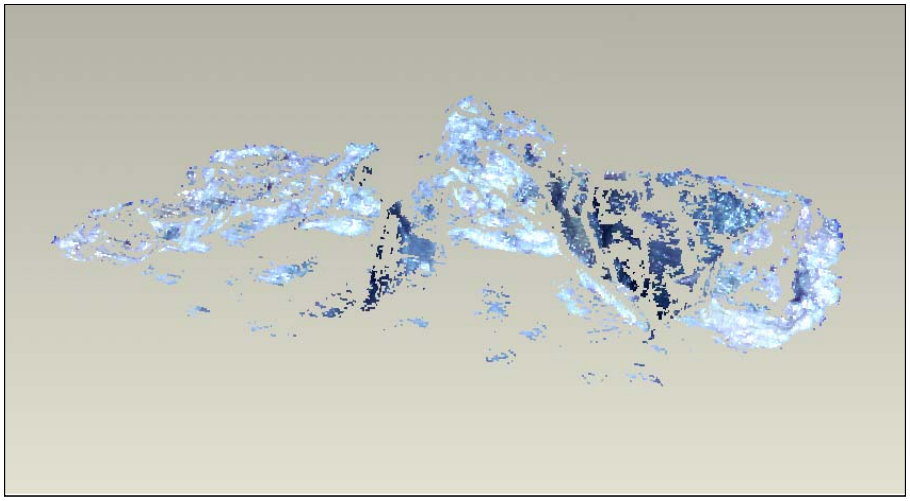


Figure 9 The shape of the fossil sometimes makes it difficult for the scanner to pick up data

There were also issues that arose as a result of poor file management when scanning the fossil data. In the case of one of the dorsal vertebrae, for instance, only about half of the bone was represented in the scan data. Before setting up another scanning session to recover it, a scan of the bone from the older PET scan data was more than sufficient to put the vertebrae together. Using PET data from the first scanning session also worked for another complication that was discovered when compiling the entire skeleton in one of the 3D applications. While using photographic documentation of the *Thoracosaurus* display case to guide the placing of the bones adjacent to one another, it turned out the 11th vertebrae had been altogether skipped during the second scanning session. The first session accounted for it, however, and the missing bone was also able to be recovered using the PET data.

It is also important to note the importance of labeling and documenting files during the process of scanning. The students who were in charge of the scanning occasionally did not adhere to strict naming conventions. These clerical anomalies caused much confusion and might have been responsible for how a vertebra was skipped. For future projects, it is suggested to have a paleontologist's direct supervision to help develop a data framework with strict clerical naming conventions appropriate for the complex task of digitizing fossils. This would reduce the number of errors that occur. Corrections to the naming errors in this project have been made, as it was important to get the files into a correctly organized state. It is imperative that the organizational structure and naming conventions of the files do not confuse anybody who might attempt to work with the data in the future.

In the end, scanning fossils is a great way to create copies that can be replicated and shared, but the current process is not really significantly more accurate than the old practice of making physical casts. In time, with advances such as implementing tools such as the turntable stitching algorithm, the scanning process may become a much more accurate way of replicating fossils, with little effort. For now it is not necessarily the best way to get the most accurate fossil replicas. It is, however, still a great way to digitize an incredible amount of detail, and, in doing so, leads to infinite possible uses of that digitized data. Most of the hard-to-scan areas included places like the inside of neural canals, which although important to the individual bone, do not change much on the scale of the full animal. Motion studies of the animal will not be compromised by the inside edges of the deep canals of the spinal column. It is no more inaccurate to reconstruction than the fact that the fossil sources themselves are often compressed and warped from being in the ground for millions of years. Despite the headaches and possible inaccuracies that arise from stitching scans together, digitizing has been proven to be a great basis on which to do a paleo-reconstruction and restoration.

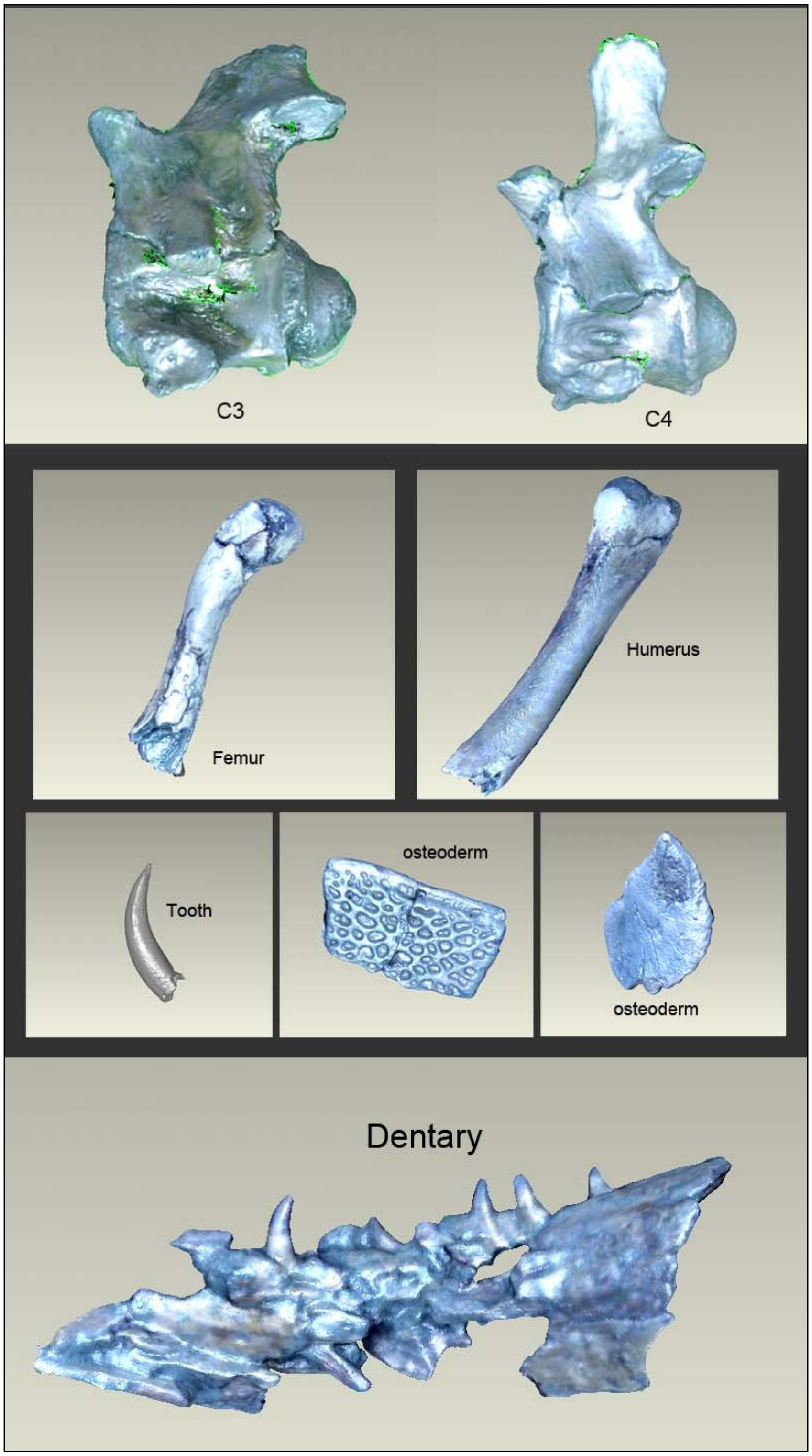


Figure 10 Fully stitched fossil scans in Geomagic Studio

2.3. Integrating for Animation

After all the scan data was put together, time had to be spent looking at ways to reduce polygon counts of the fossil models in order to make them useable for animation without overburdening the animation applications. The full resolution scans are priceless for the scientific community, but are very impractical in an animation production environment. One way to fix this would be to have to trace around, and model every bone to create low resolution versions to use, but this would have taken an incredible amount of time and would have defeated the purpose of scanning.

Fortunately, Geomagic Studio offers a tool to adjust polygonal density. Based on my past 3D modeling experience, I estimated that around 10,000 triangular faces would be a good number to use to keep the majority of the fossil detail while reducing the number of faces significantly. The original scans, once converted to polygonal meshes, were comprised of approximately 400,000 triangular faces per fossil. Reducing to 10,000 triangular faces is an extremely significant reduction. This is only 2.5% of the poly-count of the original resolution. Despite this incredible reduction in resolution a great amount of the fossil detail was still preserved in the geometry (Fig. 11).

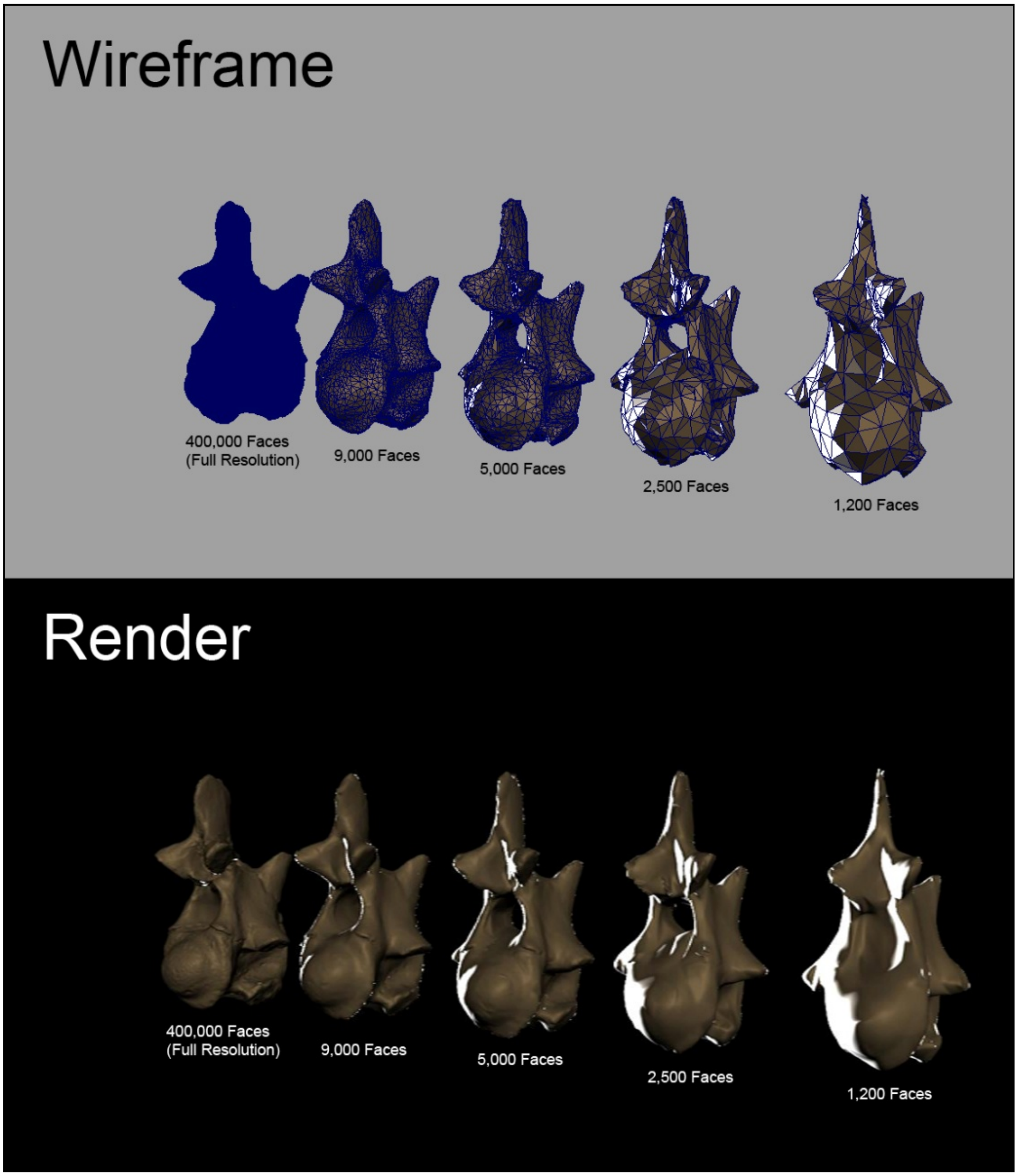


Figure 11 Resolution comparisons of a cervical vertebra

A series of corresponding lower resolution objects were then created from each high resolution bone, to help compile a full, and system friendly skeleton. These consisted of .OBJ files consisting of 10,000 tris, 5,000 tris, and 2,000 tris, respectively. Once this was done, the full digitized fossil material could then be compiled in Side Effects Software's Houdini.[1] This application allowed for much less computing power to be used when placing the lower resolution bones, and then for those positions to be applied directly to the higher resolution bones. Once higher resolution geometry was swapped in, continued finessing toward optimal positions could take place. A number of *Switch* nodes were then built for each fossil bone, as well as a control that simultaneously affected all of those *Switch* nodes (Fig. 12). This made it very easy to swap out the geometry for the entire skeleton at once; to lower or higher resolutions as I needed.

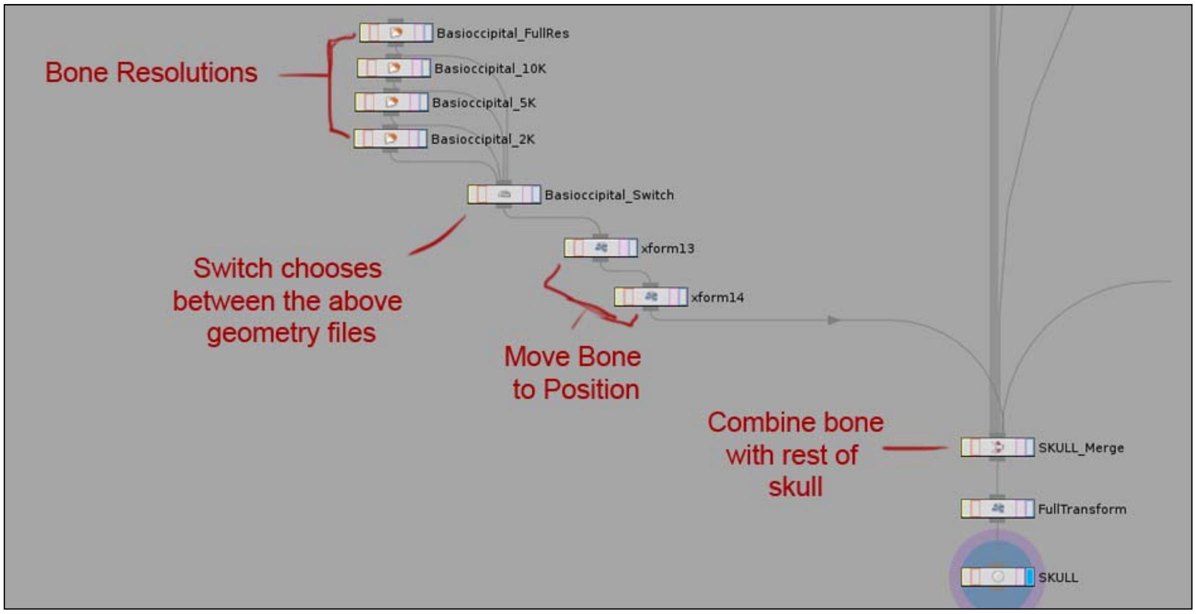


Figure 12 The Houdini workflow of one bone of the compiled skeleton

There was one last step to be done before moving on to hand-modeling the missing portions of the skeleton. Autodesk Maya is a much more intuitive tool for modeling than Houdini, and the tool that most of the project was to employ in. The reconstructed skeleton therefore had to be transferred from Houdini to Maya. This was achieved simply by exporting a Film-box® ".FBX" file which contained all of the polygonal geometry and motion data from Houdini. When importing this .FBX into Maya, the geometry came in as a single giant piece, which would not work for adjusting placement, or for the future rigging of the creature. In order to get the skeleton in a useable form, the "Mesh > Separate" option inside of Maya was used to split the geometry back up into the individual bones. This option basically takes any pieces of geometry that are independent from one another (i.e. unmerged vertices) and splits them up into separate objects based on those boundaries.

The 10,000 tri resolution of the *Thoracosaurus* fossils ran smoothly within Maya, which made working with the scans much easier throughout the entire pipeline of the project.[2] Once the digitized skeleton was fully stitched, compiled, and brought into Maya, modeling the missing skeletal pieces could begin (Fig. 13).

Figure 13 The fully compiled fossil material

3. Creating the Control Rig

3.1. Finishing the Skeleton

Before moving ahead with building bones from scratch, a lot of research had to be done on *Thoracosaurus* and general crocodylian anatomy. Luckily there was some known information about *Thoracosaurus neocesariensis* acquired from the various paleontologist advisors involved in the project, which was used as a starting point. It was known that *Thoracosaurus neocesariensis* was a longirostrine gavialoid crocodylian [3][33]. This means that its closest living relative is neither the alligator nor the crocodile, but rather the extremely endangered Indian gharial (*Gavialis gangeticus*) (Fig. 14). Gharials are the second largest of living crocodylians and are characterized by their long narrow jaws and needle-like teeth, which are used for catching and holding fish; characteristics that were also present in *Thoracosaurus* [38].

It was also known that the gavialoid body plan of *Thoracosaurus* was adapted for life in the water. The specimen (NJSM NH 2005.2) came from the green sands of the Maastrichtian-Danian (Late Cretaceous-Early Paleocene) Hornerstown Formation of New Jersey (Fig. 15). This means that this was a species that actually survived the extinction that killed the non-avian dinosaurs. The color of the green sand is from the presence of glauconite. Glauconite is commonly attributed to what were once high depositional marine environments. Because of this, *Thoracosaurus neocesariensis* is thought to have lived in a tidal mangrove forest where New Jersey once was, 65 million years ago [33].

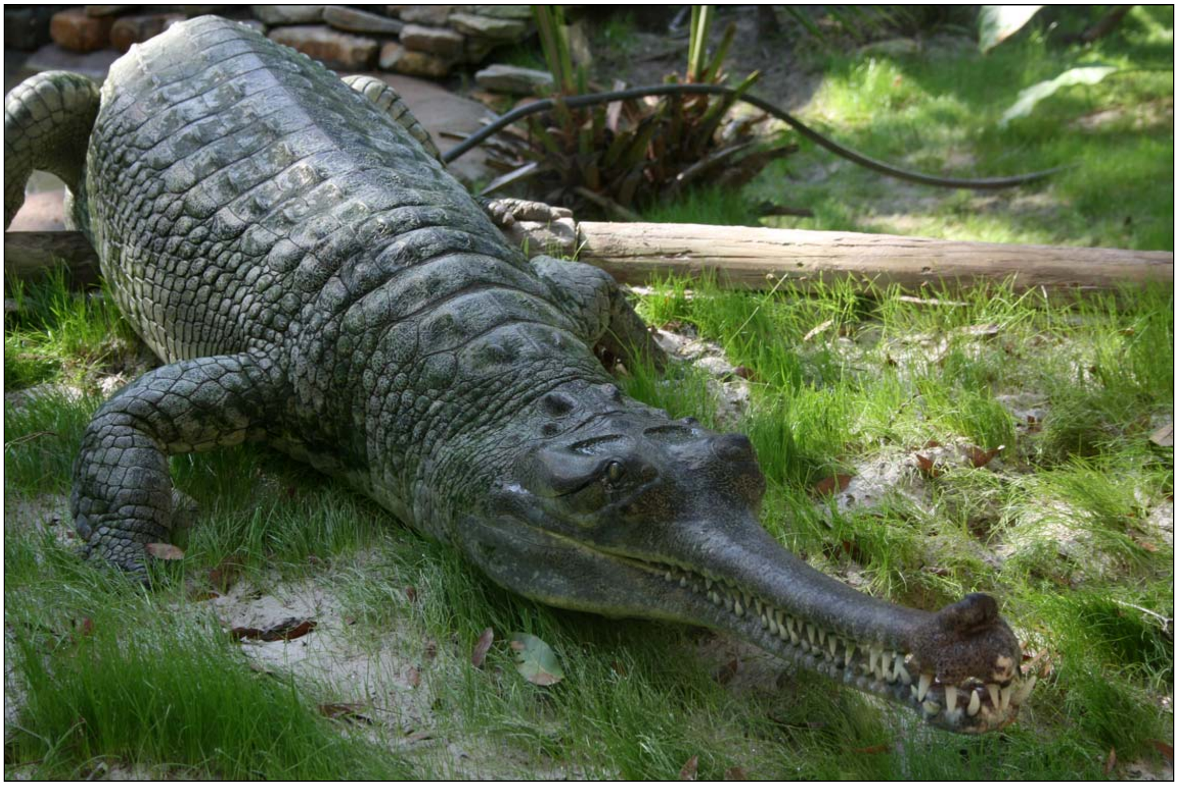


Figure 14 A male Indian gharial. Photograph attributed to: Jonathan Zander on Wikimedia Commons

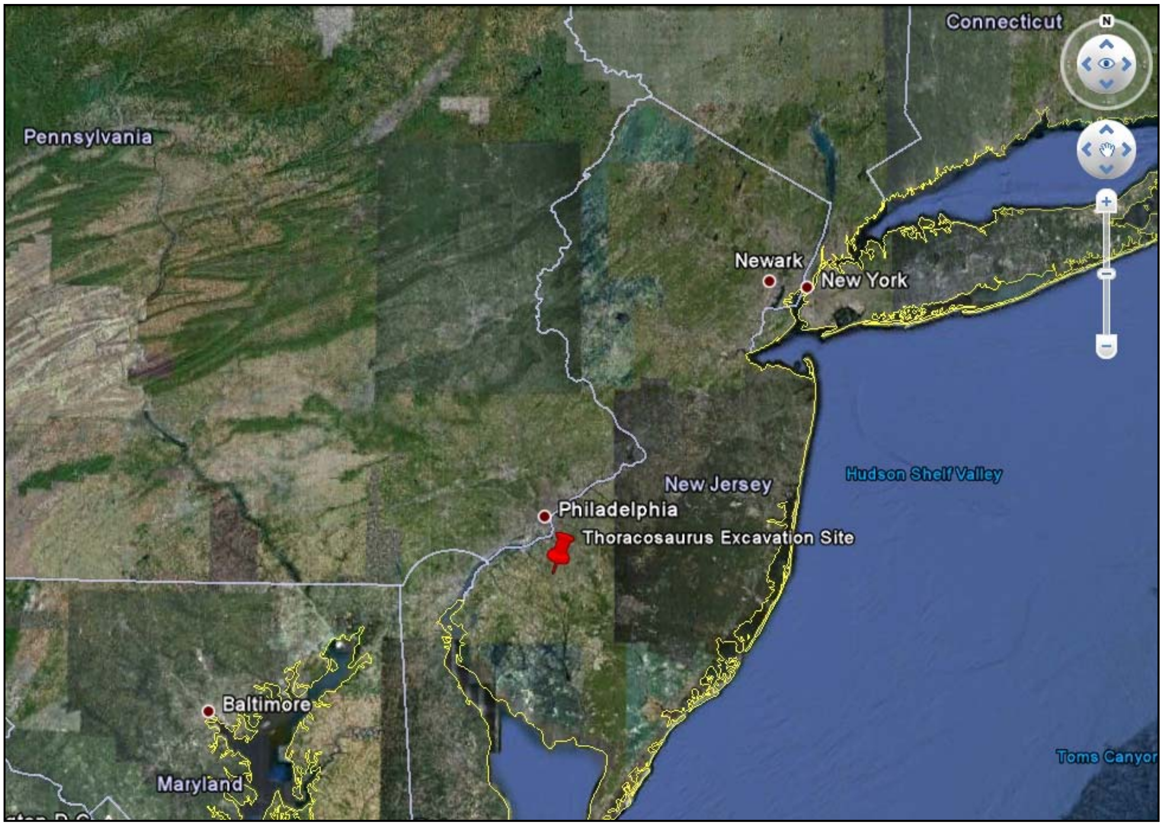


Figure 15 The location of the *Thoracosaurus* excavation site. Image ©2010 Google

This start was invaluable information; knowing to search through not the entirety of the complex phylogeny of Crocodylia, but rather to narrow down to the evolutionary history of *Gavialis* (Fig. 16). Knowing it would be the most difficult part to model, as well as the most distinguishing part of the anatomy, the skull was the first part to be built. This provided a good place to start the research – to find as much information about the skull morphology of *Thoracosaurus* and its closest relatives. Although narrowed down significantly, the difficulty of this task was compounded by the fact that there is not much literature to be found on *Thoracosaurus neocesariensis* in particular. It is a species that is mentioned and referenced a lot in the literature, but there is hardly any information that exclusively describes it. The title specimen in a paper by Kenneth Carpenter from 1983 (exclusively on *Thoracosaurus neocesariensis*) was even later redescribed by Christopher Brochu as a new genus and species, *Eothoracosaurus mississippiensis* [4].

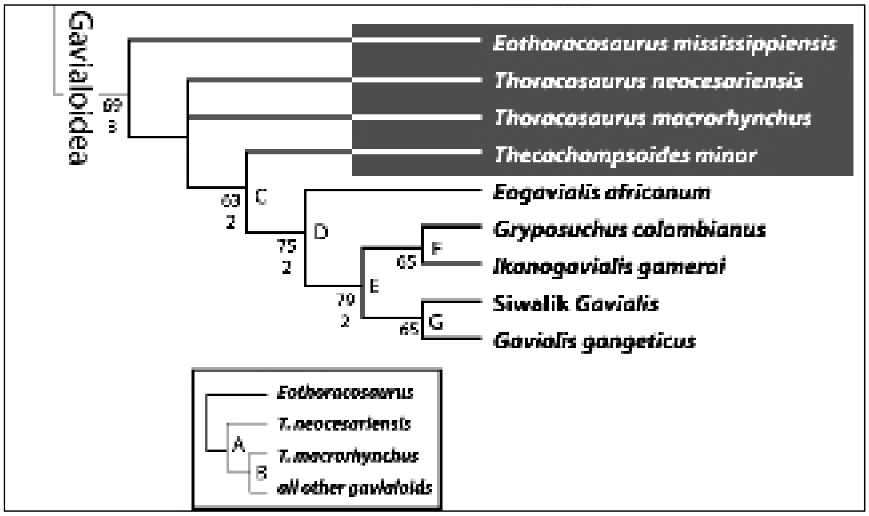
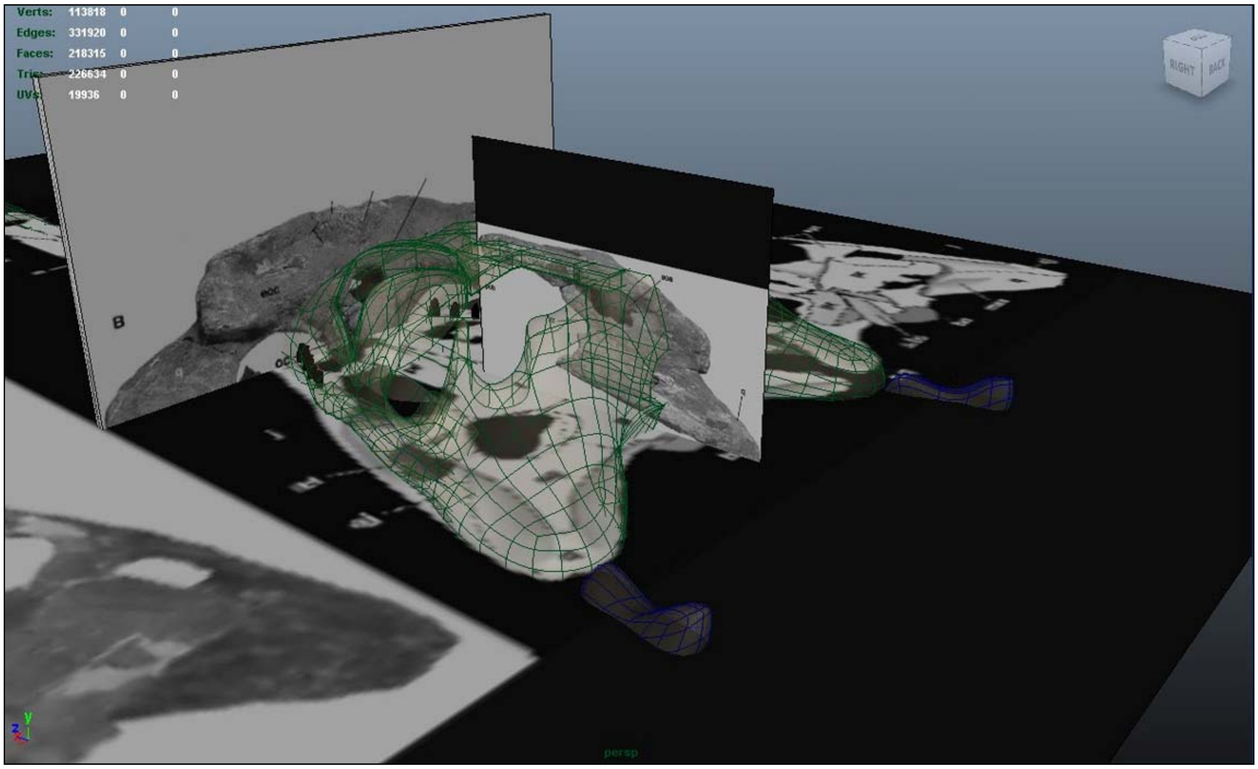


Figure 16 Brochu's phylogeny of Gavialoidea. The grey box indicates the paraphyletic group of "thoracosaurs." Image credit to Brochu 2004 [4].

With very few descriptions of *T. neocesariensis* found in the literature, the primary species that the skull model was originally based on were *Eothoracosaurus mississippiensis* and the modern *Gavialis gangeticus*. *T. neocesariensis* exists somewhere between these two in the family tree, with *E.mississippiensis* being a very basal gavialoid (closely related to *Thoracosaurus*) and the gharial being the closest modern analogue. Since Brochu is reinterpreting a described specimen in his paper, he points out key differences between the osteology of *E. mississippiensis* and *Thoracosaurus*. His paper also includes a plethora of orthogonal diagrams of the *Eothoracosaurus* bones complete with scale markers, which would be crucial in keeping all the reference imagery in real-world units for accuracy when modeling. These orthographic images were imported directly into Maya to use as cross sectional image planes to model from (Fig. 17). The images included very good top and bottom (dorsal and ventral) views of the skull as well as a great top view of the mandible, or lower jaw, from the type specimen of *Eothoracosaurus*. Brochu's paper also includes images of a side and back view of a braincase of another *Eothoracosaurus* specimen. All the relevant differences that Brochu noted between *Eothoracosaurus* and *Thoracosaurus* were taken into account when modeling [4].

For parts of the skull where no reference imagery could be found from *Eothoracosaurus*, gharial skull photographs were referenced. Extremely helpful 360˚ turntables of a CT scanned gharial skull were found to help this process. These scans have been made available for public download, and can be found on the website for the Digital Morphology database at the University of Texas at Austin (www.digimorph.org). It is important to note, despite the fact that all of this detailed reference imagery was used to reconstruct the skull, the scanned fossil bones of the *Thoracosaurus* took precedence over the reference imagery. If shapes of the model did not line up perfectly with the laser scanned fossils when based on the reference imagery, the model was adjusted to favor the fossil material.

The area of the skull ventral to the braincase (pterygoids, transpalatine, etc) was incredibly difficult to model since the orthographic photographs have a tendency to compress depth. As a result, any detail or complex topology could not be deciphered from these images. There is the explanatory text that accompanies the images to aid with this; however, trying to reconstruct a surface without adequate depth cues in the visual references to what one is reading about is very counter intuitive to an artistic mind. This area of the skull was modeled as best as it could be for the time being, with the use of various diagrams and photographs from a variety of different types of crocodylians.



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Verts:   113818  0    0
Edges:   331920  0    0
Faces:   218315  0    0
Tris:    226634  0    0
UVs:     19936   0    0
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Figure 17 Modeling the *Thoracosaurus* skull based on reference imagery from *Eothoracosaurus*

The various reference images revealed that the gharial skull was much longer than the *Eothoracosaurus* skull, creating a dilemma over which snout length should be used for the model. Through research of gavialoid crocodylians, it was discovered that snouts in modern gharial are negatively-allometric. As gharials grow, their snouts become relatively shorter and blunter over time [38]. In the fossils of the *Thoracosaurus*, the skull fragments contain very clear sutures that have not yet completely fused together. This was interpreted to mean that this *Thoracosaurus* specimen was not a full grown adult [33]. Combining this fossil data with the analogue of allometry in gharials is what led to the decision to build a longer snout than the one found in the type specimen of *Eothoracosaurus* described by Brochu.

The teeth then had to be integrated into the skull. The number of teeth was estimated based on a combination of factors: 1) the relative space between the scanned fossil teeth that are still embedded in the *Thoracosaurus* dentary, 2) the number of alveoli (tooth sockets) found in the *Eothoracosaurus* orthographic images, and 3) how many teeth with the spacing of the *Eothoracosaurus* teeth would fit in the extended gharial snout. There is also a difference in alveoli spacing in *Eothoracosaurus* and *Thoracosaurus* toward the end of the lower jaw, noted by Brochu. The third and fourth dentary alveoli of *Eothoracosaurus* are compressed and extremely close together, leaving gaps on either side. Brochu mentions how they are more evenly spaced in *Thoracosaurus* [4].

In production, the alveoli took some time to embed in the jaw, since each round socket had to be embedded into a very rectangular object. In order to properly match the edges of the geometry from the alveoli models to the lower jaw model, techniques had to be used to properly distribute the edges of the object to easily transition from the relatively dense alveoli model to the rest of the snout (Fig. 18). It required a lot of brute, repetitious modeling work. A tooth was then placed in each socket. Each tooth was a duplicate of a scanned tooth, and some variation was introduced to the size, shape, and orientation of the teeth to keep them from looking too unnaturally uniform.

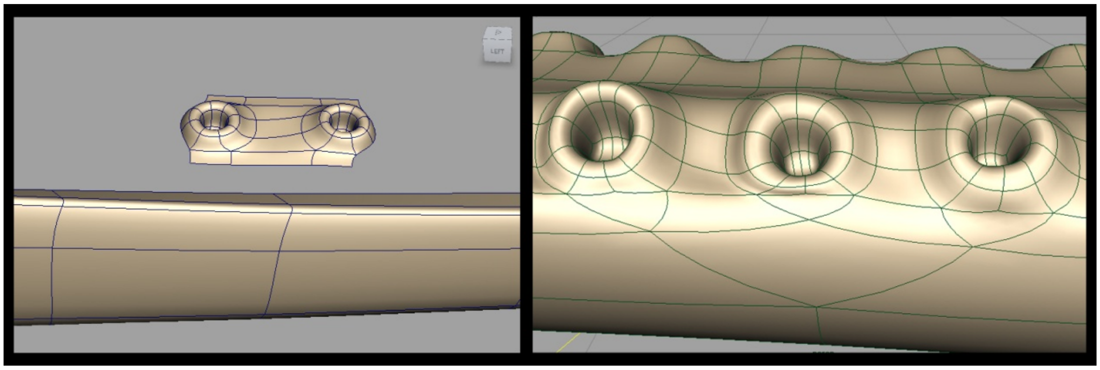

Figure 18 The alveoli model before (left), and after embedding into the jaw model (right)

The most puzzling aspect of the skull was definitely the lower jaw.
The *Eothoracosaurus* jaw is much more robust and dorsal-ventrally elongated than the gharial jaw. The gharial jaw is much more streamlined. The *Eothoracosaurus* jaw angles down steeply, and far away from the top of snout, which made it look like the teeth would never be able to clasp together if the skull had an *Eothoracosaurus* jaw. To

try to use elements from both *Eothoracosaurus* and *Gavialis*, the articular surface between the articular and quadrate bones from the *Eothoracosaurus* was used and combined with a more gharial-like jaw.

If one were to follow the reconstructed jaw at this state rostral (towards the nostrils), he or she would notice a problem with the actual scanned fossil part of the dentary. It has a pretty sharp angled kink in it when viewed from above. When placed where it matched along the length of the reference imagery of the jaw in the top view, it made it appear too tall for the gharial jaw and too short for the *Eothoracosaurus* jaw references in the side view (Fig. 19).

At this point an interesting area on the inside of the scanned dentary was discovered. There appeared to be a crack conveniently placed at the previously identified "kink" on the inside of the fossil. It appeared as if this kink was not actually osteological. The crack on the inside of the kink appears as if the kink was a result of finding the best fit for the Paleo-Bond^{TM} brand glue to hold the bone together when assembling for display purposes. This is something that was discovered thanks to my experience in fossil preparation. Highly fragmented bones, when glued together, have a tendency to warp and misshape a bit, due to the extra space between the cracks as a result of gluing. In order to test this idea, digital tools that are normally meant for animating and modeling were put to use. A deforming lattice was used to carefully warp the dentary to fix the “kink” and close the proposed crack. This allowed for the dentary to return to a more natural position, which would be impossible to achieve in the physical world. After removing this kink, the scanned dentary piece fit better along the jaw when it was moved further back (Fig 19). This then seemed to fit very close to the gharial jaw reference, and created a more gradual thinning of the snout, removing any unnaturally sharp angles along the length of the jaw.

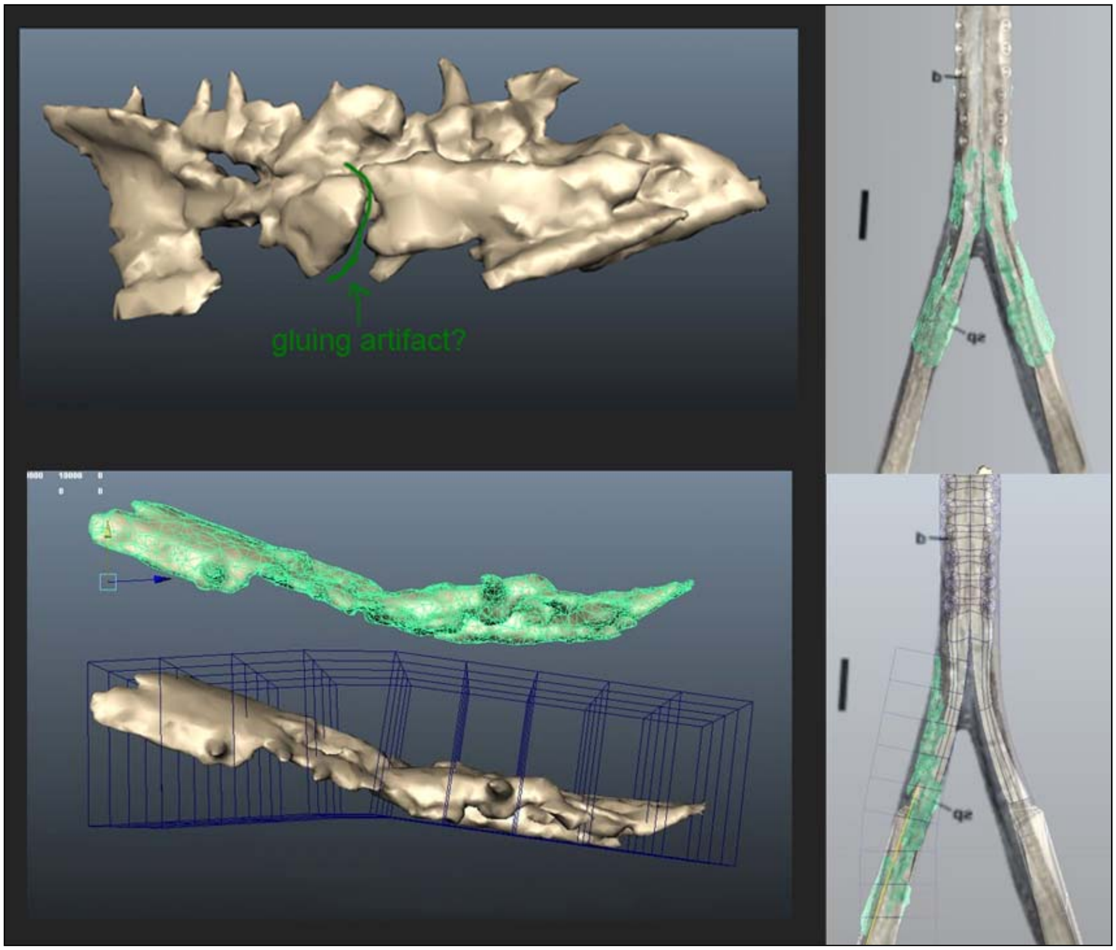

Figure 19 The dentary "kink." Top Left: The crack causing the kink. Bottom Left: The shape of the dentary before and after the lattice deformer was applied to fix the shape (dorsal view). Top Right: the alignment of the dentary along the *Eothoracosaurus* jaw reference before the fix. Bottom Right: The alignment after the lattice deformer.

Before finishing the skull, a key meeting with the paleontologists mentoring the project took place. It was clear that there were a number of changes to be made to the shape. First of all, a bit too much of this original skull model was derived from the gharial. Even though the gharial is the closest living relative of *Thoracosaurus,* it is important to note that the gavialoid line continued past *Thoracosaurus* for 65 million years. Gharials are extremely specialized animals, and not quite what one would expect to see in the more basal gavialoid crocodylians. Their traits developed over a long period of time. It is difficult to use their skeletons as a reference since they are so specialized. Before too much gharial influence permeated the model, the project mentors informed that the holotype of *Thoracosaurus neocesariensis* is in fact at the Academy of Natural Sciences of Philadelphia. This means the original *Thoracosaurus neocesariensis* specimen found (ANSP 10079), of which all other specimens are based, was local and available to inspect (Fig. 20).

Figure 20 The holotype of *Thoracosaurus neocesariensis* (ANSP 10079)

After learning of this crucial piece of information, a photographic survey of the holotype was undertaken to use as reference instead of the hybrid gharial-*Eothoracosaurus* images that were previously used. A cast of an actual, physical alligator skull was also acquired on this trip, which was lent out for the duration of the project. This was incredibly helpful when reworking the inside of the skull, where the previously mentioned images that failed to portray depth did not work so well. Major changes in the skull modeling included the following (Fig. 21):

- A much steeper angle was achieved dorsal-ventrally coming off the back of the braincase.
- A much less pronounced slope from the orbits to the maxilla. This suggested that the *Thoracosaurus* eyes would not be as high on the head as those of the gharial. Adjustments also had to be made to the angle and orientation of the frontal scan to match the new reference imagery.
- The eye shape was tweaked to fit the contours of the *Thoracosaurus* holotype, opposed to the gharial reference.
- The jugal bone became much more pronounced, and the post-orbital bar became thinner.
- The inside of the skull was altered significantly. The alligator skull cast was incredibly helpful to help perceive the three-dimensionality of the bones. It was surprising how much the still image reference confused the shape of the inside of the skull. Orthographic images of fossils can be extremely

misleading because of how compressed the space becomes. Being able to perceive depth in these images would have helped significantly.

- It is also important to note that the holotype skull is significantly larger than the one that was scanned, and lacks visible sutures in areas of the braincase where they are visible in the scanned *Thoracosaurus*. This supports the idea that the NJSM NH 2005.2 *Thoracosaurus* was indeed not fully grown at the time of death.

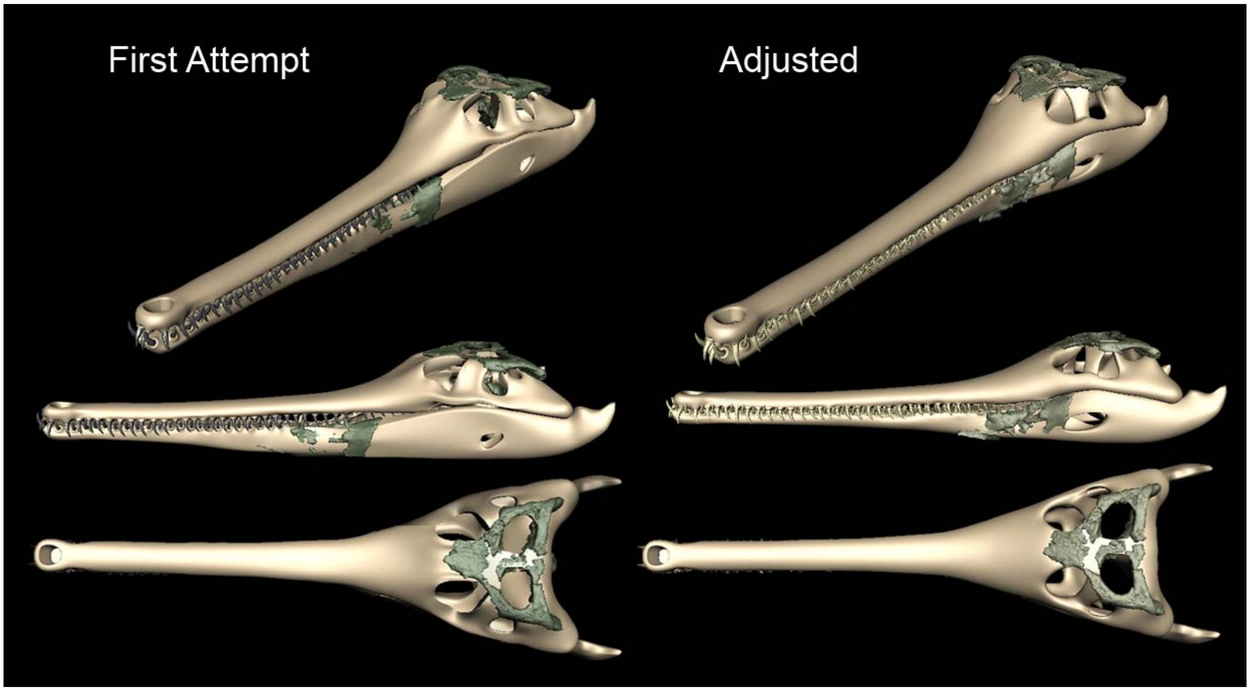

Figure 21 A comparison of the original skull model based on *Eothoracosaurus* and *Gavialis* (left) and the adjusted skull based on the *Thoracosaurus* holotype

There is one more aspect of remodeling the skull that is important to note. In comparing the photographs of the holotype of *Thoracosaurus* with Brochu's paper on

Eothoracosaurus, something curious was discovered. There is a gavialoid croc mentioned in the paper complete with photographic reference of the skull that Brochu calls *Thecachampsoides minor* [4]. The interesting point to make about this specimen, is that not only is it from the Academy of Natural Sciences of Philadelphia, but it looks *exactly* the same as, and has the *same catalogue number* as the *Thoracosaurus* holotype. This created a great deal of confusion. Even if Brochu thought that this was not the same species as others which are attributed to *Thoracosaurus*, the specimen is the holotype, and the tag with the catalogue number indicates that this is so. This means that this specimen takes precedence for what is considered *Thoracosaurus*. If Brochu is correct in identifying this as something different than what is commonly attributed to *Thoracosaurus,* then it would mean that the name of all the other specimens of *Thoracosaurus* would have to change, not the name of the holotype. This is really a topic that could be fully explored in another paper, but it is important to mention as an obstacle that caused much confusion for this project. A lot of work and re-work could have been saved if Brochu's paper labeled ANSP 10079 correctly.

Continuing on the skull, there were also some significant changes to make to the jaw. The earlier hypothesis about the taphonomic influences in the dentary kink was indeed accurate. The scanned dentary was officially moved back on the model in order to line up the kink with the rest of the jaw, as well as to put the external mandibular foramen in the correct place. The external mandibular foramen on the jaw was difficult to place, because of all the possible places for it to go. In the reference imagery of *Eothoracosaurus* there appears to be an incredibly small foramen, and it is positioned pretty far posteriorly on the jaw, much like where it is in gharials (Fig. 22) [4]. That is where it was originally placed in the first attempt at skull modeling. After some consultation with the experts, it was discovered that there was a groove of finished bone along the break of the posterior end of the dentary scan, which acted as the front end of the external mandibular foramen (Fig 23). There was some skepticism about this at first, because this would seem to make the foramen extremely large. After looking to modern crocodylian skulls to observe the placement of this foramen, it was found that if the dentary was moved back and rotated slightly, it would make the *Thoracosaurus* foramen more similar in size and position to the one found in alligators.

This caused some confusion over the phylogeny of Crocodylia, and the development of the external mandibular foramen. Since the gharial has a much smaller foramen which is situated farther back on the jaw, behind the orbit, it looks like it is congruent with the one found in the *Eothoracosaurus* reference images. It seems strange that *Eothoracosaurus* would develop a small opening, have it enlarge and move forward as gavialoid crocodylians evolved toward *Thoracosaurus*, only to then dwindle and move back again when evolving towards the gharial. It could be possible that *Thoracosaurus* developed the larger foramen independently from the rest of the gavialoid crocs, with the smaller foramen being a more basal characteristic. According to Brochu’s phylogeny, the line that led to the gharial is indeed a sister clade to the two species of *Thoracosaurus* (Fig. 16) [4]. Despite all of this information, there was a clear groove of finished bone on the dentary, noting that that was the front of the foramen, and to maintain proper accuracy, the actual fossil scans took precedence over all other available data.

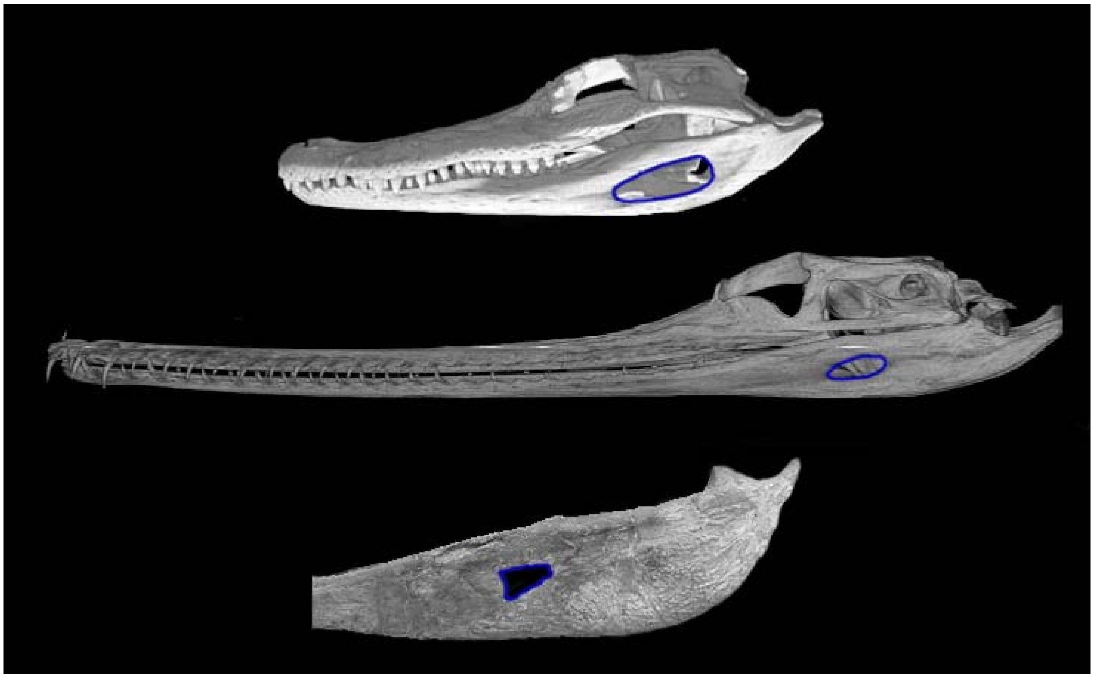

Figure 22 The external mandibular foramen outlined in *Alligator mississippiensis* (top), *Gavialis gangeticus* (middle), and *Eothoracosaurus mississippiensis* (bottom).

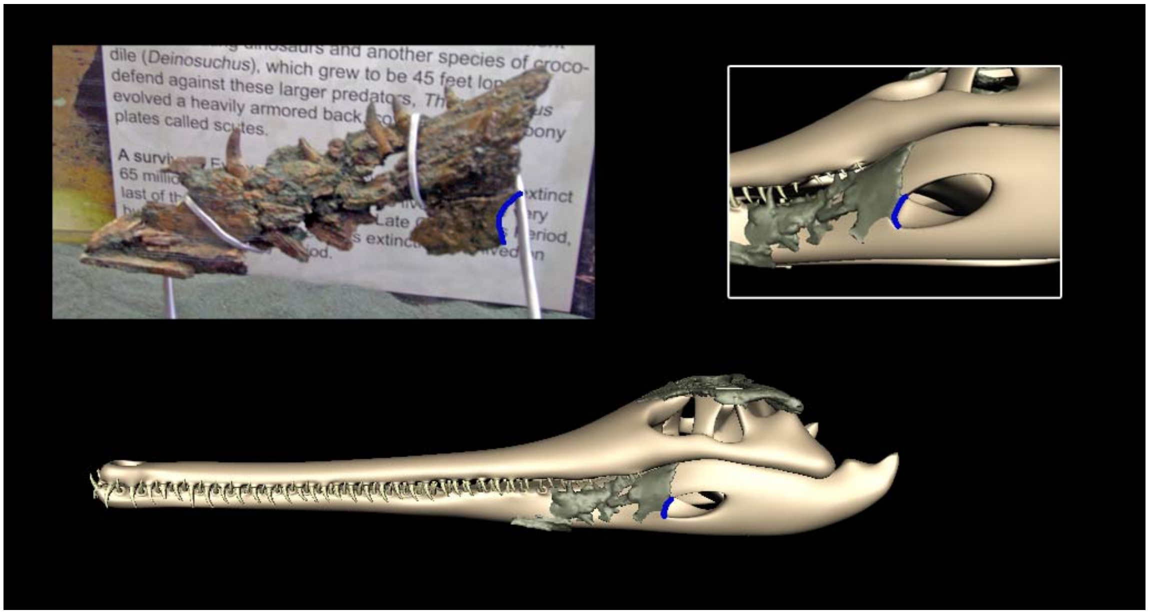

Figure 23 The groove of finished bone indicating the front edge of the external mandibular foramen

After the immense task of skull reconstruction was completed, the post-cranial skeleton modeling began. A variety of sources were used to complete the body. As previously noted, it is known that crocodylians are more or less post-cranially identical, with very few variations [5]. The literature was then examined for any reference imagery that could be found on crocodylian limb bones. There was some very good reference of the forelimb in particular, which was based on work by Meers [26]. In his paper, Meers goes into detail on the position, orientation, and musculature of the pectoral girdle (shoulder joint), the upper and lower forelimb, and the manus. The paper also includes extremely detailed diagrams of the bones, complete with outlines of where muscles originate and insert on the bones.

For the actual shoulder, the modeling of the coracoid bone was based on the specimen of *Eothoracosaurus* described by Brochu [4]. The image provided in the paper had a scale marker which was aligned to the scale of the other reference images that were used as image planes. This was to assure that proper proportions were kept throughout the reconstruction process. After the scapula, radius, ulna, carpals, metacarpals, and phalanges were constructed based on a combination of Meers' work [26] and a laboratory dissection guide for alligators [6], the broken fossilized humerus of the arm had to be fixed, and appended. This was accomplished by lining up the orthographic images of the humerus from Meers' paper with the fossil humerus. The shape of the scanned humerus was indeed just about identical to the humerus in the paper’s diagram. This allowed for lining up the scan of the humerus with the reference imagery so that it fit the correct contours of the diagram. This made it very easy to tell just how much of the humerus had to be appended, and also displayed the proper shape of the portion that had to be appended, from a number of different angles. This allowed the reconstruction of the humerus to be modeled with relative simplicity (Fig. 24).

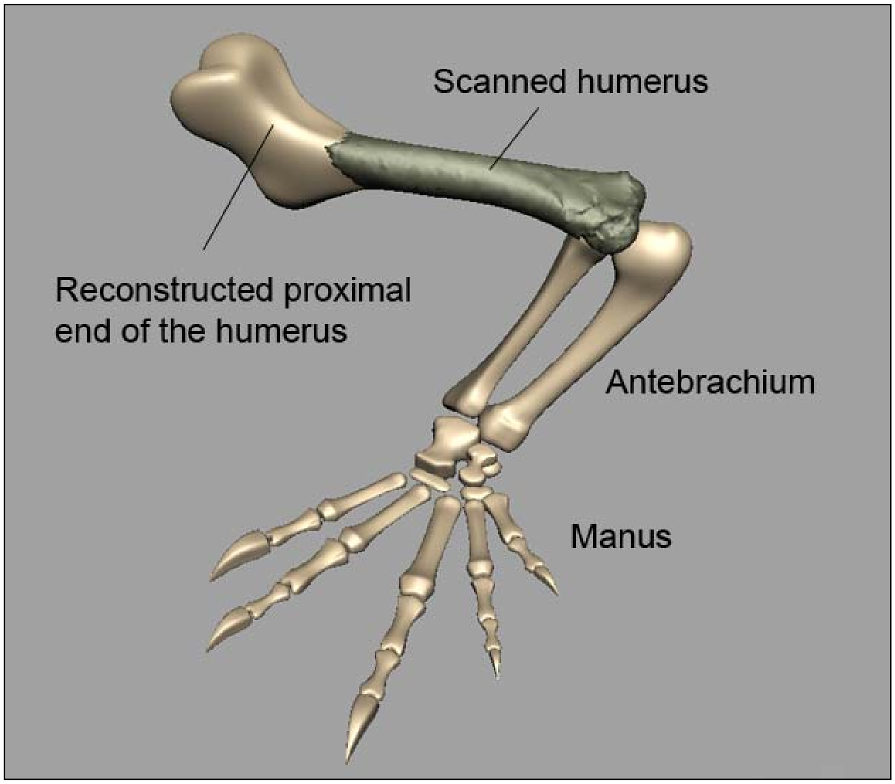

Figure 24 The reconstructed left arm of *Thoracosaurus neocesariensis*

Compared with the humerus, the pelvis was more complex to put together. The diagrams from the work of Romer on pelvic musculature were used to replicate the proper shape of the pelvis [32]. The three-dimensionality was rather difficult to perceive accurately, so deepening of the acetabulum, and thickening of the ilium, ischium, and pubis, along with re-orientation of some elements had to be done after taking a look at a fully mounted *Alligator mississippiensis* skeleton at the Academy of Natural Sciences of Philadelphia (Fig. 25). The same technique used to complete the humerus was utilized to complete the broken distal end of the femur. There was not as readily available documentation on the lower leg, and the tibia and fibula were built based on Chiasson's dissection guide as well as various photographic reference images. The metatarsals and phalanges of the pes were also built from these references [6].

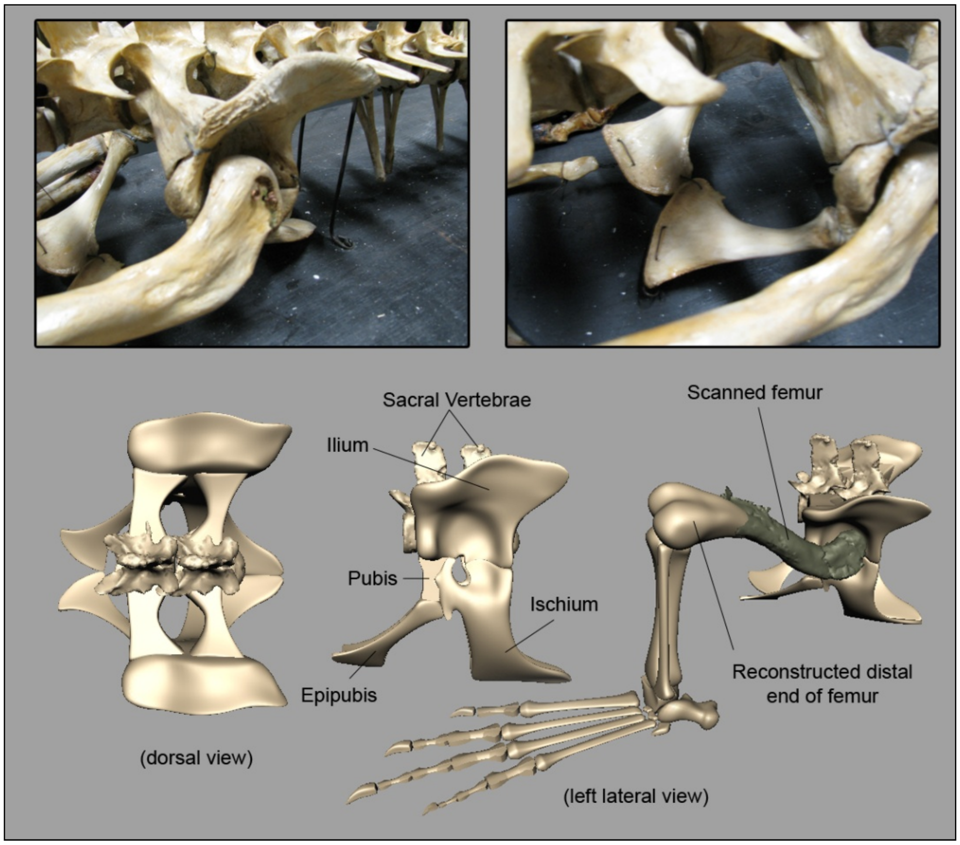

**Figure 25 Top: Pelvic bones of *Alligator mississippiensis*.
Bottom: Reconstructed *Thoracosaurus* pelvis**

The most complicated part of the skeleton to understand was the crocodylian crurotarsal joint. This is a feature that is key for crocodylian locomotion, and occurs between the astragalus and calcaneum of the pes [2]. The astragalus was created from a photograph of the astragalus of the fossilized *Thoracosaurus*, along with images of those from modern crocs.[3] The second half of this crurotarsal joint, the calcaneum, was incredibly difficult to model from image references alone, and required constant repositioning and rebuilding. It went through three or four drafts before it was finally completed. The shape of the calcaneum is so incredibly complex, that it is almost impossible to decipher it from a series of two-dimensional images. There are so many grooves and crevices in it, and it articulates with the rest of the foot in a very specific way. It was achieved eventually, with constant referencing to Brinkman [2], Parrish [29], and a plethora of custom images photographed at the Academy of Natural Sciences of Philadelphia, from the same mounted alligator specimen used for the pelvic reference (Fig. 26).

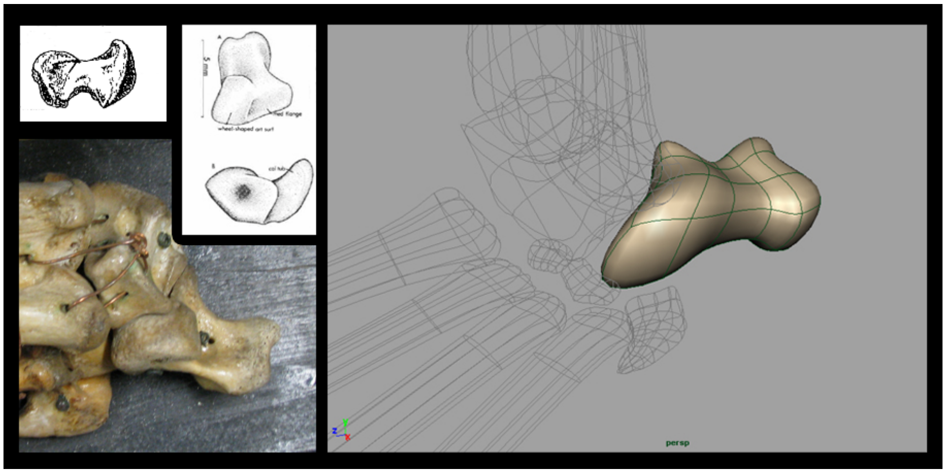

Figure 26 The calcaneum, including reference imagery (left)

Modern crocodylians have a vestigial fifth digit on the pes, which cannot be seen unless looking at the skeleton. When questioning whether extinct crocodylians should have this same fifth digit, if they should have a fully formed fifth digit, or if they should have a diminished one that eventually disappeared over time, research went to the ancestors of Crocodylia. Early crocodylomorphs such as *Protosuchus* indeed had this same vestigial fifth digit, which indicated that the extinct crocodylians also had this bone (Fig. 27).

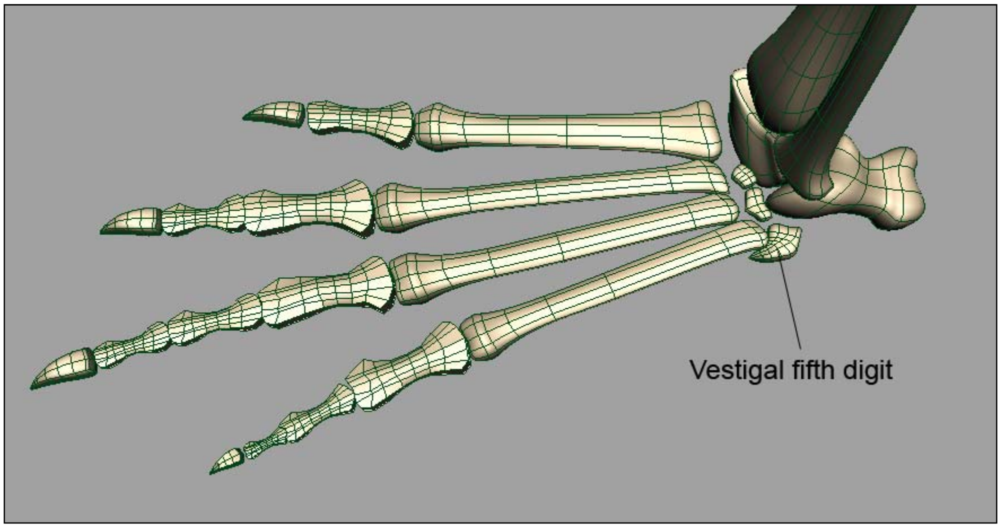

Figure 27 The vestigial fifth digit of the pes

After modeling the limbs, there was plenty of material that still had to be reconstructed on the body. Even though most of them were scanned from fossil data, there were a number of adjustments that had to be made to the vertebrae themselves, to fix damages from post-mortem processes such as erosion. For one, although the majority of the fossilized *Thoracosaurus* consists of vertebrae, there are still plenty missing. Except for variation in scale, same types of vertebrae are more or less identical to one another.

All the cervical vertebrae were accounted for. There are typically only about eight or nine vertebrae in modern crocodylians; which correlated to the fossil material. The dorsal vertebral column, however, was missing a couple bones in the lumbar region. This was first noticed during the scan stitching phase of the project. When compiling the scans and first few reconstructed bones together it became very apparent that the creature's proportions were not accurate. If no other vertebrae were added, the torso would have been too short, and the proportions of everything else would have appeared to be incorrect. It was noticed while researching that there were about two vertebrae missing, which were then recreated by duplicating and moving the scanned geometry down the spine.

The sacral vertebrae were rather undemanding to build. They closely resemble the dorsals, except for the sacral ribs which are thicker and more robust than the other ribs, since they connect to the pelvis. The tail is where most of the vertebrae were missing. The specimen only had about six out of thirty-six to forty caudal vertebrae commonly found in modern alligators [7][30]. Estimations had to be made to approximate where along the tail the scanned caudal vertebrae should be positioned based on size.

The remaining caudal vertebrae were modeled by referencing the scans as well as diagrams and descriptions of alligator caudal vertebrae. The chevrons, bones used for muscle attachment hanging below most caudal vertebrae, were then modeled based on various imagery and descriptions. According to the literature, the first caudal, as well as the last four or five, do not have accompanying chevrons, and the last five or six caudal vertebrae consist of only a centrum (the body of the vertebrae); lacking transverse and spinous processes [6][30]. Reconstructing the caudal vertebrae, despite taking time, was not a difficult task. Once modeling a couple vertebrae, the task was more of a matter of duplicating and tweaking, rather than modeling thirty five vertebrae and chevrons individually.

The last step to completing the vertebrae consisted of appending vertebrae where erosion and other earthly processes destroyed parts of the bones. There were more than a couple vertebrae that were fairly complete, but most of them required some amount of repair work. In order to maintain accuracy, this task was achieved by taking pieces from complete structures in other vertebrae, and duplicating them to use to append the broken vertebrae. This was done intelligently, however, so that only pieces of cervical vertebrae were used to complete other cervical vertebrae, and the same with the dorsals and the caudals. The second cervical vertebrae, also known as the axis, required the most reconstruction, as the neural arch and spinous process was completely worn away (Fig. 28). The fossil consists, of more or less, only a centrum.

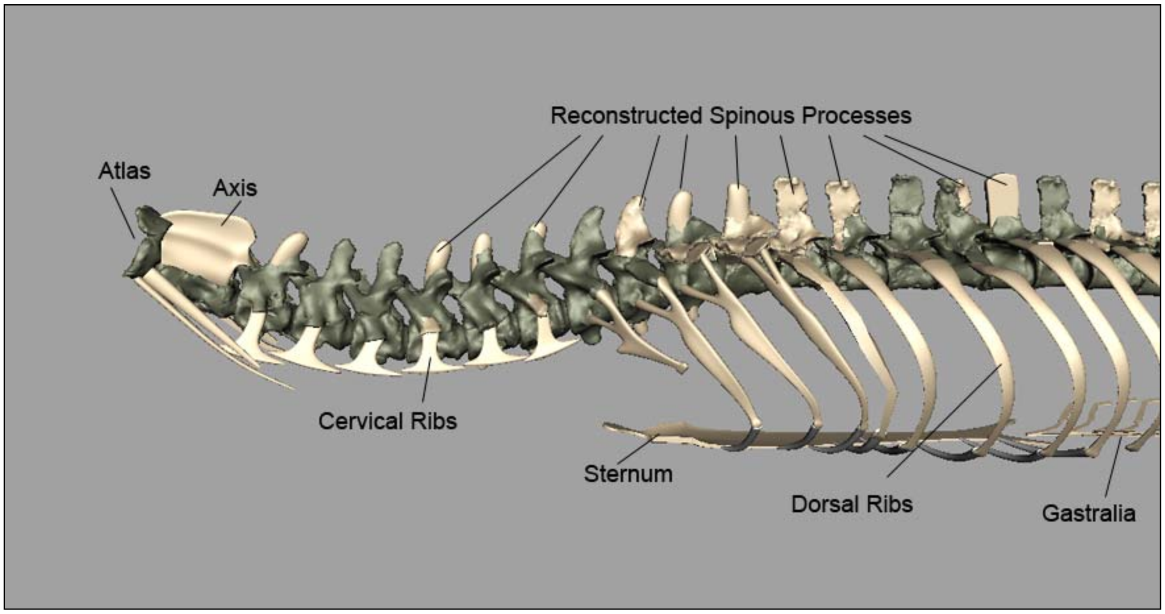

Figure 28 The appended vertebrae and ribs. The scapula and coracoid have been hidden for visibility

It was at this point where the scanned original data was becoming so integrated with the rebuilt skeletal geometry, that color coding and other methods were vital in order to keep the structures visually organized. Instead of simply combining the appended pieces of the vertebrae to the scanned models, parent constraint nodes were used in order to allow the appended pieces to follow along with the original scans, and to behave as if they were part of the same object. This method also allowed the scans and appended pieces to be organized in separate groups in the file’s hierarchy, so that components were clean, organized, and easy to find. The use of parent constraints also allowed for separating the various models onto different display layers within Maya. This was done so that turning off the “Constructed_Bone_Geo” layer, for example, would hide any skeletal material in the viewport that was not a part of the original scans, and vice versa. These display layers were set up since the final animation would depict the different stages of construction; a single display option could be used to switch between layers when previewing and rendering only certain parts of the reconstruction.

Color differentiation was used also to help visually distinguish between the original and reconstructed bone. Anything that was not part of the original fossil specimen (including duplicated and mirrored parts) was given a cream color to resemble natural bone. The original specimen, however, was given a grayish-green color; a reference to the glauconite greensands from which the fossils were excavated. Aside from making it easier to work with the models, this color coding also helped to give a better understanding of how the full animal was restored, by keeping the distinction between scans and reconstructed models perceivable during the buildup section of the final animation.

The final parts of the skeletal modeling included the sternum, ribs, and gastralia. Despite being relatively simple shapes, these bones required a lot of tweaking since most of them articulate with adjacent bones in multiple places. To build these remaining bones, a number of photographic images from mounted alligator skeletons, as well as diagrams from the literature were referenced [6][30]. The sternum had to be adjusted from the diagrams in order to articulate properly with the coracoids, which as mentioned were based on the one from *Eothoracosaurus*. It was also lengthened from the reference diagram in order to articulate properly with the rib cage.

The cervical ribs were difficult because they had to articulate with the vertebrae at two different points, and they had to overlap one another without intersecting, even in motion. The ribs connected to the first cervical vertebrae, or atlas, were particularly awkward in this regard since they are essentially very straight, looking almost like rapiers, which overlap a couple of the other cervical ribs. The first three dorsal ribs were similar to the cervical ribs in that they had multiple articulation points, but they did not have to overlap one another like the cervicals. The rest of the ribs were fairly simple since they only articulate with the transverse processes. They are also very similar in shape to one another. They differ in length and in that the transverse processes are not identical on all of the vertebrae, causing effort to be spent on articulating each and every one individually. The last part of the ribs to build was the costal cartilage. This is cartilage that connects the ribs to the sternum, and provides some amount of flexibility for the expansion of the rib cage.

The gastralia were the final part of the skeleton to reconstruct. The gastralia, also known as abdominal ribs, are a layer of bones that lie underneath the abdomen, posterior to the sternum and anterior to the epipubis bone of the pelvis [6]. They are not necessarily essential for motion, but add support to the animal's belly. The model looked incomplete without them so they were incorporated. The position and orientation of the gastralia had to be altered a couple times after reviewing reference photographs in order to properly line them up with both the sternum and epipubis. These final parts of the skeleton were difficult to build, not because of the complexities of the bones, but once again because of reference imagery's collapsing depth. The best way to understand how these structures were shaped was to directly study actual mounted specimens.

There was one last bone that did not make it into the reconstruction, the hyoid bone. The hyoid is a bone in the throat of the animal used for tongue muscle attachment.

It was not incorporated simply because systems like the respiratory and digestive systems were not being reconstructed, and the time would not have been well spent on researching, modeling, and placing it in the proper place in the throat.

In order to officially complete the skeleton, the body was easily mirrored across the midline so that only the left version of each bone had to be modeled. This could be done since all vertebrates exhibit bilateral symmetry [20]. Once mirrored, all of the right side was assigned the cream color of the reconstructed bones, even the pieces that had scanned fossil equivalents on the left side. This was, again, to isolate the colors between not specifically scanned data and hand-built data, but to maintain perceptual distinction between the original fossil specimen and the reconstructed skeleton.

The last step before moving beyond the arduous process of building a skeleton was to fix an issue that arose with the overall scale of the animal. Somewhere between exporting the bone data from the scanning software, importing it into modeling software, and then re-exporting and importing it into the animation software, the global scale of the fossils was altered. The suspicion is that there was probably a step in the scan stitching process where working units should have been declared when converting objects to polygonal meshes. This step was probably overlooked, or simply not known about at the time. Everything was still correct relative to one another in the modeling and animation environment, but this issue had been noticed when setting up scale markers to see the final length of the animal. It was noticed that the bones were not in real-world units. They were actually much too big. Once the units of the display grid in the program were adjusted accordingly, the entire skeleton had to shrink down from the normalized value of

1, to a value of .108 (10.8 % of the original model’s size). Once this was done, the scale markers on the image planes correlated to the grid, which made *Thoracosaurus neocesariensis* the correct size in real world units: 4.92 meters long, or about 16.13 feet. The skeleton was finally at a point where controls could start being built in order to allow *Thoracosaurus* to move (Fig. 29).

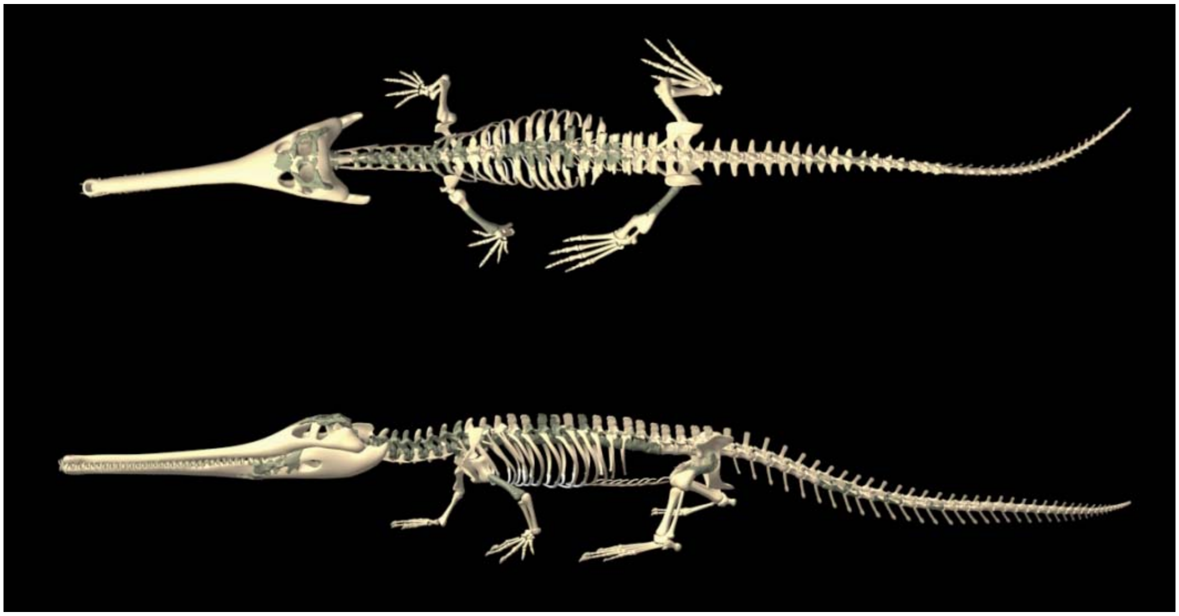

Figure 29 The completely reconstructed skeleton, displaying the color coded distinction. Greyish Green: Fossil Scans. Cream: Reconstructed Bones

3.2. Levels of Control

Once the skeletal system was completed, development of the control rig could start in order to allow for posing and animation. For the sake of this project, since the rig was completed within Autodesk Maya, the terminology within Maya is what will be used to describe the process. The tools and processes are similar if not identical in most animation software applications, even though the terminology may differ between programs.

The underlying concept to building a rig is to set up a series of joints, and then connect these joints to a skin object. Control objects and other interfaces for animation are designed to allow for greater control over the joints. So essentially, a basic rig includes a series of control objects, which drive the control of the joints as well as other deformation objects, which ultimately affect the geometry of a character.

The first step in the rigging process is to create a series of joints which represent all the points from which a character can move. Joints are nothing more than points of translation and rotation, which are connected to other joints. When multiple joints are chained together, a visual "bone" is created, but this serves no other purpose than displaying the relationships between the joints. Joints are connected to one another via a child-parent relationship, also known as parenting. When one object is parented to another object, it becomes a child of the parent, meaning that whatever the parent does, the child is therefore affected accordingly (Fig. 30). In order to comprehend this idea, think of a human arm. As the humerus rotates to raise a hand or go to pick something up, the antebrachium and manus follow it. They may also be rotating while the humerus is moving, but their final position is ultimately determined, in part, by the orientation of the humerus. In this situation as described above, the manus is a child of the antebrachium, and the antebrachium is both the parent to the manus, and the child of the brachium (the upper arm). The brachium, then, is the parent of the antebrachium.

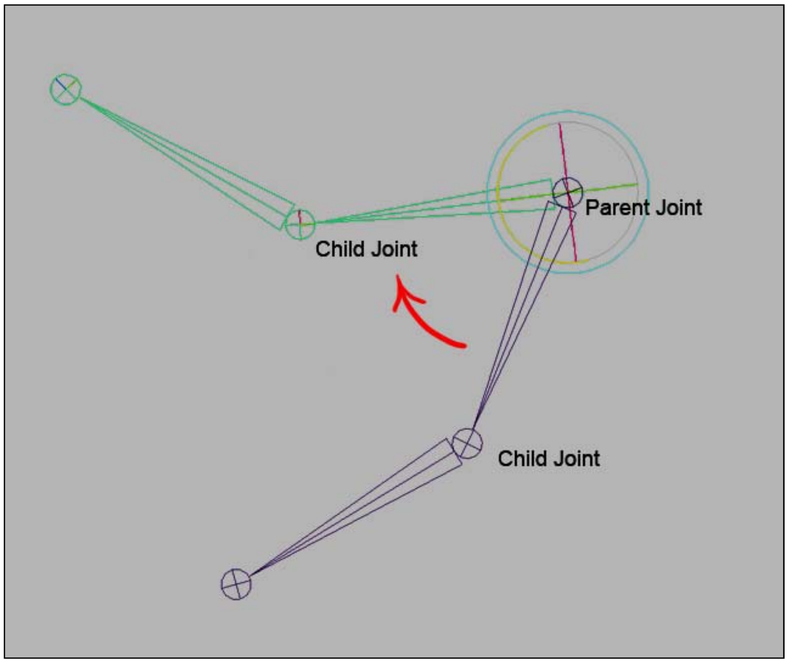

Figure 30 The child joint rotates relative to the parent

This Maya skeletal system is derived, somewhat from concepts of anatomy, and since the entire *Thoracosaurus* skeleton model was created, there would be no guess work for figuring out where the joints should be placed. They literally needed to be placed at the actual joints between the bone models. This was easy enough to setup, but the hierarchy was different than one might expect. The joint chain actually ended up consisting of four separate joint chains in order to prepare for the proper level of control that the rig would require. The first joint chain started at the pelvis and consisted of the tail, hips, hind limbs and feet. The second chain started at the last dorsal vertebrae and moved cranially, consisting of the back, pectoral girdle, front limbs and feet. The third was the joint chain of the cervical vertebrae, and the fourth consisted of the skull and jaw (Fig. 31).

The joint chains were split into multiple chains in order to allow for more intuitive methods of control. This setup would later allow for an animator to grab a section of the animal and position it independently from other parts, without having to adjust a collection of different controls in order to set a pose. In other words, at every point where there was a gap in the joint chain, a controller was built in order to affect the ends of both chains surrounding that gap. This allowed for the positioning, of say, the pelvis without affecting the entire upper body, or moving the head to a position without having to adjust all of the neck vertebrae manually. The controls would allow for setting poses of key body parts, while causing the surrounding bones to automatically follow along in a naturalistic way to save time while animating.

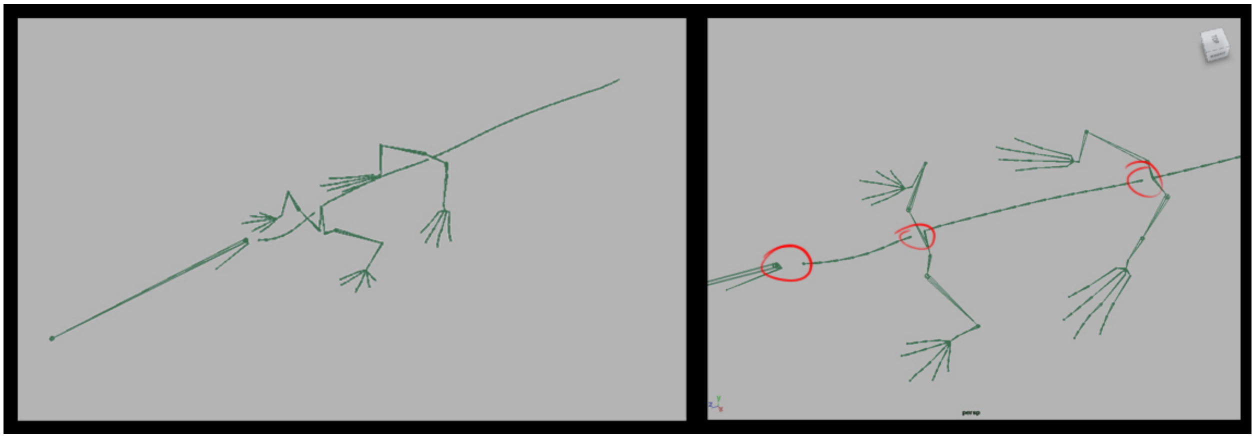

Figure 31 The final joint setup (left), and the gaps in the joint chain designated in red (right)

Once all the joints were laid out, they had to be oriented correctly. It is important to know that when a child object inherits the translations and rotations from its parent, no matter what position the parent rotates to, if the child has not been rotated from its own orientation, its new default position is wherever its original default position was, but in relation to the parent's local space. In other words, a child's default position is always relative to its parent's transformations. This concept is essential to understand when properly orienting joints.

Orienting the joints of the arms and legs became tricky, since the way these bones rotate is not always perpendicular or parallel to the environment grid. The default pose for the *Thoracosaurus* model had it in a standing posture with all four feet flat on the ground, the knees and elbows facing outward in a typical reptilian sprawl. Because of this pose, when something like a knee bends, it is not bending across a single axis according to the world space. This object has its own local space (determined in part by all the parent objects above it in the hierarchy) and if the local space was lined up to the world space, it would break the knee when bending it, by bending it slightly sideways in a way that legs cannot naturally bend. The joints in the legs and feet, therefore, had to be oriented so that their local spaces were lined up with the direction of the bone, opposed to the orientation of the world grid. Sometimes a joint's orientation is the same as the world, such as with the jaw and vertebrae (which are positioned square to the world grid), and sometimes it is not (Fig. 32).

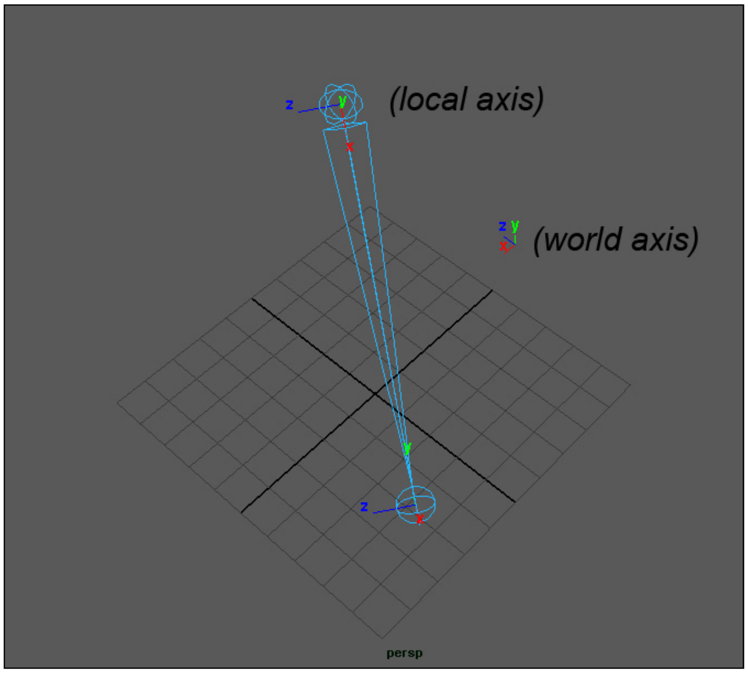

Figure 32 Sometimes local axis of a joint should not match the world axis for proper rotation

Once all of the joints were laid out, named consistently, and oriented correctly, they had to be labeled. A joint label is an option specific to joints within Maya. This labeling process requires a user to identify the side of the body and which part of the body each joint represents. This was set up for when the skin would be bound to the joints later in the rigging process.[4]

Once all of this internal structure was set up, the actual objects that control the joints were to be built. This process required thinking about the way the animal has to move, and figuring out the best way to give an animator multiple levels of control in an intuitive manner. The first controls to address were the ones to allow control over the hips, chest, head, jaw, legs, and tail.

Before creating the control objects, it was first important to determine what methods of control would be used to affect the joints. There are two major ways of affecting joints in computer animation: forward kinematics (FK), and inverse kinematics (IK). They are each advantageous in different situations. FK is used when an animator animates by rotating pivot points down the joint chain, as in the parent-child relationship discussed in the arm analogy. IK is used to allow a joint further down in the chain to affect the orientation of the joints above it. Going back to the example of the arm, it would allow one to pick up a controller at the wrist and move it where he or she would like the hand to go, with the proper angles and orientations of the antebrachium and brachium being calculated automatically based on the hand position. Each system works better in particular situations, and can even be combined for maximum usability. FK is preferred for doing gross sweeping motions, like throwing a baseball, considering this system preserves natural motion arcs with less cleanup work. IK is preferred for situations where limbs need to act independently of the body. This is particularly good for keeping hands and feet planted in a spot on the ground when performing actions such as walking or doing pushups.

For the *Thoracosaurus*, since it was a quadruped that would have used its feet to drag itself across the ground, the decision was made to go with an IK setup for the limbs. There are methods of incorporating both FK and IK into a rig, but the setup efforts would not have been worth the payoff in this case, since the only time the limbs would not be used to support weight would be during swimming. There is also another type of IK that was heavily used throughout this rig – the IK Spline.

The IK spline works on the principle of using a curve to control a chain of joints. When points on the curve are manipulated, the curve adjusts its shape to include the adjusted point. It interpolates the shape the best it can based on the number of points in the curve, trying to keep a perfectly smooth shape. The spline IK is very helpful for animating things like tentacles, whips, strings, tails, wires, neck ties, etc. It allows one to use a number of controllers to create a curvilinear shape to influence geometry. If it were not for this sort of control, an incredible amount of patience would be needed as one would have to manually position each joint, in say, a fifty-joint joint chain, while keeping track of animation for each joint, and maintaining a naturalistic curvature at all times.

After figuring out the proper techniques that were to be used in the rig, the control objects themselves had to be created. In order to create the controllers, a number of curve objects were used, since these objects are meant for interfaces and do not render in the final images. Any object could be used as a controller, but other steps would have to be taken to prevent the objects from rendering in the scene if they were made from geometric objects. The control objects were built and shaped out of curves, typically by adjusting points along a circle into a shape that roughly corresponds to the part of the body it would eventually control. For example, making an object in the shape of a snout that lies around the creature's snout should make it obvious that this control would be used to open the mouth. Control objects also have to be shaped in a way that makes them easily selectable. The more intuitive a rig is, and the easier it is to select objects and access control options, the quicker the animation process will go.

Various control objects were built accordingly; one around each foot, a box-like shape around the pelvis, another for the chest, a curve outlining the head, and two for the jaws which were parented to the head control. Small box-shaped objects were then used as elbow and knee aim controls. When setting up a basic IK system such as in a leg, another object is typically used in order to help the program calculate what direction the middle joint of the chain will point. This object is called a pole vector, and is an object for the middle joint of a three joint chain to aim toward in order to prevent the chain from breaking by bending the wrong way. In the case of *Thoracosaurus* these pole vectors simply acted as controls that determined the orientation of the knees and elbows, without affecting the position of the feet.

IK splines were used for all parts of the vertebrae. There were three splines in all. One was used for the tail, one was used for the back, and another was used for the neck. Despite the fact that there were a large number of joints in each of these areas, previous experience proved that spline IK chains work better when there are fewer points of control on the interface. If there are too many, it becomes too cumbersome and defeats the purpose of using the spline to simplify the process. It also becomes more difficult to achieve smoother curve shapes. If there are too few controls, however, the proper shapes simply cannot be made. In the end, there turned out to be one box-shaped control object for the neck spline, two for the back, and five for the tail since it had to achieve more flexible positions than the other areas.

After these basic control curves were added, more layers were slowly built up in areas where more control would be needed. There was a control object on each side of the chest to adjust the position of the corocoid and scapula, which provided control over shoulder movement. These controls were parented to the chest control object. There was also a second control object around the hips added, which became a parent to the back, chest, neck, and head controls. This control would allow for adjusting of the overall orientation of the body without having to adjust all the lower level controls. The other controls still worked additively on top of this higher level one, however. Another control was added that did the same thing, but only for everything from the chest forward. This control was used to adjust the orientation of the head, neck, and chest as a unit, with all of those individual controls working additively on top of it.

The last few controls would allow for more intricate movements. These controls were not meant to be moved in the interface, but acted as selection objects to access adjustable attributes. A sixth tail control was added, which was given control over the lateral twist of the tail. This was parented to the first of the tail controllers so it would stay relative to the pose of the tail. There were also eight small controls added – two for each foot – that would control all the intricate movement of the feet and curling of the toes. Two controls were added for each foot because one had a higher level control over the curling and spreading of toes, as well as controls for actions such as rolling the foot and pivoting from the toes opposed to the ankle. The second control was a curve that was parented to the first toe controller, and additively controlled the rotation of each individual digit in the toes, allowing for extremely precise foot poses. The reason these controls were separated into two objects was simply for legibility. The thinking was that by having fewer options on each toe control, the rig would be more intuitive to use. All of these toe controls were parented under each corresponding foot position control.

The next control was a control object that would later have attributes to control the muscle parameters for different muscle groups. It was shaped like a stubby cross, and was parented under the full upper body controller. The final control curve to be added was a top level full body control, which every other control was then parented under. This control was built to allow animators to quickly move the entire rig around, without having to adjust any of the lower level controls.

All controls were named consistently, and color coded for the sake of visibility. Having a number of curves of the same color which appear to overlap when viewed in a perspective viewport makes it extremely difficult to select proper controls, and in turn overwhelms the animator and slows down the animation process. Having control curves with different colors makes it easier, then, to distinguish between them. Another important step in setting up control curves was to make sure to change the pivot points of the curves to be in the correct spots. For example, when rotating the jaw control, the control needs to rotate from the same point the jaw joint rotates, or else the joint may not behave correctly. This is especially true for the foot controllers, where the pivot points of the curves should be moved to the wrists or ankles. All the controls also had to have their transformations frozen so that the values in all the attributes read “0” in the default pose. This allowed for an easy reset of the rig to its base pose. After all the control objects were built and set up properly, connections to the joints could then be made.

Figure 33 The joint setup along with control curves

The next step to rigging the croc was to actually connect all of the controllers to the skeleton. The primary areas to address were the gaps in the joint chain discussed previously. A couple of steps were taken in order to get the fragmented spine to act as a complete whole. The first step was to create the IK splines for the various joint chains. After creating the splines, the number of control points that made up the curves had to be reduced so there were not too many points of control. After this, each control point had its own cluster deformer attached to it. A cluster is a deformer that simply acts as a handle to ease the selection of points, faces, or vertices of a surface. These points can be manipulated simply by selecting the deformer, which behaves like an object, opposed to having to switch modes to adjust the component parts of an object. By having the clusters drive the control points of the curves it allowed the clusters to act as intermediates between the control objects and the control points of the curves.

After each point had a cluster deformer applied to it, the clusters were then connected to the individual control objects with parent constraints. The gaps in the joint chain were then attended to, by simply parent-constraining the clusters on either side of a joint chain gap to the control curve in the middle of the gap. For example, at the hip, the clusters closest to the base of the tail, and the clusters closest to the posterior-most dorsal vertebrae were constrained to the pelvis control object. This way, when the pelvis control moved, it took along the clusters on either side of the gap, which adjusted the spline curves on either side of the gap accordingly. This resulted in the appearance of moving hips, which affected the surrounding body parts appropriately. In computer-generated imagery, there are a great number of techniques like this to make things behave properly. It is often important to find a solution that works efficiently, rather than finding a solution that works exactly the way it works in nature.

The same techniques, as described for the pelvis, were used for the shoulder-neck gap and the neck-skull gap. The only difference was in the case of the neck, an aim constraint node was used to point the neck vertebrae toward the skull at all times, so the neck would not slide out of place from behind the skull. After the gaps were all closed, the remaining clusters affecting the splines were assigned to the other control curves for those various splines. Another important element was incorporated into the setup of the splines, after problems were noticed in a few test animations. An issue arose when the body of the *Thoracosaurus* was rotated to face the opposite direction, where the splines would twist. This caused the vertebrae and rib cage to turn upside down. For a while it was thought that this had to do with where the joint-affecting splines and clusters were scheduled in the file's hierarchy. After many attempts at debugging the issue, the fix turned out to be relatively simple.[5]

After fixing these spline IK handle issues, the next area where lots of intricate controls had to be connected was in the feet. The feet took longer to put together than they would in a typical biped rig for a couple of reasons. First, there were four feet which needed the same custom attributes, and second, these foot controls had to include controls for all of the digits of the toes. It is not always necessary to build controls for each toe digit into a rig, unless it is known beforehand that there would be close-up shots of the feet with that require toe animation. The technique for rigging the feet combined methods typically used for feet mixed with ones typically used for hands. The foot control objects, other than controlling the IK handles on the legs, were given two custom attributes. These attributes were the “Roll Step” and “Twist” attributes. The twist attribute was simply a setup to allow the feet to pivot laterally from the toes opposed to from the typical wrist or ankle pivots. The purpose of the roll step attribute was to automate the way a foot peels off of the ground when walking. With a simple slider, this control allowed one to lift the animal's heel off the ground, followed by the ball of the foot, and then the toes, creating a smooth roll-up in the way that feet naturally move when walking. This was important to add, since the way the fingers and toes peel off the ground is quite distinct in crocodylian walking.

To set this up, it required a number of IK chains on the individual joints in the feet, which were set up in a way to keep the foot on the ground unless the main control curve was moved. A series of nested groups consisting of these IK handles were then created. Each group's pivot point was then changed to allow for controlling the foot from different critical pivot positions, such as the end of the toes, the ball of the foot, and the ankle. The groups were then connected to the foot control, so that when the slider of the "Roll_Step" attribute hit a certain number, it changed the values of the rotations of these groups. After setting key values of the individual foot group rotations and connecting them to specific values on the "Roll_Step" attribute, it created the illusion of the foot rolling up while only manipulating one attribute. This became rather complex to set up for the croc since there were so many digits to incorporate into the system. There was a very specific hierarchy of IK handles and groups that allowed this setup to work, and setting it up for each digit quickly became, although not exactly difficult, rather tedious.

A lot of attention was also spent on the ankle mechanics because of the unique mesotarsal and crurotarsal joints present in crocodylian ankles (Fig. 34). What is interesting about this is during locomotion, the ligaments in the foot more or less prevent movement between the astragalus and the tibia. This means that the hind foot rotates around the articulation between the astragalus and calcaneum [2]. This was taken into account when setting up the joints in Maya so that the skeletal model would behave accordingly. It is also important to note how the metatarsal bones function when plantar-flexing the foot. There is not really any mobile joint between the ankle bones and the bones of the foot, but when flexing the foot, a little bit of motion between each metatarsal causes the foot to rotate slightly. Each metatarsal rotates very slightly laterally in relation to the others, creating a combined effect that rotates the across the entire foot [2].

This feature was built into the rig, so that when rotating the foot control in the negative z-axis (causing the foot to plantar-flex), a group connected to IK handles that were then attached to the metatarsal joints would rotate relative to one another and twist the foot around itself slightly (Fig. 35). The framework was also set up so that the value of the rotation could be adjusted later to make the feet twist more or less while plantar-flexing. There are two multiplier nodes called “R_Metatarsal_Rotate_Ctrl” and “L_Metatarsal_Rotate_Ctrl” which control how much metatarsal rotation occurs as the foot flexes. On these nodes, the “Input 2x” is the field that adjusts a manually input multiplier number. This number multiplies by the “Input 1x” field at all times to achieve the proper twist value. The “Input 1x” is dynamically updated from the foot control’s rotation in the z-axis. These nodes allowed for quick adjustment of the metatarsal rotation when needed. As exciting as it was too see this effect in action, it later had to be subdued slightly in order to prevent the skinned foot from tearing apart in certain poses.

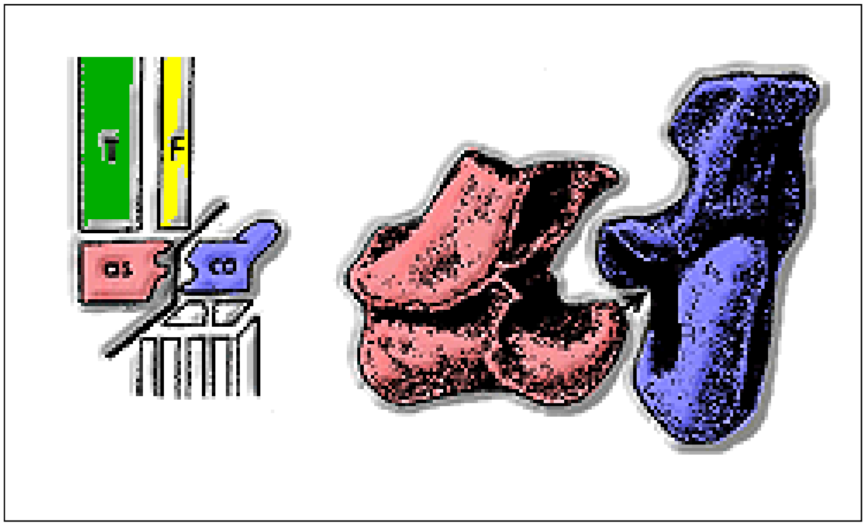

Figure 34 The crocodylian ankle joint. Green: Tibia. Yellow: Fibula. Pink: Astragalus. Blue: Calcaneum

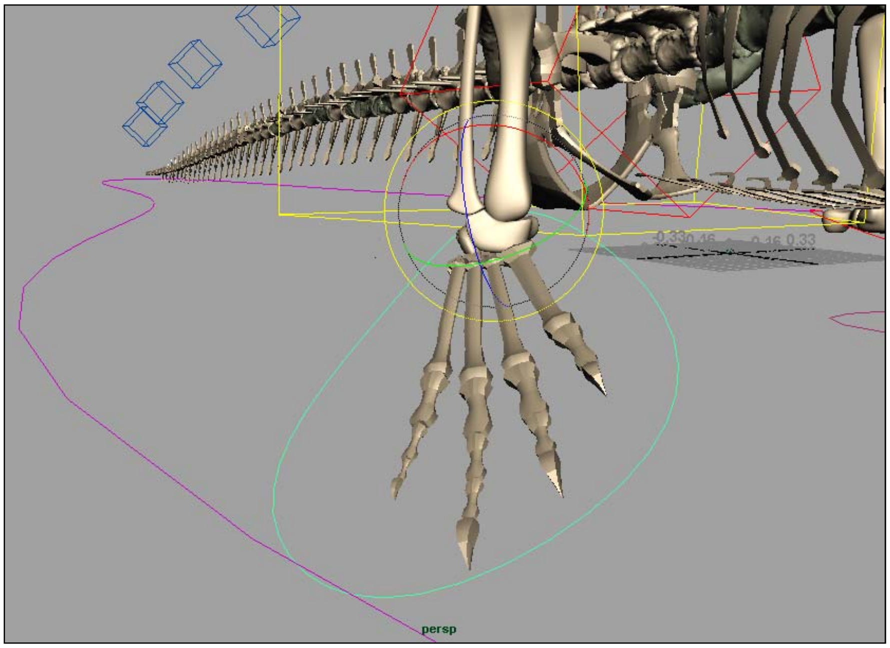

Figure 35 The metatarsals rotate relative to one another when plantar-flexing the foot

The next step in rigging was to connect the jaw controls to the jaw joint with a simple parent constraint. Then, the twist attribute on the spline IK of the tail (a common attribute automatically created when creating the spline IK) was connected to the custom twist attribute on the “Tail_Twist_Control” to allow the tail to laterally twist. The digit controls of the feet were the last ones to set up since they required a lot of planning. The digits were controlled by connecting the rotation of the individual joints to the custom attributes on the digit control objects through various expressions. The toes were set up to allow the higher level digit curl controls to affect all the joints of a particular toe simultaneously, which combined together to curl the full digit. Then, the individual digits were connected to the other, lower level digit controls, which curled specific digits individually. This setup allowed for having intricate control over the poses of the feet, by allowing one to curl a toe as a whole, digit by digit, or a combination of the two.

The last attributes created were for simplifying the rig interface. A number of attributes were created to allow lower level controls to be turned on and off so that they did not add unnecessary visual information when they were not being used. This helped keep the rig *clean*, and reduced the amount of information displayed at one time. The digit controls of the feet and the master muscle control object (to be discussed in detail later) were able to be hidden or shown through attributes on the full rig control. The jaw controls were also able to be hidden, with an attribute on the head control object.

At this point the basic controls of the rig were essentially complete. The skeleton model was then attached to the rig to start seeing the results of the interface. The skeleton model had to be connected to the joints, since all of the rig controls affected the underlying joints. This was achieved simply by parent constraining each bone to the proper joint. The parent constraint was used opposed to actual parenting in order to keep the file hierarchy clean, so that all of the rig objects were separated from the geometry of the model. This was a quick process since each joint was initially positioned based on the geometry. Each model was parent constrained to the joint it was already associated with.

In the case of the sternum, this technique did not work correctly, since there were no joints in the belly area. The ribs worked fine, since they were physically connected to vertebrae, which were then connected to joints. The sternum was connected to the spine joint closest to the front of the sternum, and then an aim constraint was created so that no matter what position the sternum was in, the back of it would always aim toward the gastralia. This way, the sternum not only stayed in the proper position relative to the shoulders, but it always remained oriented to the angle of the spine as well. An up-vector had to be added to the aim constraint of the sternum to prevent flipping, just like what was set up to stop the spline IK flipping. The gastralia also had to be connected, and were parent constrained to the joints in the spine they were each directly underneath. The cartilage connecting the ribs to the sternum then had to be addressed. There is some flexibility in cartilage, so a cluster deformer was created for the vertices at each end of each piece of cartilage. One cluster was then connected to the corresponding rib, and the other was connected to the sternum. This allowed the costal cartilage models to be slightly elastic, while keeping the ribs and sternum visually connected.

The last part of the interface of the rig that had to be created was a “shelf.” A shelf is essentially a custom built menu integrated into Maya’s interface, which includes any number of custom buttons. Scripts were written to automate a number of commonly used actions to ease the animation process. These scripts were then converted to buttons on the shelf. The buttons included a number of options, such as one to allow an animator to select all of the rig controls at once, in case a key frame would need to be set on all the controls when animating. This button would save time by not requiring an animator to manually select all of the controls in the viewport every time a key frame needed to be set on every control. Other buttons included ones that reset parts of the rig to their default pose, in order to quickly pose or repose the animal during animation.

After setting up the shelf interface, a skeletal rig was finally completed, and transformation limits were then to be set on joints and controls, which in theory would prevent the skeletal models from intersecting with one another, and prevent the rig from breaking. The application of this idea did not work as well as planned, however. Some areas worked perfectly, such as in the jaw, where the maximum rotation was set to somewhere before the quadrate and articular bones collided (Fig. 36). A couple setups like this were effortlessly created, but the extensive use of spline IK handles became a problem. Each object within Maya has an option to limit the maximum and minimum rotation, translation, and scale to any values predetermined by the user. The idea was to set these limits up for every joint, so that when controlling the rig, even if the controls were moved past a certain point, the mechanics of the bones would prevent anything from breaking. The vertebrae joints controlled by the spline IK were limited correctly, but in doing so, they prevented the splines from working at all. This meant that, unfortunately, limits could not be set for the vertebrae, and therefore would require spot checking of the skeletal poses by the animator to make sure interpenetration was not occurring. It was incredibly unfortunate that a solution could not be found to this problem, but the only way to get the limits to work in animation would require one to hand animate all the vertebrae individually without using the advantages of the spline. This would have made the animation process vastly inefficient.

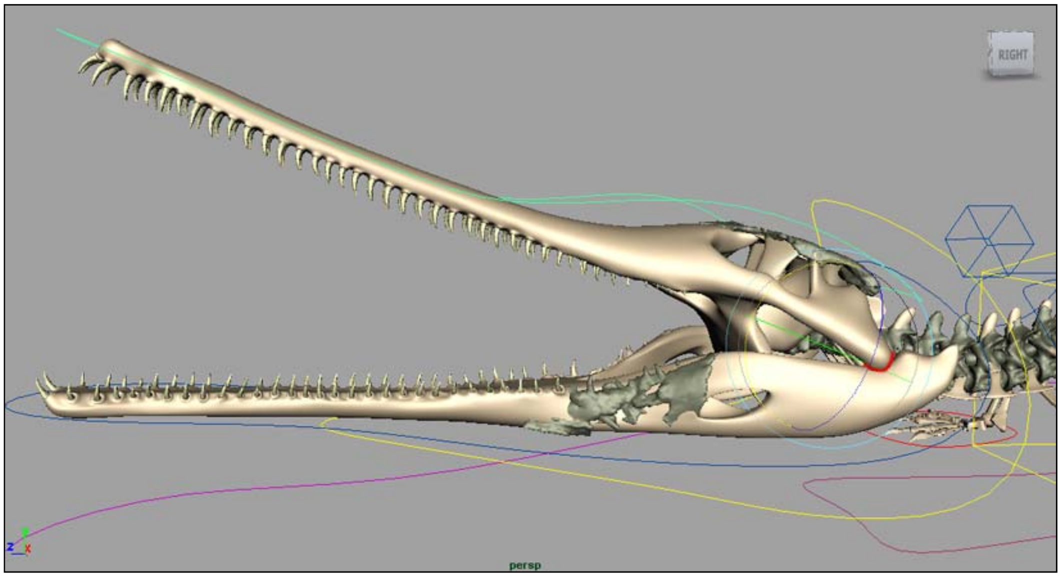

Figure 36 The rotation of the jaw cannot exceed the limit influenced by the mechanics of the skull

This problem carried over into other parts of the rig as well. Even in areas where limits could easily be set, such as in the shoulder, the values would be misleading. For example, when raising the shoulder by rotating it around the z-axis, it could only go to a certain point before the scapula collided with the vertebrae. However, when first rotating the shoulder forward, around the y-axis, and then rotating around the z-axis, it could actually rotate much less in the z-axis before intersecting with other bones. The limit of the value of the “RotateZ” attribute, in other words, differed depending on the orientation of the other two axes. It became next to impossible to find the proper combination of values to prevent collisions in any possible pose.

The real world automatically detects collisions in a way that would be incredibly computationally expensive to do in the digital world. The cheapest solution to this problem was ultimately to rely on the intuition of a talented, and detail oriented animator in order to make sure that collisions were not being made during the animation process. In the case of any rig, it is practically impossible to make it one hundred percent unbreakable because of issues like this. Riggers do all they can to prevent rigs from being broken, but ultimately, it is up to a trained animator to know to avoid unappealing poses. The situation in this project was advantageous in the sense that the rigger and animator was the same person, so the rig limitations were known well before animating. These current limitations are also detailed throughout this document, so the information can be applied to improving the control rig in future adaptations of the project.

Despite these sorts of limit issues, in the case of the vertebrae, since there were so many bones in the spine, and since a spline IK adjusts not one joint, but all the joints relative to one another, it was actually quite difficult to get the vertebrae to intersect with one another. They would only do so in extreme, unnatural poses, which would not be used in the final animation anyway. In this sense, it was beneficial to construct the rig with anatomical accuracy, since the natural mechanics and proportions of the bones did help in building a better rig. The next step was to incorporate an accurate muscle system, in order to only further the accuracy of the control rig.

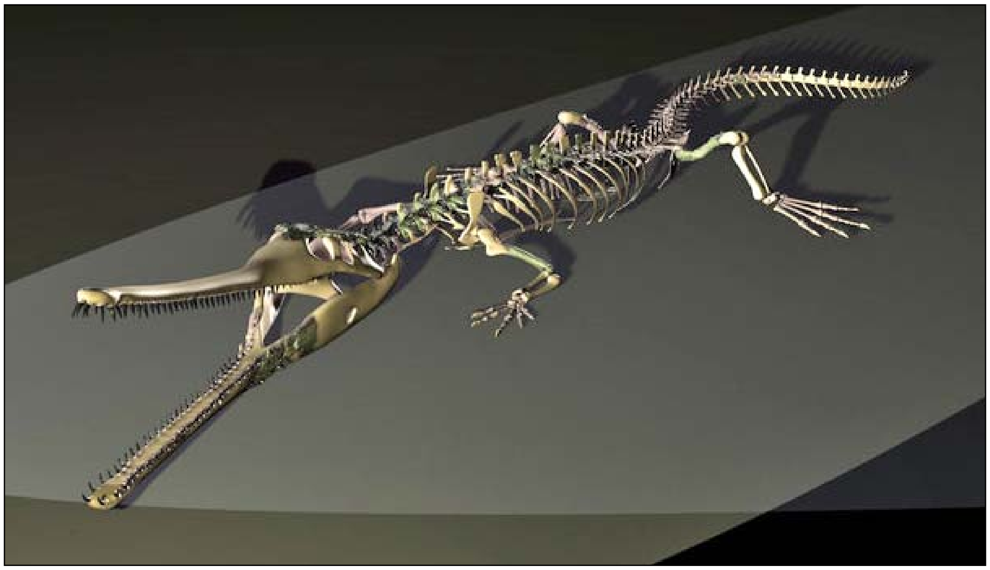

Figure 37 A fully poseable skeletal rig

3.3. Creating the Muscle System

The creation and implementation of the dynamic muscle system was by far the most complex task of the entire project. This includes both the technical and anatomical aspect of the project. This task required intense research on the musculature of crocodylians, as well as the learning and implementation of an unfamiliar and relatively new rigging tool. There were other ways of achieving the same sorts of effects before, but Maya's built in muscle system was rather new. For the *Thoracosaurus*, sixty-eight different muscles were created for both the left and right sides, creating a total of 136 muscles used in the rig.

Relying on the built-in muscle system was an incredible risk for the project, because of how heavily the muscles were to influence not only the motion, but the shape of the final animal. Using so many muscles was a radical approach. Muscle objects are frequently used to simulate only where they would be extremely visible, such as in the arms and chest of a body-builder character. The number of calculations it would take to simulate a full, anatomically-correct muscle system, as well as the amount of time to construct such a system would, for the most part, be more trouble than the payoff from the final product would warrant. Despite knowing this information, an accurate muscle system was still attempted so the *Thoracosaurus* restoration could hold scientific integrity. The philosophy behind this was to stay true to the high standards of good paleoart rather than conforming to what is easier from a production standpoint. This conflict of time versus quality is likely a substantial factor contributing to a lot of scientific errors in widely released CGI paleontological television programs.

The creation of the muscle system commenced with two components. These steps included researching and experimenting with the muscle system (going through the process multiple times before actual muscle production began), and intense anatomical research on crocodylian muscles. Learning the muscle system occurred before the anatomical research so the muscle studies and muscle rigging could occur simultaneously, making the overall production process more efficient.

The muscle system within Maya is an interface that allows a user to create objects that behave as if they have high elasticity. The muscle objects are NURBS (Non-uniform Rational B-spline) objects that have special attributes allowing them to do things like squash, stretch, jiggle, and affect the points on another geometric surface. The process of setting up a muscle object starts in the "Muscle Creator" window. There are two types of muscles that can be created, the "Simple Muscles" and the "Muscles." The simple muscles are an older version of the muscles which offer less control over their shape and functionality. For this project, all muscles were created with the "Muscle Creator" interface to use the updated muscle system.[6]

The "Muscle Creator" window has options for mirroring muscles, which will be discussed in detail later. It became important to indicate the side of the muscle in its name, so that it would be easier to mirror. In order to prepare for mirroring, all the left muscles were created first. Since each muscle was built on the left side, upon creation each muscle name contained "_L_" before the actual muscle name, to clearly label it as being on the left.

After defining these initial parameters, a muscle can be created, and the viewport updates by displaying the newly created muscle. The muscle consists of a number of parts. There is the muscle object itself, a number of muscle controller objects, and the attach points. The controls are used to adjust animation settings, such as the amount of jiggle on the respective parts of the muscle. The attach points help define the position and shape of the muscle. There are always four locator attach points that are generated, two for each end of the muscle. These locators are parented to the joints that the muscle originates from and inserts into, and determine how the muscle attaches and orients to those joints. There are also a number of other attach points that define the positions of the muscles. There are three sets of these, defining the position in the rest, the squashed (flexed), and the stretched (extended) states.

The *Edit* tab of the "Muscle Creator" window is where the adjusting of the muscle shape and position is determined. There are a number of intricate options on this interface that affect the radius of the muscles, as well as the placements of the various attach points. This allows one to define the squash, stretch, and rest states of the muscles, to help them function properly (Fig. 38). [7]

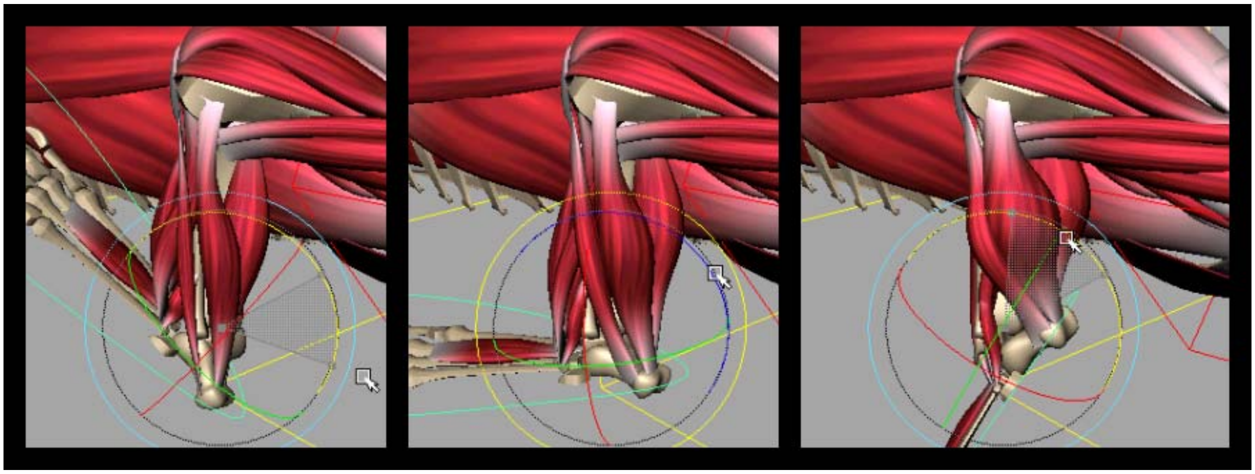

Figure 38 Muscles have a stretch, rest, and squash state (left to right)

After the basic process of creating a muscle was established, anatomical muscle research was done while building the muscles, so that theory and practice were working with one another, informing each other. Crocodylians are very well known and heavily studied animals, and there is a plethora of literature on their anatomy and musculature. Since the crocodylian body plan has remained relatively consistent throughout history, the musculature for *Thoracosaurus* was safely created based strictly on modern analogue. The muscle reference used was primarily from the American alligator (*Alligator mississippiensis)*. Alligators are commonly used for comparative anatomy studies since they are close relatives of dinosaurs and early archosaurs. They are also commercially raised in the United States, and therefore can be made available for such studies.

It would have been preferred, however, to use gharial muscle reference since they are the most aquatic of crocodylians, and are highly adapted for life in the water, like *Thoracosaurus* was. Literature on gharial musculature was difficult to come by. Some sources that were primarily based on alligators still mentioned known differences between different types of crocodylians in their discussions, though. Two papers were found that focus on gharial musculature, and they elaborated on areas where gharials differ most from other crocodylians. These include the work of Endo, e. al, (2002) on the jaw musculature of longirostrine crocodiles, and the work of Frey, et al, (1989) on the comparative tail musculature of modern crocodylians, which includes specifics on the gharial [9][11].

In most of the literature informing the creation of the muscles, there was extensive use of diagrams that accompanied the descriptions. These helped accurately shape and position the muscles. Seeing where the muscles lay and how they relate to one another was incredibly useful (whereas strict text can sometimes become difficult to comprehend). Even more helpful, were diagrams of the muscles accompanied by diagrams of bones. These visuals included outlines indicating where the different muscles originate and insert on the bones. This was particularly helpful toward achieving accuracy (since the sizes and shapes of the muscle attachment sites were taken into consideration).

The ideal way to study the muscle system would have been to actually undergo a dissection of an alligator, and film the dissection process, making sure to see all angles of the muscles. Unfortunately resources were not conducive to this. Well documented literature was therefore the best option. Having a working control rig helped to comprehend the literature when building the muscles. The control curves could be used to move parts of the body in order to test how the muscles worked in accordance with one another. The majority of the muscle research focused on the names, shapes, and locations of the muscles, since once those were set up properly, the muscles' "action" came automatically. Once their states were set up, the muscles would automatically flex and extend based on how the rig was manipulated.

While creating the muscles, a balance had to be struck between being one hundred percent accurate, and what was practical to achieve with the Maya muscle system. A number of muscles were rather difficult to set up simply because the attachment sites had more complex shapes than what could be created with only two end locators on either side of a Maya muscle. Some muscles, such as is the case with *pectoralis major* of the chest, required a broad attachment site, while other muscles consisted of multiple heads that connected together to act as one muscle, as in the *triceps brachii*. These sorts of complications had different solutions, which had to be applied on a case by case basis. With broad attachment sites, the end locators could only be pulled apart to a certain extent without the muscle being torn apart or twisted. Also, when an attachment had a broad, rounded attachment, nothing could really be done. In this case, the locators could be pulled apart to correspond with the two furthest ends of the attachment site, but without any more locators between them, the shape could not be finessed too much more.

In the case of multi-headed muscles, there were generally two options. Either multiple Maya muscles would have to be created to simulate the multiple heads, or the muscle would have to be simplified, and only take into account the attachment of one of the heads. Which of these solutions to use was decided on a case by case basis, depending on how prominent the different muscle heads were. In the case of the *triceps brachii*, for instance, the heads were lumped together, since there were five of them. Five different muscles connected to the same patch of skin and trying to work as one would have been more trouble than it was worth to set up. There were other multi-headed muscles, such as the *gastrocnemius* in the lower leg, which only had two heads. In cases like this, the heads tended to be large and prominent. Because of this, both heads were created as separate muscles since they were so distinct (Fig. 39).

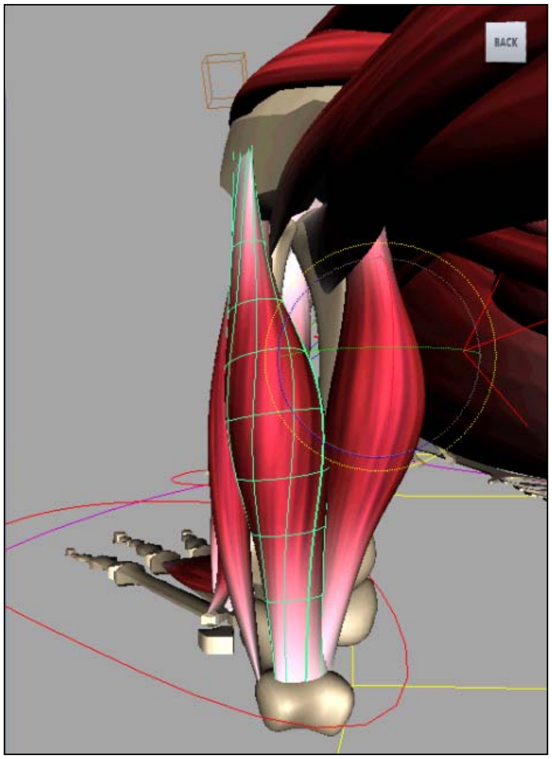

Figure 39 The external (left) and internal (right) heads of the *gastrocnemius*

There was also an issue involving complex tendons, which really could not be accounted for with the Maya muscle system. The most notable example of this is seen in the *caudofemoralis longus* muscle of the tail. Although this muscle inserts into the fourth trochanter of the femur, there is another tendon which diverges and connects into the thick tendonous network of the knee joint [30]. This sort of structure was one that was not particularly possible to create with the Maya muscle system. It could probably be created in another way, such as by modeling it with geometry, but it would not have behaved as part of the muscle. In circumstances like this, the most prominent attachment point was used.

The muscles were recreated based on a number of different literary sources. These include the work of Meers (2003) [26] for the pectoral and forelimb muscles, as well as some of the neck musculature. The work of Romer (1923) [32] was used for the pelvic muscles as well as a couple of trunk muscles. Frey, et al, (1989) [11] was used for the tail, and Endo, et al, (2002) [9] for the jaw muscles. The work of Reese (1915) [30] was used for the lower leg muscles, as well as any other muscle not mentioned in any of the other sources. Chiasson's alligator dissection guide (1962) [6] was also used for various trunk and neck musculature, and the work of Cong on the Chinese alligator (*Alligator sinensis*) (1998) [7] was used to spot check and adjust muscles throughout the body. Most of this reference was based on alligators, although Reese notes where differences are found between crocodylian species. The work used for the tail and jaw musculature also describes, in depth, some differences found in gharials. The preference for this project was to use gharial musculature whenever possible, since gharials are the closest living relatives to *Thoracosaurus*.[8] The final muscle system ended up being a primarily alligator based muscle system, with some key influences from the musculature of the gharial.

The body of literature on crocodylian musculature is incredibly thorough, and really helped to validate a major portion of the project. The only problem with having so many different sources for muscle research, spanning about a century's worth of work, is that the names of the muscles have a tendency to change over time. It appeared at first as if the various sources were not matching up with one another at times, as some sources appeared to be describing muscles that others would completely omit. In reality, it turned out that different authors were using different names to describe identical muscles. Despite these discrepancies, since all muscle names are Latin names, it was relatively easy to figure out what different names were describing the same muscle. The Latin names are all based on anatomical terms, particularly the bones in which the muscles originate and insert. This realization, along with the descriptions of the muscles in the text helped distinguish which muscles were which. An example of this is found with the *caudofemoralis longus*. *Caudofemoralis* is a name that is derived from *caudal* and *femur*. The name essentially means that the muscle originates from the caudal vertebrae and inserts into the femur. In the work of Romer, however, there is a muscle that fits the description of the *caudofemoralis* that is referred to as the *coccygeo-femoralis* [32]. After reading the description, it became clear that these two names refer to the same muscle. Romer simply used a name that is derived from *coccyx* instead of *caudal*. The coccyx is the term for the fused vertebrae of the tailbone found in apes. Both of these muscle names mean the same thing despite their different roots, and both describe the same muscle.

For the actual creation of the muscles, the more complicated muscle areas were built first, starting with those of the pectoral girdle and forelimb. The strategy here was to work bone by bone. Using the diagrams in the literature, all the muscles attached to one bone were created before moving on to the next bone. This procedure worked rather gracefully, since each muscle was connected to at least two different bones. The process flowed naturally from one area to another. Since the pectoral girdle was the first place to be restored, it became more intricate than other areas. At this point, the practicality of production was not taken into account as much, and more muscles were created than were needed for the big picture, such as deep muscles attached to the scapula. Some of these muscles would not only never be seen, but also would not be able to be attached to the skin, since more prominent superficial muscles would be attached to the skin in those areas. Examples of these types of muscles included the *brachialis brevis ventralis, costocoracoideus, scapulohumeralis caudalis, deltoidus scapularis, teres major, subscapularis, rhomboideus,* and the *serratus ventralis cervicis* of the shoulder. They were not particularly necessary for the final animation of the creature, but they still created an extremely intricate shoulder musculature (Fig. 40).

The muscles of the forelimb became so small and complex that it would have been next to impossible to get them all to work together and affect the skin properly. After constructing the upper arm, it was decided to not attempt to reconstruct the incredibly intricate musculature of the manus, since the complications that were present in the upper arm would be compounded in the hand. These muscles would not add anything significant to the flexing and extension of the digits. They would only unnecessarily overcomplicate the task of combining the skin model to the rig. Nevertheless, the work of Meers includes fabulous reference on the complete musculature of the manus, and could be explored in another project if desired [26].

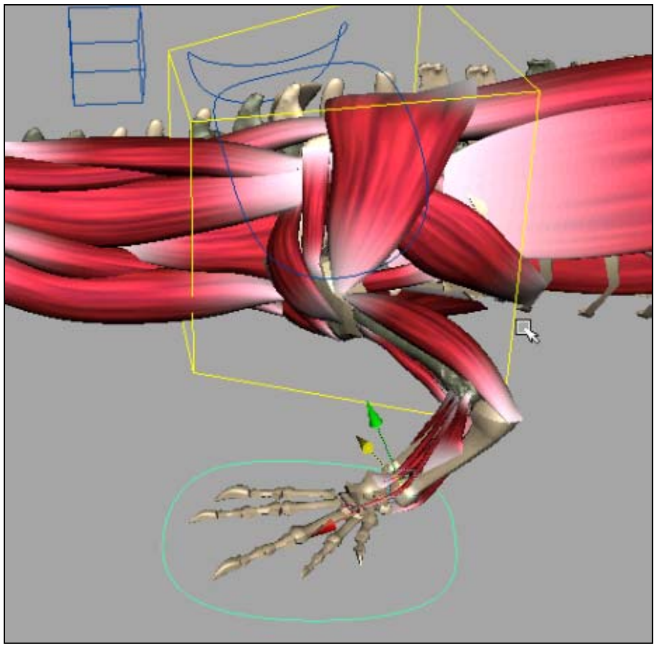

Figure 40 The pectoral girdle

The pelvic musculature continued the concepts proven effective and efficient in creating the muscles of the pectoral girdle. Less deep muscles were included; however, there were still a number of muscles created that, in the end, probably did not need to be. The process of building up the muscles from the inside out proved helpful. Even though more muscles were built than were needed, building deep muscles and layering more on top of them aided in understanding the structure of the limbs. It also helped to position muscles more accurately, since the textual reference in the literature describes positioning through associations with surrounding muscles and bones.

The musculature of the lower hind limb was much more prominent than that of the antebrachium. As mentioned before, the *gastrocnemius* was split up into two muscles, to represent the external and internal heads, in order to accentuate the prominent calf muscles. There were some areas where a number of smaller muscles were actually lumped together, and represented by only one muscle. These were for instances where multiple small muscles worked together to achieve the same action. For example, the *peroneus anterior* and *peroneus posterior* were combined to simplify the musculature of the lower leg. The two of them together were represented by a single muscle labeled as the *peroneus posterior* on the rig. It is also important to note that there was not as helpful reference diagrams found for the lower leg as there were for the pelvis and forelimb muscles. As a result, the attachment points on the tibia and fibula were approximated, (as best as possible) based on textual reference, and may not be quite as accurate as those of the pelvis and forelimb. The musculature of the pes, like in the manus, was omitted.

The tail was the next section to be added. This was relatively simple to do, since only two major muscles were incorporated into the restoration of the tail. The most important one was the previously mentioned *caudofemoralis longus*, and the other one was the *dorsalis caudae longissimus* (a caudal extension of the *longissimus* of the trunk). This tail musculature was inferred from that of the gharial. There are a couple of differences that were noted between the tail muscles of gharials and other crocodylians. First of all, in most other crocodylians, there is a second, smaller *caudofemoralis*, called the *caudofemoralis brevis*. This muscle is missing in the gharial. The *caudofemoralis longus* is also not as long as it is in the other crocodylians. Where in most species it originates around the thirteenth or fourteenth caudal vertebrae and extends to the femur, in the gharial it originates around the tenth caudal vertebrae instead [11].

The neck and trunk were simple enough to put together, since they included a series of large and broad muscle groups that lay flat against the vertebrae and ribs, providing structural support for the body. The intercostal muscles of the ribs were omitted, as well as a number of other deep muscles. Many of the trunk muscles in particular were simplified to only include the muscles that would be observable. The neck was slightly more involved, since the muscles had to work with the pectoral girdle and the skull, in an area with more mobility than the trunk.

The last area to construct muscles for was the jaw. For the restoration, five muscles were included for each side of the jaw. These included the *pterygoideus anterior, adductor mandibulae posterior*, *depressor mandibulae*, *pseudotemporalis*, and *pterygoideus posterior*. This jaw musculature was derived from the gharial since *Thoracosaurus* was also a fish eating gavialoid crocodylian. Since both species shared a similar niche, albeit at different time periods, their jaw musculature should have been rather similar as well. Because of the fish eating lifestyle of the gharial, the *pterygoideus* muscles - the large muscles under the skull that control the bite force - are smaller than those found in other crocodylians (Fig. 41). The *pterygoideus posterior* also has a weaker attachment point on the angular than in other crocodylians. These features indicate that the bite force of the gharial is much less than that of alligators and crocodiles [9]. The long, thin snouts of longirostrine crocs gave up bite force in favor of speed [22]. These animals do not require the raw power that alligators and crocodiles need to take down large terrestrial animals, and instead use their thin beaks to quickly snatch up fish. The difference in the size of these *pterygoideus* muscles is clearly seen when looking at any live specimen of these various crocodylians. The muscles underneath the jaw look almost like a large pouch in alligators, and are hardly noticeable in gharials. This distinction was taken into account when reconstructing the jaw musculature of the *Thoracosaurus*. The attachment points for these muscles are also relatively complex, and once again had to be simplified in order to replicate them with the Maya muscles. These were the last of the muscles to be set up before moving on to the next step in muscle creation.

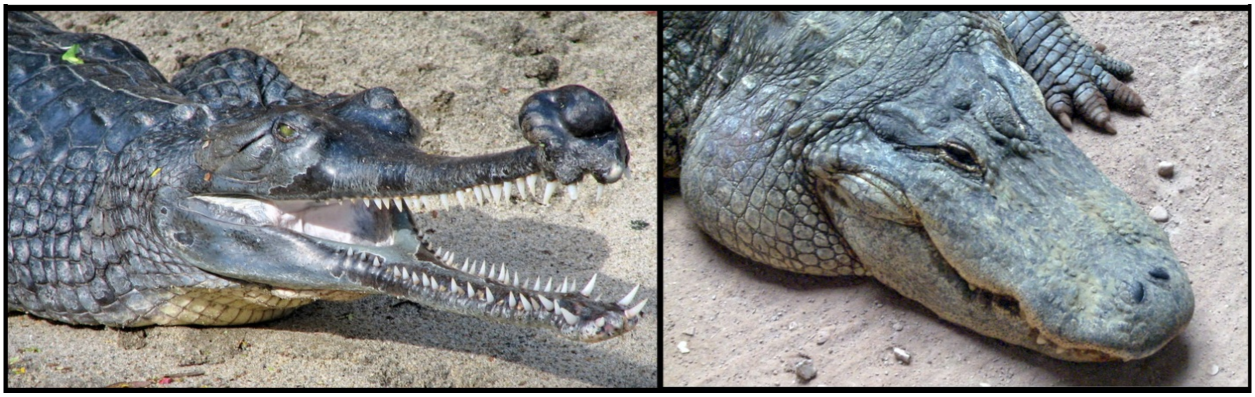

Figure 41 The *pterygoideus* muscles are much larger in alligators than in gharials, and are visible on the larger living animals. It is the structure that looks like a large growth just behind the lower jaw. The Indian gharial (left) and the American alligator (right).

After all of the muscles were created for the left side, they had to be mirrored to the right.[9] An issue with mirroring became apparent when testing the mirrored muscles with the rig. After mirroring the muscles of the pectoral girdle, and adjusting the front leg controls for the right side, the newly mirrored muscles on that leg would stay in place. However, when moving around the left forelimb, everything on the right side would suddenly start moving around and distorting. The issue was that when the muscles themselves were mirrored, the end locators were not. The end locators of the muscles were duplicated and renamed, but were parented under the corresponding joints on the left side. This required going into the rig hierarchy and manually searching for the locators of the mirrored muscles, and re-parenting them to the appropriate joints on the right side.[10]

The muscle system then *looked* complete, but there were further issues when manipulating the rig. The limbs and jaw worked great, but the trunk, neck, and tail were not behaving how actual muscles should. Since a lot of the muscles in these areas had origin and insertion points that were quite far from one another, there was an issue where the muscles were not following along with the joints between the origin and insertion points. This was only problematic in the case of muscles driven by spline IK chains. In the actual world, there is connective tissue that helps pack muscles to one another and to other bones. A way of simulating connective tissue would allow these muscles to stay attached to all of the vertebrae they lay across. Unfortunately, the Maya muscle system only takes into account the positions and orientations of the origin and insertion joints. Because of this, when moving, say, a tail control that is somewhere between the start and end points of a muscle, the skeleton and joints would actually pull away from that muscle on the tail, leaving it more or less where it was. This would happen any time the rig was manipulated in an area that affected a portion of the body between the start and end points of a muscle along a spline IK chain.

When experimenting with solutions to this by attempting to simulate the effect of connective tissue, it was found that if these broad, long muscles were actually skinned to the joints, in the same way that a geometric mesh can be skinned to a skeleton, the muscles followed along with the joint chains correctly. Even better, they also retained their muscle properties. This meant that they could still be used to influence a skinned mesh later. This solution was used for the trunk muscles, the tail muscles, and most of the neck muscles. The fix seemed like the perfect solution at the time, but created another problem, which would be discovered during the skinning and animation processes. The final step to this solution involved preventing double transformations.

The muscles were skinned to the skeleton, so would follow along with the joints. These muscles also still retained their muscle properties, which register their squash, stretch, and rest states based on the relationship between the start and end locators of the muscles. Since the end locators of the muscles were still parented to the joints, these influences plus the influence of the skin deformers would cause the muscles to deform twice as much, causing them to distort and fly off of the bones. This was solved by simply un-parenting the start and end locators from the joints, and letting the skin drive the positions of the skinned muscles.

The final step before moving on to the skin was to set up the “Master Muscle Control.” As previously mentioned, this control was created to affect dynamic muscle attributes, so that they could be controlled by an animator. This process required opening the “Setup Master Muscle Control” window. For this master muscle control, instead of giving control over every muscle, the different parts of the body were lumped into groups. These groups included the skull, jaw, dorsal and ventral neck muscles, the shoulders, upper arms, forearms, trunk, the thighs, lower legs, and tail. These groups would allow for control over the dynamic properties of a muscle group opposed to setting values for every muscle individually.

What was nice about the way this system worked was that the values that were added to the master muscle control object acted as multipliers on the dynamic properties of the individual muscles. If a value was set for a muscle group, but one muscle in that group still did not work correctly, the user could rummage through the rig hierarchy and adjust the value on that particular muscle, offsetting how it would be controlled by the master muscle control.

Following the decision on how to split up the muscle groups, the next step involved hunting through the muscle hierarchy and selecting all of the desired controls for all of the muscles in a particular muscle group. The attributes on these controls were then connected to the "Master Muscle Control" object.[11] This resulted in attributes controlling the dynamic properties of the muscle group being created on the master muscle control object. This process was repeated for each muscle group.

After this control object was set up, a full muscle system was finally completed, and ready to be bound to a skin. The complete underlying structure of the restoration phase of the project was complete (Fig. 42). The next step was to create the final appearance of the "living" animal, by restoring its outer skin.

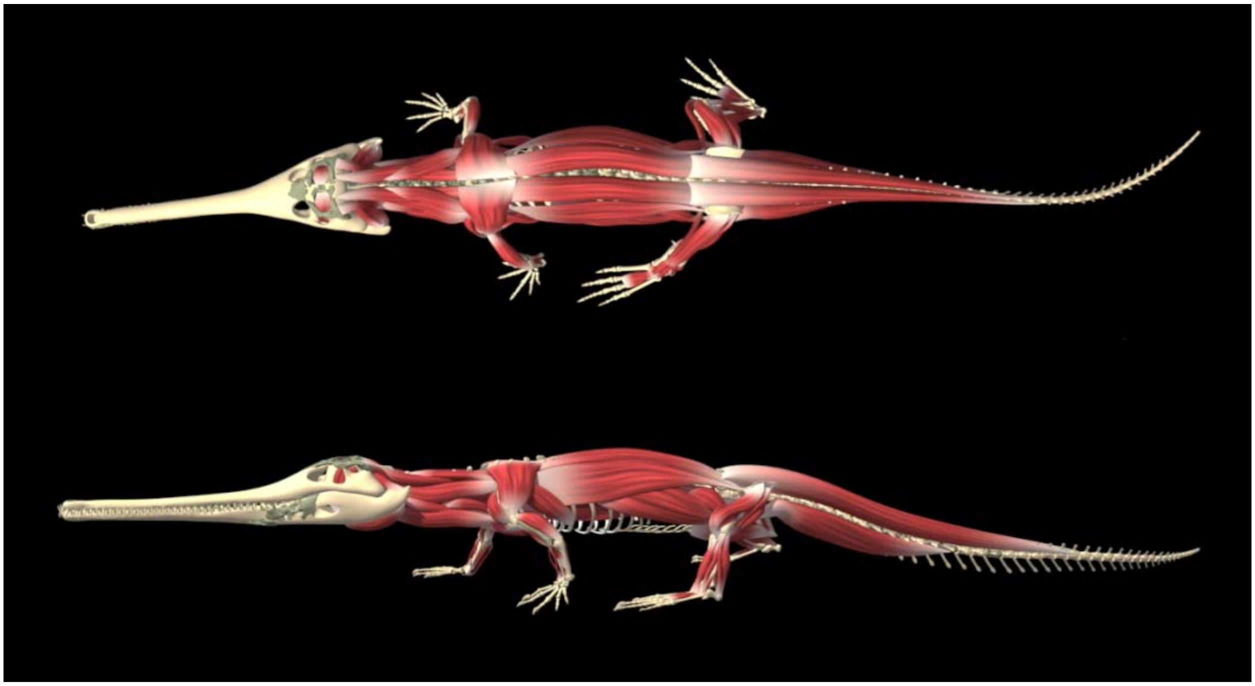

Figure 42 The completed muscle system

3.4. Creating the Outer Skin

Creating the final skin of *Thoracosaurus* required a number of different processes. Simply building the model in a similar manner that the skeletal models were built was only the first of many steps. The model afterwards needed to be sculpted, painted, and connected to the muscle and skeletal systems in order to finish the restoration.

Having an underlying structure in place for the *Thoracosaurus* helped the modeling process move more quickly than the character modeling process normally takes. Instead of having to rely on two-dimensional image planes, a full three-dimensional model was already available. It was determined early on in the modeling process that the majority of the scale and osteoderm detail would be created through sculpted detail, so a large majority of the modeling involved encasing the existing model inside of a skin mesh.

The modeling started at the skull, and moved posterior until it was finished. The head was started by actually duplicating, adjusting, and cutting up parts of the skeletal jaw models. The snout, despite having a thin layer of skin on it, would be about the exact shape of the bone underneath. In order to prevent from having to hand model all of the alveoli of the jaws again, this technique of starting with the duplicated skeleton model allowed for time to be better spent on other areas of the model. When building the nostrils at the end of the snout, reference imagery of female gharials was used. Gharials are actually the only living crocodylian that exhibit sexual dimorphism, meaning that the males and females are visibly different. Male gharials have a growth, known as the *ghara*, on top of their nostrils that they use to amplify sounds [38]. Since the gharial is the only crocodylian to have this trait, it is likely that it is a specialized adaptation that would probably not have been present in much more basal species. Also, there is really no way of knowing if the *Thoracosaurus* specimen was male or female, so it was decided to not specify either way by leaving the *ghara* out of the restoration.

Since there were still openings in the duplicated skull to make room for muscle attachment, work had to be done to close these openings and form the palates of the mouth. The roof of the mouth was peculiar, because of how it blends in to the back of the throat, which actually sits lower than the surrounding jaws. The opening of the throat is found at the bottom of the mouth, unlike in other animals. This is largely due to how the pterygoid bones of the skull are shaped (Fig. 43). When modeling in the default, neutral pose for the rig, the mouth was closed, so it was difficult to navigate when structuring it. It took a bit of work to build the throat in a way so that it would deform correctly when the jaw opened and closed. This also required going into the cheeks and building the flesh that represented the visible part of the cheeks driven by the *pseudotemporalis* and *pterygoideus anterior* masticatory muscles.

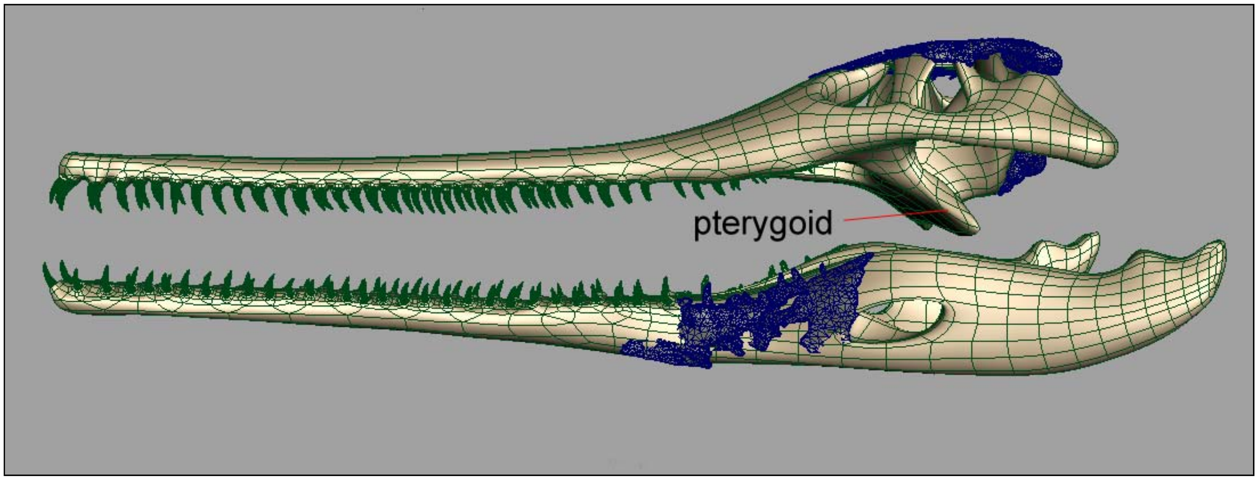

Figure 43 The shape of the pterygoid bones cause the opening to the trachea to lay at the bottom of the mouth

When building any polygonal mesh, it is important to keep clean topology that naturally flows from one area to another, and retains four-sided faces throughout the entirety of the model. Edge flows on models also have to be constructed in a way to mimic natural muscle groups, so that they behave as expected when deforming, without tearing or creating undesirable poses. Trying to create the aforementioned throat and cheek area so that it not only flowed properly, but also worked for animation, was particularly difficult with the mouth in the default closed position. Previous modeling experience helped plan how all of it was going to work in conjunction with everything else. When finished, it functioned exactly as expected once connected to the rig (Fig. 44).

The actual trachea and epiglottis were not modeled directly into the mesh, since there were not going to be any close up shots of the throat in the animation. The jaw also would not be open enough in the animation in general to warrant building an accurate trachea. The trachea and epiglottis were reductively incorporated into the texture later on, however, so that there was at least some detail for what would be visible.

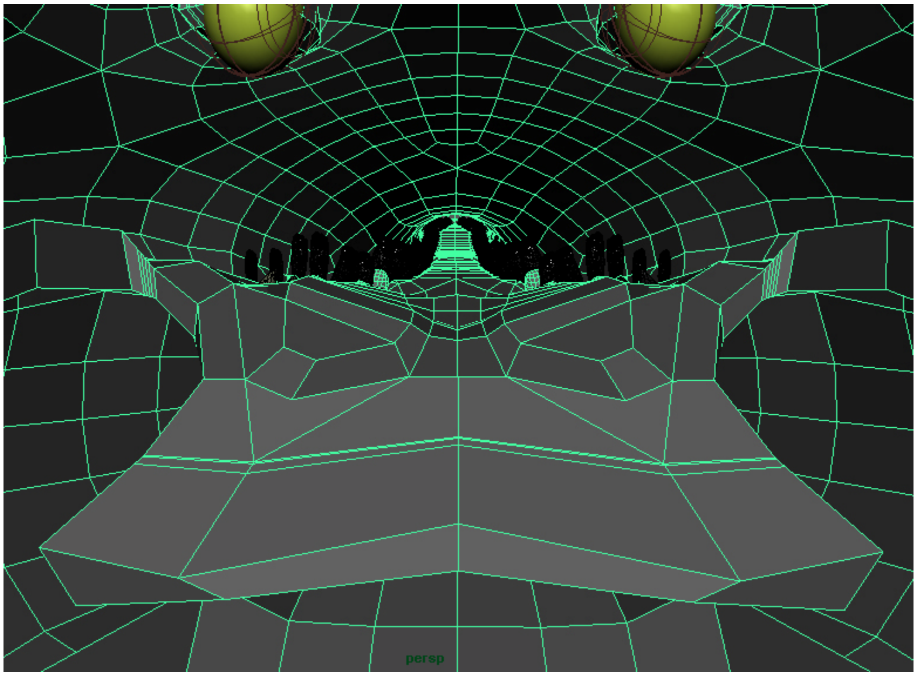

Figure 44 The throat topology from inside the model and behind; looking down the snout.

The other major part of the head to rebuild was in the area of the eye socket and brain case. The back of the head required mostly tracing along the shapes of the skull, but the difficulty came in matching up the complex edge flows to neighboring topologies. The eyes were a key part to build, since they had to resemble the eyes of a gharial, yet conform to the shape of the *Thoracosaurus* orbits. The eyes were built separate from the head. They were created using gharial reference imagery to make sure to include the proper folds of skin and the nictitating membrane in the front corner of the eye. After the eye socket model was finished, it was then embedded into the rest of the head, adding and removing edge loops where needed in order to maintain a consistent edge flow (Fig. 45).

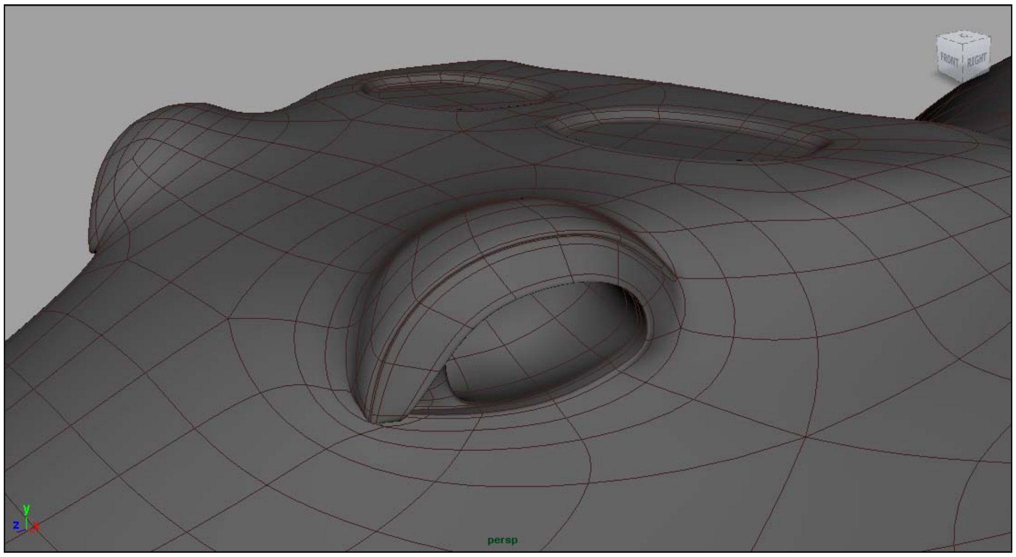

Figure 45 The eye socket

The majority of the body progressed rather quickly. Since the bony scutes of the skin were going to be sculpted in later, the body essentially had to be a modified cylinder that extended from the neck through the torso, and tapered into a thin paddle for the tail. The legs were essentially four more cylinders extruded from the body geometry; later adjusted into their appropriate shapes. The feet were a bit more complex in order to retain a higher polygon resolution for the toes without the rest of the body becoming too dense. It is always best to use areas where little deformation is going to affect the geometry to transition from a denser to a sparser polygon resolution. Otherwise unpleasant pinching and tearing artifacts in the mesh could show up as a result of skin deformation. To avoid this as much as possible, the edge flow from the digits was reduced through the area of the metacarpals and metatarsals in order to flow properly into the lower resolution of the legs.

In areas where major muscles would be deforming the geometry, circular edge flows were created to mimic the shape of the underlying muscles. Notable areas where this occurred included the throat area around the *pterygoideus* muscles, as well as the large *latissimus dorsi* in the shoulders and the *pectoralis* in the chest.[12]

The only area of the skin mesh where the edge flow caused awkward deformations was at the connection between the hips and the hind limbs. The hind leg was too integrated into the torso, which caused a little bit of awkward stretching in the inner-thigh area (Fig. 46). There was supposed to be a little skin stretching in this area, as was observable in various motion reference videos, but not quite to the extent as what occurred in the final model. The way this could have been prevented was to use a different default pose for the rig, which would have required some re-rigging of the limbs. If the default pose had the arms and legs stretched outward laterally from the body, rather than a more lifelike basking pose, the legs could have been more distinguished, and remained a little more separate from the body. This issue was not discovered until after animation tests were started, but did not warrant the time it would take to backtrack, rebuild, re-texture, and re-rig the legs.

The *Thoracosaurus* was also modeled slimmer than a number of the crocodylians seen in photographic reference. There were two reasons behind this approach. First, slimness would support the idea that this animal was not full-grown. Most larger crocs' obesity is a result of aging. Secondly, the muscle system had an option to create a *fat offset* from the muscles when binding to a skin mesh. This feature could be employed to bulk up various parts of the body as necessary; hence, areas like the upper arm and torso were not bulked up as much in the model.

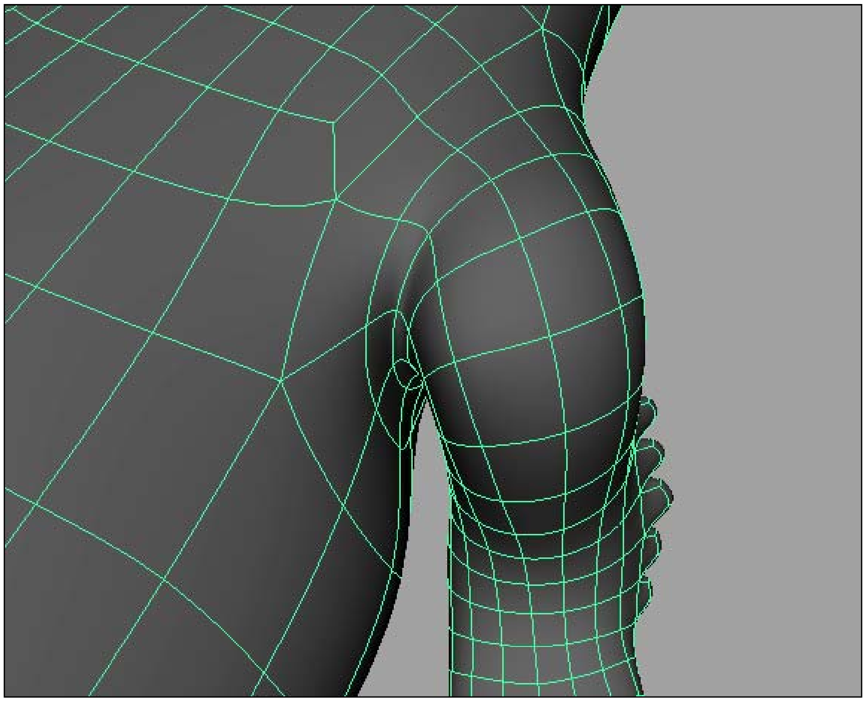

Figure 46 The edge flow of the hindlimb

There were a few miscellaneous features to add into the model before sculpting could begin. Even though the osteoderms were to be sculpted in, the flat pointed scutes of the tail were too large and pronounced to achieve in the sculpt. These spikes were built based on the paddle-like tail of the gharial; a shared adaptation for an incredibly aquatic lifestyle. There were also scute-like fringes on the lateral edges of the limbs; observed when referring to photographic reference of extant crocodylians. These were incorporated into the legs. The cloaca was also added, by simply extruding a circular edge loop inside of the body underneath the pelvis to create the vent. The location of this was approximated based on diagrams of the pelvic and trunk muscles. Even though it was not essential to the motion, and there were no shots that would exactly feature it, it was included for the sake of authenticity and since it was simple enough to create.

The next couple of places that had to be created were built as separate objects. The claws of the feet, and the teeth were used from the skeleton model, since they show through the skin, and do not have any extra covering. The foot webbing of the pes was created as a series of separate objects as well. This could have been incorporated into the rest of the model, but the technique that was used for the webbing was the same technique that worked rather well for the foot webbing of a cormorant on a previous project. Instead of embedding the webbing into the model, the flaps of skin were built as separate objects, and later skinned to the joints of the feet. This setup allowed them to deform along with the feet. Webbing was not built for the manus, since modern crocodylians do not have webbing on their front feet.

The tongue was also built, based on reference photography of gharials. It appears as if gharial tongues are shorter and blunter than those of alligators and crocodiles. Because the beak is so thin, the tongue does not really extend down the snout at all, but stays in the mouth cavity. The tongues in other crocodylians, however, seem to resemble the overall shape of their jaws. The final parts of the *Thoracosaurus* model to build were the eyes. The eyes were rather simple to build, and consisted of two objects. There was the object that represented the lens of the cornea, and another object parented inside it, consisting of the rest of the eye. The eyes were built out of modified spheres turned on their sides, so that the pole of the model faced outward. The eye was given a slit for a pupil, and there was a simple geometric surface kept behind this opening, so that the eye could later be shaded correctly.

After adjusting minor blemishes, the half of the model that was built was mirrored over to the other side, and the connecting midline edge between both halves was touched up. The animal was intentionally built at a fairly low resolution, knowing that more detail would be added through the sculpting process. It was also built at a low resolution since it was set up to be rendered as a subdivision surface. This would allow the faces and edges to be smoothed at render time, preventing the need to use incredibly high resolution geometry in the workspace (Fig. 47). The final poly-count of the model was 13,290 quadrilateral faces.

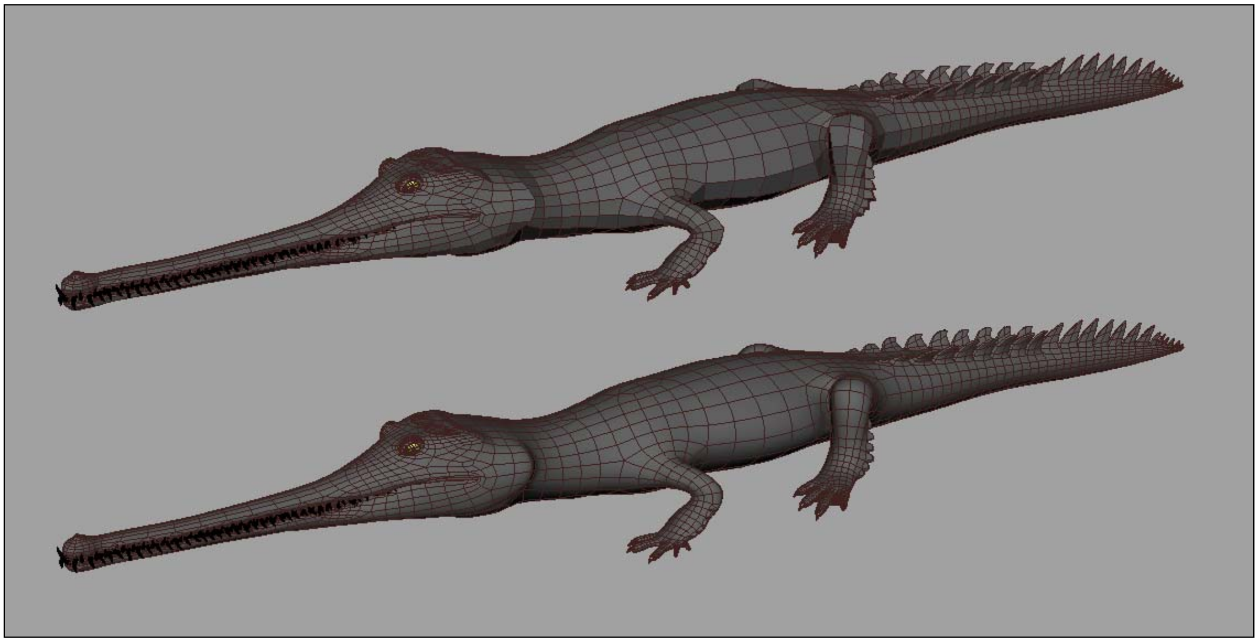

Figure 47 The skin model (above) and smoothed subdivision preview (below)

The next step was to start setting up the model for painting and sculpting. This required a process called UV mapping. UV mapping is the process of laying out UV coordinates to create a two-dimensional representation of a three-dimensional object. This then allows one to paint directly on a two-dimensional image, and have it wrap around the model in three-dimensional space, according to the coordinates.

A number of factors must be considered when laying out UV coordinates. It is important that none of the UVs are overlapping in the two-dimensional UV coordinate space. Overlapping UVs cause problems for the skinning process, as will be discussed in detail later. The UV space also is contained within a square grid, where, by default, the horizontal resolution is equal to the vertical resolution. This means that all of the UVs must be laid out within this box, and they must be arranged in a way so that maximum image resolution can be used for the more important parts of the mesh. Ultimately, the square resolution of the UV space will be equal to the pixel resolution of the image file used for the texture. This means that a higher resolution image would allow for better shading detail, while also using more memory, and causing the computer to take longer to render a frame.

In order to create the UVs, instead of using Maya's internal tools, the final *Thoracosaurus* body model was exported as an .OBJ file and brought into a program called Headus UV Layout, which is specifically designed with an intuitive workflow for setting up UVs. The process in UV Layout required bringing in a mesh, cutting it apart, and flattening it. The workflow was analogous to the skinning of a real animal, in a way that attempted to remove the hide as one piece. The process required cutting in strategic places, where seams would be less likely to be noticed. It also required having as little seams as possible in order to prevent problems with the texture matching up across the mesh. The *Thoracosaurus* was actually able to be laid out so that there were only seams across the belly, the inner surfaces of the legs, around the feet, and around the eyes, but ultimately had to be cut up further. Since the animal's body was incredibly horizontal, having the UVs laid out in one piece would require the coordinates to become much smaller in order to fit them in the appropriate UV space. This would in turn cause the resolution of the image file for the textures to be unnecessarily large, and would have been extremely impractical. As a result the UVs were broken up so that more image resolution could be given to each part of the body (Fig. 48).

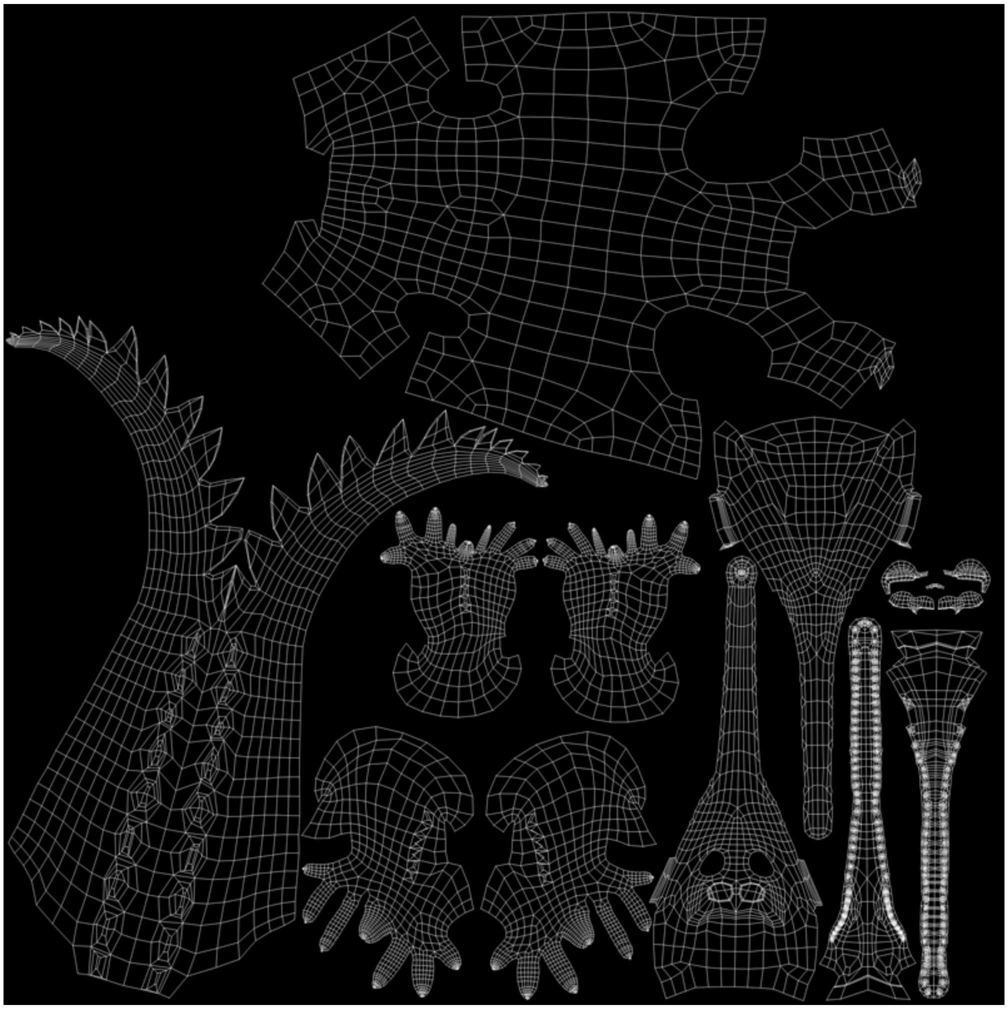

Figure 48 The final *Thoracosaurus* UVs

After the UVs were completed, the model was exported out of Headus UV Layout, and imported back into Maya, so that the model used in the rig would have the proper UVs. This model was also ready to be sculpted and painted, which would require the use of yet another software application. Pixologic's ZBrush was used for the sculpting process.[13]

ZBrush is a high-end sculpting and painting application that allows the manipulation of a model, as if it were a piece of clay. In order to sculpt more detail into a model, the pipeline requires subdividing the base mesh a number of times to increase the polygon resolution. The resolution of the model quickly becomes comprised of millions of polygons while sculpting. With this higher resolution, finer dimensional details can be built into the mesh. After the sculpting process is complete, the detailing then needs to be transferred back onto the original low resolution model. The high poly-counts of sculpted meshes are unwieldy and unusable for animation purposes, so the detail must then be converted to a displacement map. Any pixel on this grayscale texture map that is lighter in value than black represents a point on the surface of the mesh that is elevated. The brighter the pixel is, the more the corresponding point on the mesh is displaced. This technique allows the image to add details like wrinkles, scales, bumps, and cracks to a low resolution model at render time. A speed-up in the production process is achieved by obtaining high levels detail, without requiring the renderer to calculate an exuberant amount of polygons.

With this process, a lot of subtle detail was added, by pulling parts of the mesh around, molding more specific shapes, and by cutting into it to create more pronounced creases. Folds of skin and wrinkles were also added throughout the mesh. Most of the sculpted detail involved creating the osteoderms along the back, and creating imprinted shapes to simulate the scales. The majority of the osteoderms were sculpted by hand, while looking at reference imagery from gharial backs. The scales were created using custom ZBrush alpha images. An alpha works essentially like a displacement map, but instead of conforming to the UV space, it works more like a stamp or brush. Alphas can be used to make sculpted effects like beveled text, or create patterned and textured surfaces. There are a number of alphas pre-installed in ZBrush, but crocodylian specific alphas were created directly from high-resolution photographic images. Multiple alphas had to be created since scales on different parts of crocodylian bodies are shaped differently. The belly scales are different from the arm and leg scales, which are different from the tail scales. Photographs of these different parts of crocodylian bodies were sampled and converted into black and white images to use as alphas in ZBrush (Fig. 49). A number of reptilian skin alphas were also found for free download through Pixologic's website, but only alphas from crocodylians were used to supplement the final high-resolution sculpt (Fig. 50).

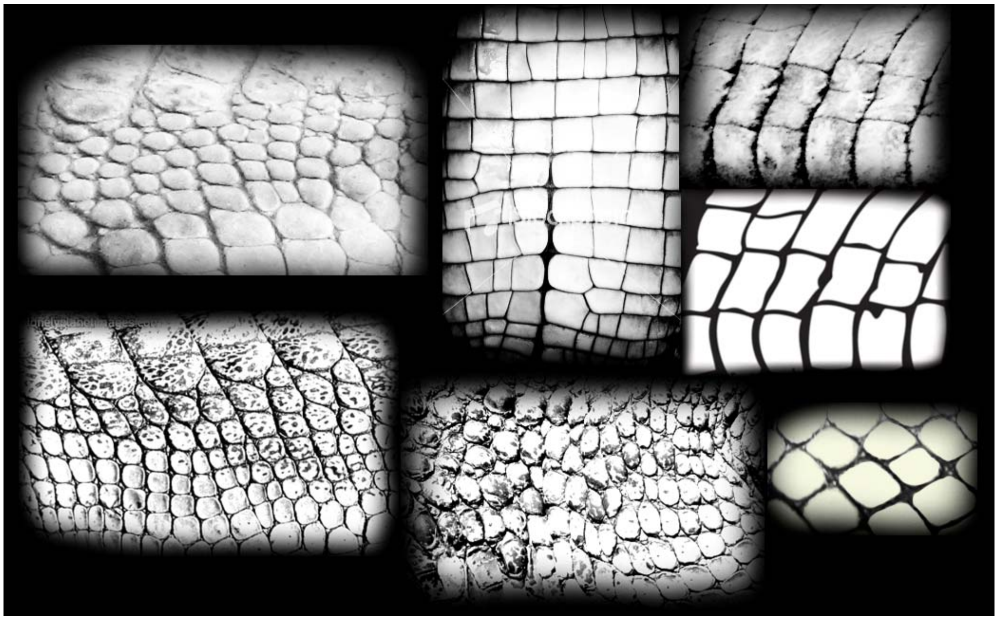

Figure 49 Sample ZBrush alphas created from crocodylian photographic reference

After sculpting, the displacement map was generated from ZBrush based on the UVs of the model (Fig. 51). Another map was created as well, which supplemented the displacement map. Displacement maps tend not to match the high resolution sculpts perfectly. There are settings that can be used to adjust the displacement attributes, but a lot of the fine and subtle details have a tendency to become lost in translation. Normal maps are helpful to help restore some of this lost detail. A normal map uses three color channels (red, green, and blue) in a way that fakes lighting on a surface in order to emphasize details. The normal map was exported to supplement the displacement map by bringing out details such as the shapes of individual scales (Fig. 51). All texture maps for the *Thoracosaurus* were created at a 4K resolution (4096 x 4096 pixels) to preserve as much detail as possible, and were later converted down to a 2K (2048 x 2048 pixels) resolution for actual use in production.

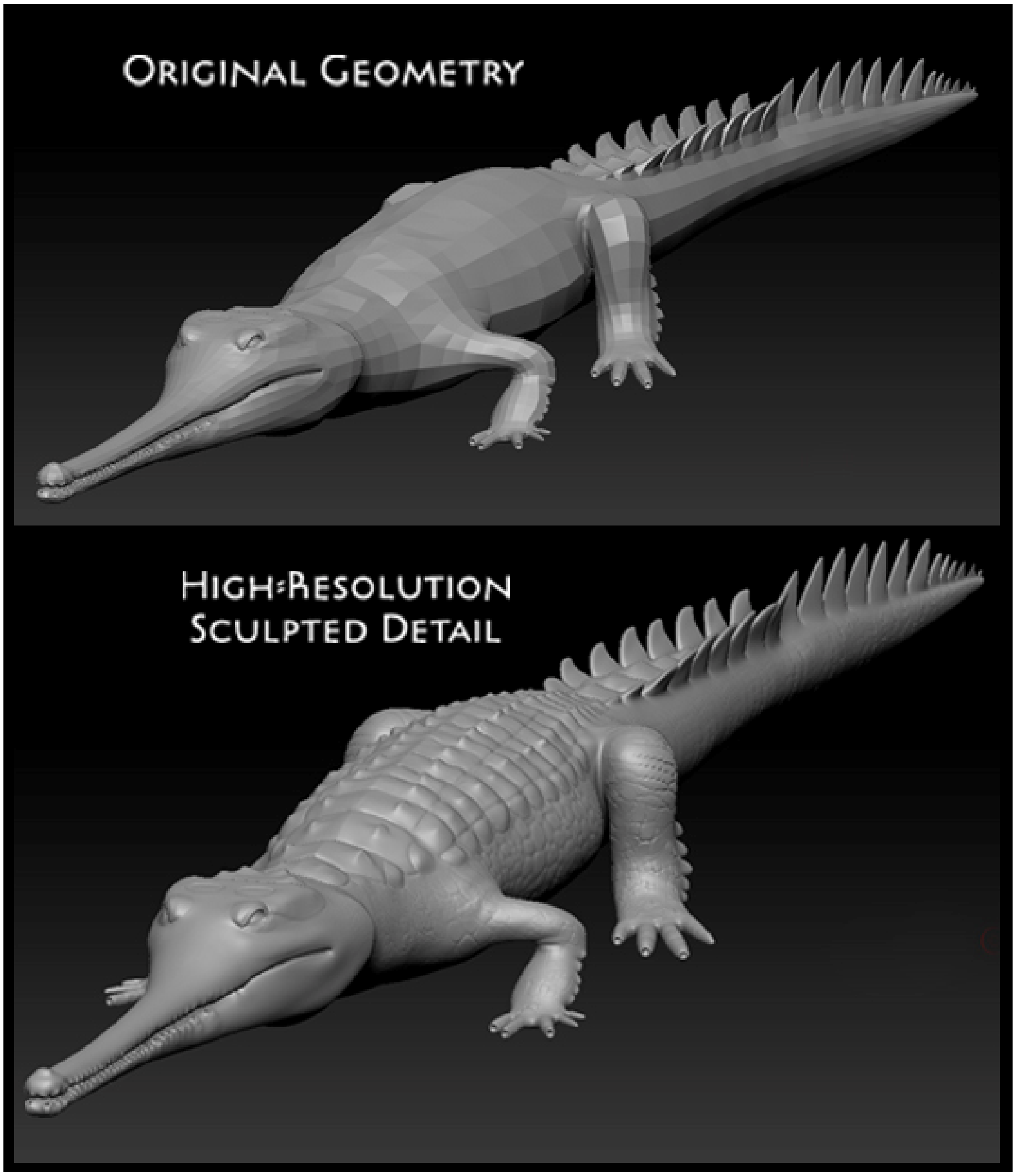

Figure 50 A comparison between the original geometry and the high resolution sculpted geometry

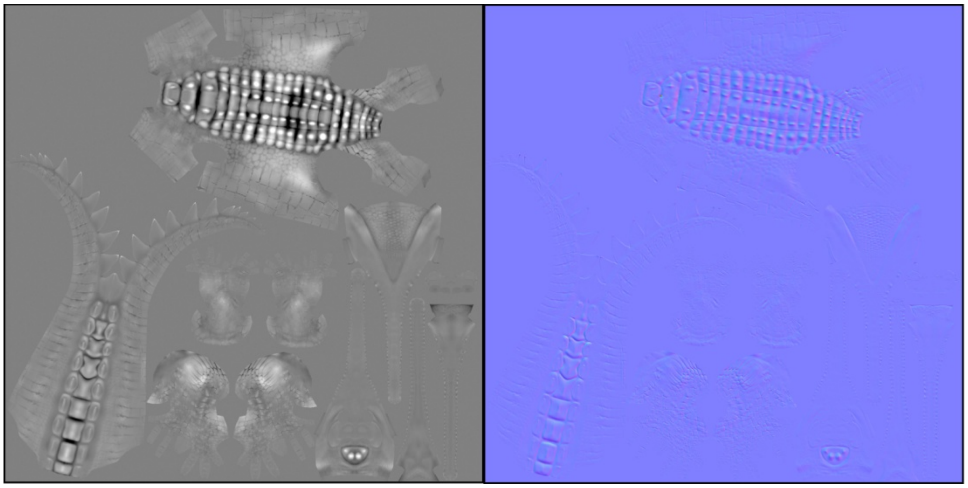

Figure 51 The displacement map (left) and normal map (right)

After sculpting was completed, ZBrush was used once again to paint the actual texture map of the skin. This was an enjoyable process because there was room to include some amount of artistic interpretation. The colors used on the skin were inspired by gharial photographic reference, but a bit of creative license was taken as well. In comparing a variety of images, it appeared gharials range in color, from gray, to brown, to slightly blue, to even a touch of green. This was a result of the different lighting sources in the various images. The perceived colors were also different due to factors such as the water quality of their habitats.

Based on these factors, an overall palette of dark grayish-brown with a tint of blue-violet was chosen for the base color of the skin. There was textured variation in color throughout the animal, with subtle darker stripes across the back. The inside of the mouth was painted a lighter color, and the cheek flesh, a pale pink; in accordance with gharial imagery. The belly of the *Thoracosaurus* was also given a lighter whitish yellow color, to mimic the counter-shading camouflage of most aquatic animals, including crocodylians. In most aquatic animals, the dorsal surface is dark so it blends in with the murky water when looking down from above the water. The belly is typically light, so it blends in with the skylight coming through the surface of the water seen when looking up while submerged.

A lot of grungy, naturalistic detail was added, using the black and white alphas to control not only sculpting tools, but also paint brush shapes. The same alphas employed to sculpt the animal were then used to help emphasize the sculpted detail, while painting. Surface details were added such as scratches and scrapes on the tough skin, along with other basic wear and tear. A slight hint of green was also added on the sides of the animal, between the scales, to simulate algae starting to grow on the skin from spending so much time in a highly productive aquatic environment. The last touch of the painting was to add mud and dirt coating the feet, the underbelly, the tail, and the neck. The idea being that when crawling out of the water onto a sandbar, the *Thoracosaurus* would have likely accumulated a lot of mud on its underside (Fig. 52).

Figure 52 Final ZBrush painting

The painting from ZBrush was then converted to a texture map. This map was exported, and all the generated maps were then applied to a shading network in Maya. There were a couple of adjustments that had to be made to the colored texture map after exporting, however. Two other maps were created to be combined with the texture map. The first was a cavity map, which was exported out of ZBrush. A cavity map is essentially a map that emphasizes the nooks and crannies of the displacement. It is similar to a displacement map, but instead of being used to adjust the surface of a model, the cavity map is multiplied on top of the texture map to simulate slight shadowing into the crevices of the sculpted detail. An additionally vital map was the ambient occlusion map. This map provides a way to imitate the soft self shadowing of a surface. This was created by exporting the high resolution sculpted mesh from ZBrush, and bringing it into

Maya. Using the Mental Ray rendering engine, a global light source was used to mimic the subtle self shadowing that objects naturally have. This process allowed for an ambient occlusion map to be baked out of Maya based on the high resolution sculpted geometry. The map was then brought into Adobe Photoshop, and multiplied over the texture map to add a bit more subtle shading detail (Fig. 53).

Since the mouth was closed in the model's default position, its inside surfaces of the jaws could not be painted easily in ZBrush. The mouth was therefore adjusted in Photoshop. The back of the throat in particular could be painted much easier in this application. The opening to the trachea was painted by using elements of a photograph of an alligator throat. The trachea was cut out of the original photograph and blended into the back of the throat of the *Thoracosaurus* in Photoshop. Another version of the texture was eventually created for when the *Thoracosaurus* would have its jaws wide open underwater. If the trachea was open as in the original texture map, the animal would drown when underwater. To prevent this possible blooper, another version of the texture was painted which had the epiglottis of the throat covering the windpipe. This alternate texture map was then applied to the animal for all of the underwater shots.

Figure 53 Final composited diffuse texture map

For the remaining geometry, textures were created in a number of different ways. For the teeth and claws of the feet, procedural shaders were created in Maya. The teeth were given a simple yellowish whitish color. The claws' UVs first had to be unwrapped, which was quickly set up in Maya. The color for the claws was then created by blending a whitish yellow color with a brown muddy color, using a noise algorithm to control how the color blended. This resulted in a whitish yellow nail color that looked splotched with brown. This was a quick way to simulate the mud that was also on the rest of the feet.

The foot webbing texture was rather quick to create as well. Since it consisted of flat planar objects, it took no effort to lay out the UVs. The texture and displacement maps were painted in Photoshop, avoiding the process of bringing anything into ZBrush. There was no need to use ZBrush since the detail did not need enhanced specificity. The webbing simply needed some sort of a texture, matched up enough with the feet such that the feet as a whole presented a homogeneous look.

The eye was the final part to be textured. The eye itself utilized three textures. The first was a shader used for the cornea. The cornea shader was essentially a transparent shader with an incredibly sharp specular highlight on it. The cornea object in computer graphics is used to simulate refractions and the light on the eyes more than anything else. For the iris of the eye, a texture map was created by sampling parts of a close-up photograph of a gharial eye. The geometry behind the pupil was shaded with the last of the eye shaders, consisting of a black surface shader. This was done since a pupil is essentially a hole in the eye, and the surface behind it should not have been visibly affected by the light. The only time that this would be otherwise would be if the effect of eye-shine was being simulated. There were no shots of the planned animation that would take place at night, though, so the pupil was simply assigned a black surface shader (Fig. 54).

Figure 54 The eye texture

The last thing to do in order to emphasize the sculpted detail was to substitute the base model of the *Thoraocosaurus* in Maya. The model of the *Thoracosaurus* from the first subdivision level in ZBrush was exported for use as the new base mesh in Maya. The difference in detail between the fully sculpted geometry and the original modeled geometry was so vast, that it would have been incredibly difficult to transfer all of the detail over to the low resolution model with maps alone. The displacement, normal, and cavity maps were all used to aid this process, but the final step in transferring detail came from using a slightly higher resolution base mesh. It is much easier to transfer detail when there is at least a starting point in the underlying topology for the sculpted details to transfer to. Using this higher resolution mesh allowed there to be base geometric model detail for the osteoderms of the back and neck, opposed to trying to achieve all of the detail from image maps.

After all of the texture maps and shaders were compiled and applied to the models, the restoration process was essentially complete (Fig. 55). Everything that had to be completed after this step involved bringing the project beyond reconstruction and restoration, and bringing the animal to life through animation. With a completed skeletal and muscle rig, and a fully restored skin, the next step was to combine the two together, and attach the skin to the rig.

Figure 55 The completed *Thoracosaurus* model - sculpted and shaded

Skinning first required connecting the *Thoracosaurus* model to the underlying joint skeleton. Since muscles would not be used to drive everything, this was a necessary first step. The muscle system would then be layered on top of this basic skin deformer, effecting only what it needed to. Attaching a skin essentially requires first letting the system know which joints to affect to the skin. It then creates a default bind that sometimes works, but almost always has to be adjusted by hand. The interface for adjusting how the skin behaves involves painting skin influence weights. What this means, is that a user must open the skin weighting interface, and find the joint from which to add or remove skin influence. This appears in the interface as color feedback. There is a black to white gradient that appears on the actual model. Any point on the surface that is white is controlled entirely by the selected joint. Any point that is black has no affect, and shades of grey are in-between values.

The issue that arises when painting weights involves not only going through every joint and manually painting and adjusting these values so that everything deforms properly, but having to comprehend the workflow of holding weights. Each vertex of the model is affected by a normalized value from 0 to 1. This is what the black to white value seen in the interface represents. The part of weight painting that is difficult for most users to understand when first learning, is that each vertex can only have a combined total value of 1 (white). Multiple joints, then, cannot have an influence of 1 over the same vertex. Two joints can each control 50% (a value of 0.5) of the vertex, or 20% and 80%, but both cannot have 100% control. The vertex could even be controlled by 100 different joints, with a value of .01 each. The number of joints controlling a vertex does not matter, but the combined influence of the vertex has to equal 1 at all times.

In practice, this means that when adding influence to a joint, it actually deducts influence from another joint. In order to prevent having to constantly redo work, weights can be locked or held on joints so that nothing can be added or removed from them. This requires going through each joint systematically in the skeletal hierarchy, and holding/un-holding skin weights as they are adjusted, until everything works as intended. After much experience with this process, it became fairly efficient. The only aspect that made it more difficult than usual was the fact that the base mesh was the high-resolution subdivided version from ZBrush. Because of this, there was double the number of vertices to manage. It therefore took more time to smooth weights out and get the proper creases and wrinkles when deforming.

It is always helpful to set up the control rig interface before the skinning process, so the rig can be manipulated while painting weights. This allows one to see how the actual skin will behave in production. It is also helpful to complete the joint labeling and UV layout steps before skinning, so that the painted weights can be mirrored to the other side of the body, greatly reducing the time it takes to paint skin weights. The UVs should be laid out because of how the skin weights use the UV coordinate system when exporting or mirroring weights. If the UVs are overlapping, the weights cannot mirror properly. When transferring weights, it uses the XYZ coordinate system to find the other side of the body, and the UV coordinates to find the proper vertices to affect on the other side. The joint labeling step also helps, so that the system can determine where a matching joint is on the opposite side of the body. Remember, each joint is given not only a name but an assigned side when labeling. Joint labels can be used to find the proper joint on the other side of the body with much greater accuracy when mirroring skin weights.

After attaching the skin to the skeleton, skin weights then had to be painted for the foot webbing objects. These weights had to be averaged between the toe joints in a way so the toes worked together to stretch the webbing properly when they curled and spread apart. After this step was taken, the *Thoracosaurus* was connected to the skeletal rig. The final step before animation could officially start was to layer the effect of the muscle system on the underlying skin deformer. This process, however, surprisingly turned out to be one of the more difficult steps of the entire project.

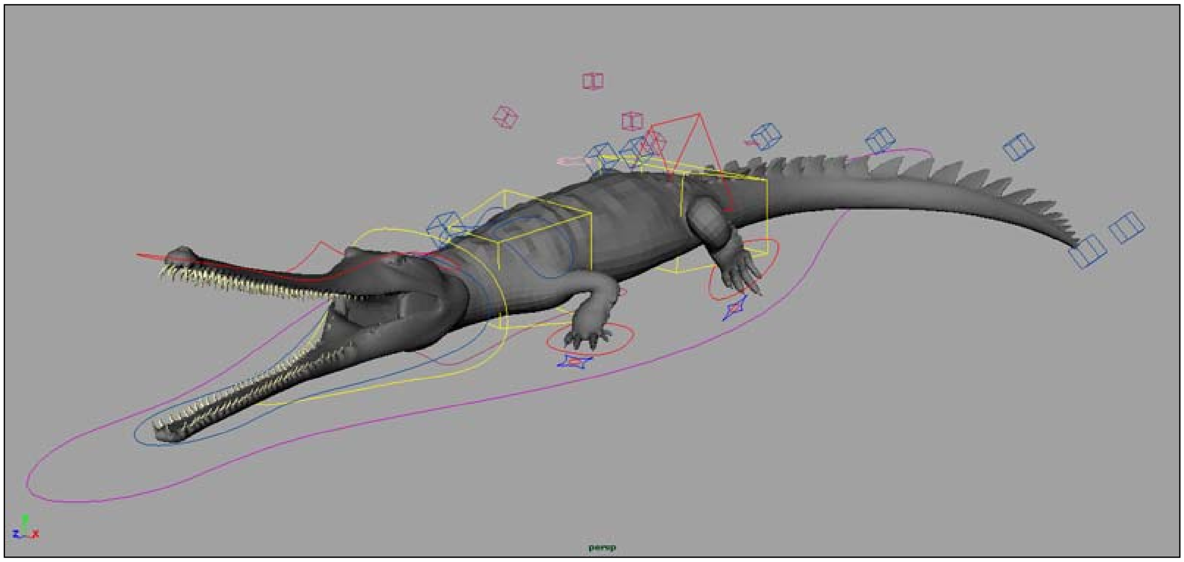

Figure 56 The basic skin deformer attached to the control rig

In order to attach the muscles to the skin, the skin first had to have a muscle deformer assigned to it, which was done through the Maya muscle menu. The muscles then had to be connected to the skin. This could only be done a few muscles at a time. At first, all the muscles were selected at once, and the option to attach them to the skin was chosen, but the application crashed every time this was attempted. Systems would get pretty far through the process before crashing, though, so it was decided to attach a couple of muscles to the skin at a time.

A number of muscles were omitted from attaching to the skin. There were a number of different criteria which prevented a muscle from being included in the muscle deformer. First there were the deep muscles that were not close to the surface of the skin. These would not be able to directly affect the skin, so were omitted. Then there were the muscles that were too small for the size of the polygons that they would influence. Without sufficient geometric resolution, not much, if any, deformation would have been affected by these small muscles. The majority of these small muscles were in the antebrachium. When attaching muscles, the Maya muscle deformer has a maximum of 72 muscles that can affect a single skin. This was realized when the last muscle would not connect to the skin. A lot of time went into trying to debug this issue, originally thinking it was a problem with how the muscle was set up. When detaching another muscle, the last muscle attached perfectly fine. This made it clear that there was a limit. Out of the 74 muscles that were attempted to be attached, two (one from each side) had to be disassociated, resulting in 72 out of 136 total muscles being attached to the mesh.

After attaching all of these muscles, significant slow-down in the interface was instantly noticed when manipulating the control rig. The number of muscles attached to the rig was clearly causing performance issues. This was also a major problem that affected the process of painting muscle influences on the skin mesh. To compound the difficulty of painting muscle weights, there are some 28 different *types* of weights one can paint for muscles, most of which control very specific attributes such as jiggle, wrinkling, and self collision to name a few. Not all 28 sets of muscle weights had to be painted to benefit from the muscle system, however, and they are simply available to give an incredible amount of control over how the muscles affect the skin, when needed. To simplify the process of painting, the only muscle weights that were painted were the "sticky" weights and "sliding" weights. Sticky weights are the default weights, which tell Maya what part of the skin geometry to connect to which muscle. Sliding weights go beyond sticky weights by allowing the geometry to slide across the surface of a muscle, simulating loose skin. Sliding weights also allow a user to add a "fat" offset which is used to bulge out the skin geometry.

Painting weights for the muscles was quite a laborious task, even aside from the over-taxed system issues. The only difference from the basic skinning process was that instead of selecting joints to paint influences to, one selects muscles. The complexities of weight painting were compounded by having to paint multiple sets of weights. It was difficult to keep track of everything and decipher what exactly was influencing what.[14]

There were not any options on the interface to hold and un-hold weights for muscles. These options are so integral to the weight painting process that it became next to impossible to correctly paint weights without them. In order to resolve this issue, the Maya Muscle scripting API was researched so that a series of MEL (Maya Embedded Language) scripts could be written to allow muscle weights to be held and un-held. Four buttons were then added to the shelf interface of the rig. These scripts included two for holding all of the weights (one for each muscle weight type), and two for un-holding the weights (one for each type). The painting process then required holding all of the muscle weights, then entering the following script into the Maya script editor to un-hold weights on the muscle that was being worked on at the time:

```
cMuscleWeight -system cMuscleSystem1 -mi n -wt "sticky" -lock true;
```

This defines the name of the muscle system with the “-system” flag, the muscle with the “–mi” flag, the types of weights with the “-wt” flag, and whether the weights are to be locked or unlocked with the “-lock” flag. The “–mi” flag stands for “muscle index” and requires the number of the muscle that is being locked. The number can be found next to the name of the muscle in the paint muscle weights interface. The “-lock” flag simply takes a Boolean value of true for lock, and false for unlock.

After painting the sticky weights, a fat offset was attempted on a number of muscles by painting sliding weights. The plan was to use this fat offset to bloat the skin outwardly from the arms and the torso. Unfortunately, this technique did not work quite as well as was expected. Areas, such as those in the torso, did not create pleasing results with the fat offset, so it was omitted. The offset worked acceptably well on the shoulders, and the *triceps brachii*, however. It worked particularly well on the *triceps*, since the multiple attachment heads of the muscle were simplified into one mass. The fat offset did not work effectively for the other muscles of the brachium, since there were a few muscles involved. They would bulge out the geometry in unpredictable directions, creating awkward deformations, opposed to acting as a single unit. This is because of how Maya muscles are intended to be used to simulate the visible effects of real muscles, opposed to behaving like real individual muscles. Without tendons, ligaments, and connective tissue, there was no built-in way to keep muscles tightly packed together enough to insure them to work as muscle groups. Certain areas of the muscle system worked better at this than others. The most successful area was probably the lower hind limb, where everything was tightly packed enough that it really appeared to work as a cohesive unit.

The weight painting process became an ongoing procedure throughout the animation, as there was no way to paint perfect weights without having motion to test it with. Manipulating the rig with the painted weights helped to find positions in the rig where muscles would move out of place, which required some attention toward adjusting not only weights, but also muscle positions. This was arduous to address due to the incredible decrease in system responsiveness. Luckily, the mirroring muscle weights option worked perfectly. Only one half of the muscle weights had to be painted. Otherwise, the slowdown on the system probably would have prevented this step from ever being completed.

After the muscles were incorporated into the final animations, test frames had to be rendered periodically to double check weight painting in areas. Since the final rigged model was going to ultimately be rendered as a subdivision surface, awkward looking deformation areas in the rig would be smoothed out slightly when rendered. In order to see what they would ultimately look like (from the correct camera angles that were used in the animation) these test frames were rendered and critiqued. If the deformation in the pose was awkward when rendered, muscle weights were once again adjusted.

While rendering frames to find weighting issues, another problem arose: The weight maps from the muscles would render in place of the texture of the *Thoracosaurus*, despite the correct *Thoracosaurus* shader being applied to the model.[15] It turned out that a node was generated and attached to the skin object; a result of using a muscle deformer. In order to help Maya display the weight maps correctly when painting weights, a node called the "polyColorPerVertex" was automatically attached to the mesh. This node had a dropdown menu assigned to it. When this setting was set to "Normal," the texture in the render showed up as a muscle weight map. If this dropdown menu was changed to "Has No Effect," the overriding weight map texture would disappear, allowing the correctly assigned shader to render. This was an easy fix, but every time a scene containing the muscle rig was opened, the weight maps would show up again, and yet *another* polyColorPerVertex node was generated. The issue had to be fixed all over again, upon opening any file containing the muscle rig. This was a bit of a nuisance, but at least the root of the problem was known every time it happened, and the issue could be fixed quickly.

Even after all of the muscle weights were adjusted correctly, and a finished muscle rig was created, the system slow down (due to the upper-limit amount of muscles attached to the skin) caused yet another problem. If the rig could not be manipulated in real time, there was no way that the rig would be able to be animated with any efficiency; a legitimate reason for a great deal of concern. If an acceptable workaround could not be found, then either the muscle system would have to be adjusted, creating an even less anatomically-accurate muscle system, or many muscles would have to be removed from the skin deformer, leaving only the most important areas affected by the muscles.

A solution was sought out to permit the current set of muscles to stay attached to the system. If for no other reason than to provide insight on future work in the effectiveness of creating and using a more anatomically accurate muscle system for restoration, a solution needed development. This project was attempting to further the long tradition of paleoart, and aiming for scientific accuracy. It was vitally important that in every step of the process, scientific compromise was always the last option.

The key concept of the solution was to create a separate, parallel rig to animate with. If animation could be transferred from a muscle-free rig that worked smoothly in the viewport, to the full muscle rig, then no compromise would have to be made. Plans were started to create a programmatic procedure to allow animation to transfer smoothly from one rig to another. Before attempting to write a new script from scratch, however, research was done to see if any similar solutions already existed.

While searching, a script was discovered on an online CGI forum. This python script, called PAIE (Python Attribute Import/Export), was written by a working professional named Jakob Welner.[16] This script not only transferred animation, but did it in an efficient way; it allows the selection of all of the control curves of the rig, and exports all animation on those control objects to a small external “.XAD” file. Another rig with the same control curves and attributes is then opened. After once again selecting all the control curves, the .XAD file is imported, transferring all animation data to the second rig. This is where the “select all control curves” button on the rig shelf was particularly useful. Since the names and attributes of the control curves in both rigs were identical, and because the shelf button selected the controls in the same order every time, it made animation transfer incredibly easy.

This script allowed for a much more streamlined process. It allowed animating in real time in the Maya interface, on a *Thoracosaurus* that did not have a muscle deformer attached. The motion could then be transferred to the fully muscled rig with ease. Any issues in the motion resulting from strange muscle deformation could then be spot checked and adjusted accordingly on a shot by shot basis. This animation transfer solution was the final step in working through necessary technical hurtles which would finally allow for *Thoracosaurus neocesariensis* to come to life.

4. Locomotion and Animation

4.1. Research and Reference Footage

It was known from the outset of the project that analyzing and recreating crocodylian locomotion accurately would be no small task. Because of this, research on the motion of crocodylians actually started well before the thesis officially began, and continued throughout the length of the project. In researching locomotion, it was found that most all animals essentially have three gaits. These include the walk, the trot, and the gallop. Transitions between these gaits typically happen when an animal reaches the maximum or minimum speed that can be reached with a certain way of moving [25].

In the case of crocodylians, although they also have three terrestrial gaits, they are not all the same as those found in other animals. They have two types of walks and do not have a trot. Crocodylians have a belly crawl, a high walk, and a gallop (Fig. 57). The belly crawl is used to push them across the ground over short distances. It is also the locomotive pattern that is used for transitioning from a stationary to a mobile state. It is characterized by the sprawling limb posture common to most reptiles and amphibians. The high walk is what crocodylians use to travel across long distances. This gait requires them to stand up so their bellies are off the ground, and allows them to move across more difficult terrain. The high walk is characterized by a much more erect limb posture, closer in characteristic to the postures of mammals, dinosaurs, and birds [31]. The gallop is the fastest gait, and is very peculiar to watch. In the gallop, the he animal sweeps its limbs forward in an awkwardly symmetrical fashion to push itself forward in a rapid hopping motion.

Transitions between crocodylian gaits also differ from other animals in that they do not always occur based on speed. Alligators, for example, have been found to use both their belly crawl and high walk gaits at a number of different speeds. Instead of reaching further with their proximal limb bones, alligators actually speed up by simply taking more strides in a shorter amount of time. The duty factor, or amount of time the foot is on the ground during a stride, actually consists of the same percentage of time during a single stride, regardless of speed. Most of the difference in speed is achieved in the distal limb elements, by extending the ankle further and faster [31].

Figure 57 The sprawling posture of the belly crawl (left), and the semi-erect posture of the high walk (right)

A major focus of the animation was to be on all of the motions that *Thoracosaurus* was likely to do. The key motions that would be included were the belly crawl and the high walk, along with swimming and feeding behaviors. It was advised early on in the project not to attempt to incorporate the gallop. The reasoning behind this was due to physiological and behavioral constraints. Larger crocodylians simply cannot perform the gallop because of the sheer amount of weight they would have to be able to carry and control. The bigger crocodylians do not move much on land, and the majority of their terrestrial locomotion is simply to move into and out of the water. Since the *Thoracosaurus* was over 16 feet long, it is incredibly unlikely that it was highly mobile and agile on land.

While referring to the scientific literature was essential for the project, the most useful motion research came from watching and analyzing reference video. The BBC's online motion gallery contained a myriad of fantastic references for all types of crocodylian motion, from a wide variety of species [13]. As with the anatomical research, reference of gharial motion was preferred over that of other crocodylians. There were a number of highly-informative clips that were found, showing gharials using the belly crawl, basking, lurking in the water, and feeding. Good swimming reference of the gharial was hard to locate. The only swimming reference that was found of gharials was from hatchlings, whose small size and weight would be too remotely different from a large gharial, and therefore unrealistic for motion reference. Instead, much better reference of alligator and crocodile swimming was used.

References of gharials performing the high walk also could not be found. It was read online that gharials actually lack the musculature required to perform the high walk, but there were not any sources (let alone scholarly ones) credited, and no further information regarding this could be found in the literature. The closest insight to this that was found was in Thorbjarnarson's work on gharial feeding habits, in which he states that larger individuals are not able to high walk [37]. This is probably the case with any large crocodylian, however, and not exclusive to gharials. The paper does not state anything about the species being unable to high walk as a whole, and the phrasing implies that smaller individuals can indeed do it. It was decided to include the high walk in the animation nonetheless, since it is a characteristic crocodylian gait, and since no definitive evidence against it could be found.

Most of the online video references found for the high walk depicted younger alligators or crocodiles. The best way to gather motion reference was naturally to set up a scenario and shoot the footage oneself. This is precisely what was done to acquire the most useful reference footage of the project. Thanks to committee member Jason Poole from the Academy of Natural Sciences of Philadelphia, a meeting was arranged to drive up to Allenwood, Pennsylvania, the location of a fantastic AZA-(Association of Zoos and Aquariums) accredited zoo, called Clyde Peeling's Reptiland. Clyde and his son Chad allowed for video capture of their 11.5 foot American alligator, Rocky. Granted the animal was a couple feet shorter than the *Thoracosaurus* was estimated to be, but this represented the best possible opportunity to collect essential reference footage. This would have also been much more effective than trying to infer motion from the young alligators kept at the Academy of Natural Sciences.

For the video capture, two cameras were used. One was a Sony XDCAM to shoot in full 1080p HD. The other camera was a small Sony Handycam, which could only shoot in standard 480i. Both cameras were assisted with tripods. When arriving at Reptiland, it was fortunate that the two alligators were out of the water, which was supposedly the first time in weeks. When in the water, they are nearly impossible to guide or control. Close-up shots were taken of the basking gators for textural reference (which were used to create ZBrush alphas as previously described) before attempting to get the alligators moving. Shots of the footprints in the sand were also taken for reference.[17]

For the filming, the Handycam was situated on the balcony overlooking the enclosure to capture a front view of Rocky. The XDCAM was brought inside of the alligator enclosure, and operated a couple feet away from Rocky; to capture a side view (Fig. 58). The goal was to videotape two different perspectives of the alligator moving across the ground and entering the water.[18]

Once the cameras were rolling, the keeper used a pole to herd Rocky as best as he could. Vocal commands, along with tapping the alligator with the pole, were used to try to get the animal moving. Rocky clearly did not want to move. He was hesitant to get up, and was hissing the entire time he was being herded. It became clear how infrequent this large animal actually moved. Rocky was so heavy, that after he turned around to face the water, and stood up to attempt the high walk, he actually lost his balance and fell flat to the ground. No other action could have conveyed the sheer weight of the animal better. A second attempt to move him forward had Rocky back up and slowly walking. He almost lost his footing again, but made it to the water's edge, where he once again tried to stop. The animal was then persuaded to enter the water and swim around the corner, where he joined his colleague. The videotaping session could not have gone better. The footage turned out to be very useful, and the staff of Reptiland was incredibly helpful with the whole video capture process. [19]

Figure 58 The two camera angles shot at Clyde Peeling's Reptiland

Other reference video was shot more loosely when on a trip to Costa Rica to visit tropical environments. An American crocodile was caught walking in an enclosure, and a camera ably caught the last couple seconds of it (Fig. 59). What was great about this footage was that, although not as long or detailed as the footage from Reptiland, it provided some muscle dynamics insight. The footage showed the scapula and shoulder muscles shifting under the skin, revealing a lot more mobility and skin sliding at the shoulder joint than was previously thought.

Figure 59 A frame of reference video shot in Costa Rica

With well documented reference gathered for the belly crawl, high walk, and swimming, the last major behavioral aspect to research was feeding. Since *Thoracosaurus* was a fish eater, and most definitely did not use death rolls to take down large prey as is seen with other crocodylians, gharials were once again used to infer feeding behavior. Reference video from the BBC Motion Gallery was found of gharials swallowing their prey. They move the fish backwards through their jaws by repeatedly tossing it up and catching it. When it comes time to swallow, they almost always swallow it head-first [13][37].

A paper was found on the gharial hunting strategy which both supplemented and confirmed what was documented in the reference video. Gharials apparently use two methods of hunting. The more common of the two involves the animal being submerged, resting the head on the stream bed, with its snout opened and positioned in the direction of the current. The limbs are typically outstretched and relaxed. Before a fish comes in contact with the snout, the animal strikes, almost exclusively with its head and neck. The strike is primarily laterally, but often contains some vertical movement as well. After catching a fish, the animal surfaces and swallows in the way previously described [37].

4.2. Animation Pre-Production

After all of the key motions and behaviors were assessed, the planning of the actual animation could begin. This required putting together an animatic (or previsualization) that would address the sequence of shots, and how all of the research would ultimately influence the final piece. It was incredibly important that the research was the major determining factor in how the animation was to be portrayed. The goal was to remove and reduce as much imaginative speculation as possible from the behavior of *Thoracosaurus*. A rough animatic was created. It consisted of a number of sequential still-frame sketches, which were put together into a movie that depicted the expected pacing and timing of the animation. It is always much quicker to think in sketches, and this allowed to quickly assess what shots and compositions worked best to convey the proper ideas in the animation.

As was originally decided when planning the project, there were to be two sections of the animation. The first was the “schematic” section, and the second was referred to as the “narrative.” The main goals of the schematic portion were, 1) to give proper attention to the fossils, 2) to visually reveal the process of paleontological reconstruction, and 3) restoration, and in doing so effectively associate the original fossil source to the final restoration. The goal of the narrative portion was to show a “slice of life,” depicting how *Thoracosaurus neocesariensis* likely moved, behaved, and interacted with its environment some 65 million years ago.

In the original animatic, the schematic portion opened with a reveal of the original fossil material. It began with a close-up of the bones of the braincase, and then the camera swept past the rest of the body. This was to introduce the full piece by using the fossils, and hopefully keep an association between the final restoration and the original fossil source. After moving through all of the fossil material, a wider angle was used to reveal the fossils as a whole. The fossils then started moving, and the different layers of the restoration were built up, revealing the animal walking. As each layer of the restoration was added, text would accompany it, helping to inform the viewers of what stage of the restoration was being depicted. The *Thoracosaurus* then crawled into the water and started swimming. The restoration buildup was then shown again, while the animal was swimming. This was all originally drafted from a side view and was intended to be a single shot.

The narrative then opened with a close-up of the left eye. It then slowly faded into another close-up, but of the snout from the front. Both of these shots were to have a shallow depth of field and be used to introduce the animal in its habitat. Text also accompanied these opening shots to let viewers know where and when the narrative was taking place. In the second shot, the idea was that the *Thoracosaurus* would turn its head, forcing the camera to shift focus to the full head of the animal. The creature would then start moving out of frame. The next shot was to be the full environmental reveal, showing the *Thoracosaurus* on a sandbank, belly-crawling into the nearby water. This was followed by a camera angle looking down on the *Thoracosaurus* from above, showing it swim through the water. At this point the animal then submerged acting as a transition into the underwater environment.

The following sequence was underwater, depicting the *Thoracosaurus* swimming into the distance of the murky water. It then dissolved into a shot to showcase the feeding behavior. After doing the required research, it was decided not to have the animal swim around and actively snatch up fish as it moved. Instead, this croc used the “sit-and-wait” method of hunting found in gharials. The depiction started out focused on a couple of fish swimming together. It showed them going about their daily routine, as a waiting *Thoracosaurus* was revealed. The fish would be unable to detect the croc camouflaged in the murky water until the vibrations from its sudden strike gave it away. The *Thoracosaurus* then struck and caught one of the fish while the others scurried off. The final shot depicted the swallowing behavior of gharials. The shot started with a look at the mangroves on the water's edge, followed by the *Thoracosaurus* surfacing to eat its meal (Fig. 60). After this, the animal once again submerged, ending the animation.

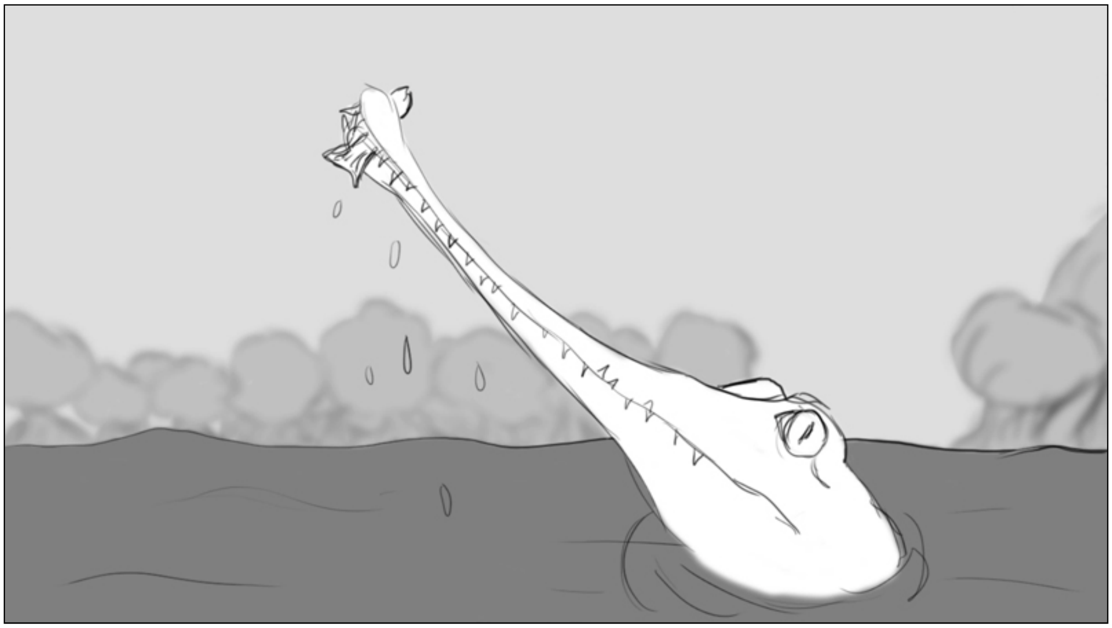

Figure 60 A sample frame of the animatic

Although the shots remained mostly the same, compositions, and small details changed throughout the project. Most of this was due to using two-dimensional sketches to compose the shots, and three-dimensional models for the actual execution. Since the animatic was created long before the final restoration was, some of the proportions of the roughly drawn *Thoracosaurus* were not quite right. The beak in particular ended up being longer than originally sketched. Also, positioning three-dimensional objects properly in space, relative to one another had a tendency to change compositions, especially when camera moves were added. In order to frame everything properly, and maintain compositions, camera moves had to be added in certain shots. Shots also ended up being added throughout the piece in order to give it a more natural flow.

A couple more close-ups were added at the beginning of the narrative, and another underwater swimming shot was added. This was essential to prevent the narrative section from feeling rushed. This was not the type of piece to exhibit snappy quick cuts. The pace of the animation was set up to imitate the life of a large, slow, cold-blooded animal in an incredibly hot and humid environment. The slower camera moves, and fading transitions were meant to emphasize and parallel the behavior of the *Thoracosaurus*. This is also why the pace became slightly quicker around the time the animal catches the fish. At this point, there would no longer be slow, faded transitions, and it would mimic the more active striking predator in the pacing.

The schematic portion also changed quite a bit from the original idea. The introduction in particular underwent a lot of changes. The problem with the introduction was that it was originally too quick. It was paced in a snappy, cinematic way that was too focused on moving into the next shot. There was no time to review and observe the fossils. As a result this opening was re-drafted. In the second draft, so much time was given to viewing the fossils that it became incredibly difficult to watch all the way through. A balance was reached after thinking of the sequence more as a product advertisement. After looking at a number of ads for items like cars, phones, and other devices, it was realized that more of the fossils could be featured in less time by using a number of different sweeping camera movements, and intercutting a number of beauty shots that featured different parts of the specimen. This allowed for multiple angles of the bones to be shown, and also helped this portion become more engaging, and visually appealing.

The rest of the schematic also changed from its initial conception. It was decided to let viewers see the final restoration without having to wait through the restoration buildup sequence of animation. This would help hold viewers' attention, while also allowing them to appreciate the buildup sequence much more, seen in context. The schematic was also broken up into multiple shots, to feature different angles of the *Thoracosaurus's* movement. Both the walking and swimming motions of the schematic were introduced by showing the fully restored animal transition into its actions, from a three-quarters perspective. This was done to better introduce the motions as well as to help convey the dimensionality of the creature. After the motion continued for a couple seconds, the buildup from fossil to skin would then take place, displaying both side and top views simultaneously.

The last part of the animation that went through some pretty significant reworking was the layout of the environment. It was known from the beginning of the project that the site where the *Thoracosaurus* was excavated was likely a tidal mangrove forest 65 million years ago. A rough swamp was created when originally attempting to lay out the environment. This depiction of the ecosystem was very claustrophobic and incredibly dense with foliage. It was later decided (based on discussions with the committee and research on mangroves) to portray the environment much more open. Mangroves act as a barrier between fresh water and salt water. They grow on the edge of the water, and actually build up sediment in their tangled root systems.

The redesigned environment turned into a much more oceanic setting. The idea was to make the environment closer to a seaway or estuary than a swamp. This would not only be more accurate to mangrove environments, but would also cut down on production time of the environment. This also changed composition of one of the shots of the narrative. The shot where the *Thoracosaurus* enters the water from its basking position was originally too heavily influenced by video reference of a gharial crawling down the slope of a river bank. Since the environment was going to be a mangrove forest, there would probably not be many open banks on the edges of the water, as typical densities of mangroves preclude open spaces. Instead of a beach or river bank, the *Thoracosaurus* was placed on a sandbar in the water, with the mangroves being further away in the background. Since sandbars are much more flat than riverbanks, the composition was altered, with the *Thoracosaurus* moving down a much milder slope to reach the water.

By investing the effort in creating and reworking the animatic, production efforts could be more efficient. Although changes to compositions and timing naturally occur throughout the process, the animatic served as a crucial step in delivering a successful final animation. It allowed for thinking and testing of ideas in a much more malleable medium, instead of wasting time on work that would ultimately have to be redone. This initial work of organizing and planning shots made sure that nothing in the piece ended up detracting from the goal of the final product.

4.3. Animating the Schematic

After both the restoration and the animatic were completed, final animation could begin. Animation tests were created throughout the length of the project to test the rig, so there was at least some familiarity with the processes of animating the *Thoracosaurus* before starting the final shots. In trying to obtain paleo-authenticity, the animation process was executed very carefully, with constant referral to video reference. This was sometimes difficult because of how much the art of animation encourages exaggeration. With entertainment oriented animation, the animator is often not necessarily focused on accuracy, but rather on giving a credible performance, creating nice fluid arcs of motion, and acting. With narrative animation, the goal of reference footage is to get inspiration and to combine ideas from that inspiration with an animator's intuition to create something fresh and interesting that tells a story. Because of this, video reference is usually used as a starting point, and motions are clarified by being pushed to extremes. Having a background in this sort of thinking made it difficult to tone down exaggeration and to focus on accuracy.

As for the process, the two typical ways to approach a shot are known as straight-ahead and pose-to-pose. Straight ahead is essentially starting at the beginning, and animating each beat as it comes, chronologically. Pose-to-pose is a technique that requires setting up all the important poses of the shot first, and letting the system help compute what happens in between. Both techniques have pros and cons, and can also be used together to benefit from both schools of thought.

For the majority of the project’s animation, the straight-ahead technique was used. Straight-ahead worked best in this case, because of all of the gaits and motion cycles. It is easier to find where the foot will fall next in a walk, and how far the body will travel when it is pushed forward, when working in straight-ahead mode. When working pose-to-pose, it is a lot more difficult to judge proper trajectories of a walk, or proper distances between footfalls. Instead of spending an incredible amount of time trying to prevent the planted feet from sliding around on the ground, the straight-ahead technique was preferred. There was some combination used, though. The straight-ahead technique was used to animate the majority of the body, to get the broad motions down, and then the pose-to-pose technique was used to go back and adjust all of the foot and toe positions.

There were many moments during the animation process where there was a desire to add more flair, or smooth out curves to keep everything in nice fluid arcs. This desire was particularly prevalent since terrestrial crocodylian motion is so incredibly awkward and even clumsy at times. Urges to smooth out the animation curves for purely aesthetic reasons were resisted. The attempt was to match the reference imagery perfectly. However, despite all of the work that was done to sustain accuracy, not all of the poses of the animals in the reference footage could be matched exactly, since some of the model's proportions were not identical to the ones found in the reference footage.

The first section to be animated was the schematic portion. This was done for a couple reasons: 1) To get used to the basic body mechanics of the animal before trying to put it in more active poses. 2) Some of this motion, especially in the swimming section, would be able to be reused for the narrative portion. For the walking portion of the schematic, the *Thoracosaurus* was animated getting up from a stationary pose, and transition into using the high walk.

When animating the animal moving into its standing pose, review of the reference footage of Rocky's fall from the Reptiland footage was incredibly informative. This action was the absolute best part of the footage at conveying weight. Since the *Thoracosaurus* was likely even heavier than the alligator, a legitimate opportunity to show weight like this could not be ignored. As a result, the *Thoracosaurus* was animated getting up, losing footing on its left forelimb, and falling to the ground; the perfect provision for adding a few quick strides of the belly crawl as a transition back into the high walk.[20] The timing and poses of these actions were based on the ones from the Reptiland reference footage.

Following the fall, a couple of unique footsteps were animated to retain some variety in the animal's steps. Cycling animation loops become extremely obvious to viewers relatively quickly, so having some variation in the walk aided the transition into the walk cycle. The walk cycle consisted of 95 looping frames (all the animation was animated at 24 frames per second, the film standard), and was essential for use throughout the transitions to the different layers of the restoration. This allowed for animating the transitions of the buildup portion of the schematic in the editing process. If a cycle had not been used at all, any problems in the timing of the final edit would have required a lot more animation work to be done, so that more frames could be produced and incorporated into the final edited sequence.

The walk animation went through review and a number of iterations before it was finally finished. In the first iteration, despite measures being taken to resist exaggeration, there was too much vertical motion in the upper body, as a result of trying to convincingly depict the *Thoracosaurus*'s mass. An interesting thing revealed in review was that animals tend to reduce extraneous vertical motion like this because of the energy it wastes to constantly combat gravity. After revisiting the reference footage, it was realized that though the animal was heavy, it lived with its own weight and knew how to function with its own body mechanics. Its balance was kept by taking its time when walking, and staying in control of the incredible amount of weight. In the second iteration of the walk, there was an issue with the deformation in the shoulder. The osteoderms on the shoulder were stretching as the *Thoracosaurus* walked. These osteoderms, being bony plates, are not supposed to flex. Even if the skin around them were to deform a little bit, the scutes themselves should not change shape. The skin of the back in general is relatively rigid, with the arms, legs, neck and belly being much more flexible. This issue was fixed by going back into the rig, and re-painting both skin and muscle weights of the shoulder area.

Out of all of the animation on the project, more time was spent on the shapes and poses of the digits of the feet than anything else. The number of incredibly intricate shapes that were needed to peel the feet off the ground, without having the toes intersect anything was astounding. This did coincide somewhat with the research, however, since the speed of alligator motion is controlled by the distal limb elements, such as the bones of the ankles and feet. The toe animation also benefitted greatly from the pose-to-pose technique. The timing of the key poses was first established by the straight-ahead motion used to animate the rest of the body. This was done without worrying about the shapes of the feet until the rest of the body mechanics were established. The individual foot poses could then be adjusted after the overall timing was already in place, to complete the final details of the walking animations.

The swim sequence was overall much more demanding than the walk, despite it being shorter. The transition into the water was not much different from the techniques used in the walk sequence. A significant difference was that the animal was eventually crawling down a slope, and had to perform the signature move of tilting its head back upon entry into the water. The swim cycle, despite being only 25 frames, took far longer than the walk to get to work correctly. When swimming, crocodylians propel with their tail, and tuck their limbs in close to their torso (except for when slowing down, making sharp turns, or when drifting slowly through the water). Their spines undergo a sinusoidal movement which moves from the front to the back, and sweeps through the tail. It is not a simple wagging motion, but actually appears as if a sine wave is moving through the body.

Animation of the tail was difficult because of how the spline controls of the rig were set up. The first technique that was used involved oscillating the different controls back and forth, offset from one another on the timeline. This ended up looking as though the body parts were moving independently of one another. To complicate things, the video reference for swimming was not quite as clear as the reference for walking. Most of the swimming reference was of crocodylians drifting slowly through water, with only a few videos exhibiting appropriate propelling swimming motion.

The solution to animating the swim cycle was the addition of a control to the rig. Knowing that a perfect sine wave had to be transferred down the tail, where most of the problems in the swimming motion were, instead of trying to manually make the tail behave like a sine wave, a true sine wave was programmatically affective. In Maya, there is a sine wave deformer that allows for this type of functionality. The challenge was to figure out how it could be incorporated into the setup of the rig. It was realized that everything in the tail was controlled by a curve, because of the spline IK. If the sine deformer was applied to that curve, all the joints, muscles, and skin would follow accordingly. The sine deformer was attached to the tail, and adjusted to create the proper shape in the tail, with a falloff of the effect at the base to transition back into the more rigid pelvis. There was then an offset value on the sine deformer, which controlled the distribution of the sine value along the curve. This value could be adjusted, and animated to allow for the sine to shift down the tail, and look exactly how it appeared in the swimming reference (Fig. 61).

The final step of this solution was to create an interface for it, which would allow an animator to adjust the sine with one simple control. An attribute was simply added to the "Tail_Twist" control object to control the swimming motion of the tail. The attribute was connected to both the offset value of the sine wave, and the “envelope” value, which triggered the effect of the sine wave. The final interface was a single attribute that, when at zero, turned off the sine wave. Increasing the value in the positive direction would cause the sine wave to gradually turn on and start moving through the tail for as long as was needed. This fix had to be incorporated into both the animation rig and the muscle rig so animation could transfer properly.

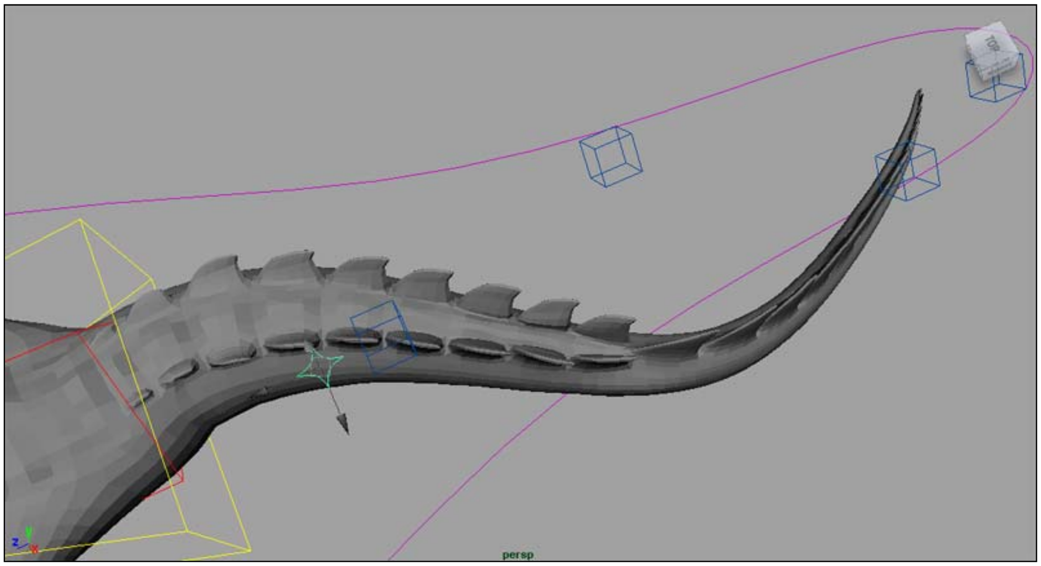

Figure 61 The sine wave affecting the tail

The animation was able to be adjusted much more quickly after the tail fix was implemented. This rig adjustment was incredibly effective. Even though the sine wave was controlling the overall shape of the tail, the control curves of the tail rig were still controlling the clusters of the tail spline. This meant that the control curves worked additively with the sine wave, and were able to be layered on top of it to add more functionality to the rig. In areas the sine wave was not working as desired, the control curves could be used to alter the sine's pattern to achieve a more visually pleasing result.

The final test to see if the swim was working properly was to physically move the entire rig through a geometric plane (proxy-geometry representing the surface of water) as the swim animation looped. This was set up to see if the swim looked believable when the animal was partly submerged and travelling forward. The swim overall looked much more convincing when the body was moving through space, in the context of swimming through water.

4.4. Animating the Narrative

Upon completion of the schematic animation, attention was turned to the narrative section. The narrative was simpler than the schematic in that a lot of the animation difficulties were already known. Also, some of the motion samples from the schematic could be reused, and only needed minor adjustments, such as in all of the swimming shots. It was also simpler in the fact that very few of the shots depicted the animal's full body. When animating, it is important to not spend valuable time in areas that do not appear on screen, or in areas that will barely be seen. This saves time since, if it is not on screen there is no point in making it absolutely correct. In the case of the schematic, since full body cycles would be shown from multiple angles, it was important that everything was correct and accurate. In the narrative, if a foot is occluded by the body of the animal for the duration of the shot, there is no reason to spend time cleaning up poses in that foot.

Despite the fact that they were split up into more shots, there were essentially four major motions to animate in the narrative: 1) There was the opening, which required the basking *Thoracosaurus* to sit up, and drag itself into the water. 2) Swimming, 3) the sequence of catching a fish, and 4) the final shot where the fish was to be consumed. The first of these that was animated was the sequence of entering the water. Although there was already a sequence depicting the animal entering the water in the schematic, the version in the narrative was different because it showed off the belly crawl instead of the high walk. The belly crawl in this sequence was based primarily on the belly crawl of gharials. Instead of alternating opposite limbs and dragging itself forward constantly, which was seen in many types of crocodylians, most of the reference video of gharials entering the water displayed another way of belly crawling. This alternate method involved moving all of the limbs forward, finding solid footing, and then using all four feet to push forward. The result was a sequence of adjusting the footing, sliding forward a couple feet, stopping, and repeating. This motion ends up looking like a choppy, fragmented advance.

The production of this sequence was similar to the schematic walk. There were more difficulties in figuring out the best way to adjust the compositions and camera angles of this sequence than in producing motion. The process of animating was much more rewarding when doing so in the context of the narrative, than when animating cycles of motion that take place in a void of space. It was more exciting to see the result when there was more context to the motion.

The next sequence was the series of swimming shots. Since the swim cycle was already animated, this primarily required estimation of how far the animal would be propelled during the shot based on the speed of the swim cycle. For the underwater swimming shots, since the majority of the motion was already there, motion was simply layered on top of the swim to add variety. Most notably, head movement was added to give the appearance that the *Thoracosaurus* had some sort of deterministic control over where it was going.

There was temptation to do more, and have the *Thoracosaurus* open its jaws as it swam toward the camera, creating a more dynamic shot, but restraint was held in situations like this. The animal would not put on a performance like that, doing extraneous motion just because it may be compelling to look at.[21] One issue with a lot of current paleontological based television programs is that the animals, even if they move realistically, have a tendency to not *behave* like real animals. There is a key difference here. An animal can move correctly, and accurately, and physically be able to do all the actions in a scene, but that does not justify that they would perform the actions. A lot of dinosaur television programs in particular have a habit of making all types of animals make extraneous noise; throwing their heads around and growling at one another, complete with drool flying everywhere. Even the large herbivores have a tendency to start jumping around and snarling, probably because the animators either do not know how actual animals behave, or because there is pressure from a director or producer to try to make the action more entertaining. In seeing this sort of flaw in countless programs over the years, it was decided that only believable motions, which were justified in context to what was going on would be allowed.

The next sequence of the narrative was by far the most complex, because of how many different elements were present in the shot. This was also where the most environmental work was done, and was a sequence that had no accompanying reference footage. Only textual reference could be found to inform the sequence. This was the shot where the *Thoracosaurus* catches its meal. In order simulate the *Thoracosaurus* feeding, first, a fish hat to be modeled and rigged. The project advisors suggested looking to the genus *Enchodus*, also known as the "saber-toothed herring." Fish of this genus have been found in the same deposits that the *Thoracosaurus* was found, so it was reasonable that they could have been part of the croc's diet.

Since the efforts of the project were to focus on the *Thoracosaurus*, only some limited research went into *Enchodus* before restoring it. The restoration went rather quickly, due to the reduced level of detail and underlying structures compared to those of the *Thoracosaurus*. All that was needed was a relative size, and some skeletal reference imagery to restore the fish. The individual species of *Enchodus* was not a point of focus, since the genus was relatively common during the period, and narrowing down to the species level would not have added anything substantial to the final animation. It was important to do some quick research, though, so there would be at least some level of paleo-authenticity behind it. If a generic anachronistic fish was created it would have been noticeable. By doing the background check to build a fish appropriate to the time and locale, the net result would appear natural in the environment, and viewers would accept it as part of the world, without particularly focusing on it.

The *Enchodus* mesh was completed, and was rigged in the same day the model was built. There was not an anatomically accurate skeleton modeled or any muscles used to create the rig. The rig consisted of a single control curve, with attributes for opening the jaw, and for controlling the sine-wave based swim motion of the body; utilizing the same technique that was implemented in the fix of the *Thoracosaurus* tail. There were also attributes that controlled other deformers, which allowed the fish to curl its spine from side to side and up and down. The rig was also organized in a way so that the entire creature could be easily resized, to add some variation to the multiple fish replicas that would help to fill out the shot. The UVs were laid out within Maya, since fish are relatively simply shaped animals, and then the model was exported to ZBrush to sculpt and paint the fish in the same manner as the *Thoraocsaurus*. The difference in this situation was that the alphas used for the brush shapes resembled fish scales instead of crocodylian scales. The surface textures were based on reference imagery of modern herring. All of the proper texture and displacement maps were generated from ZBrush and brought back into Maya, exactly as with the *Thoracosaurus* (Fig. 62). The only added texture map was a transparency map. This was used so that the webbed skin on the fins of the fish would be slightly transparent, like those of actual fish. The eye was shaded in the same manner as the *Thoracosaurus* eye, by sampling from an image of an actual fish eye.

Figure 62 The texture map (left) and final shaded model of *Enchodus*

Once a fish was built, animation on the shots that required it could begin. The first of these was the shot where the *Thoracosaurus* catches a fish. Three fish were brought into the scene, and scaled to different sizes. Since the fish were on screen for the majority of the shot, they were the first elements to be animated. This did not start until after the timing of the entire shot was first roughed out. This was done partly so the camera movement could be locked down before the bulk of the animation started.

The animation of the fish had more complications than initially expected. Part of this was because of how the sinusoidal movements of the fish's spines were not as readable from a side perspective, which constantly required adjusting. Also, the simple curvature shapes used to quickly rig the fish were making it difficult to perfect the animation curves. When cleaning up the animation, each fish was worked on individually, with all other visual distractions hidden in the scene. The different fish were also animated with slightly individuated characteristics based on their size. The smallest fish was quicker, more sporadic, and more curious than the other ones, and the largest fish was supposed to be much more relaxed and sluggish. The mid-sized fish's behavior fell roughly in between the two others'. Most of the fish animation process involved adjusting the animation curves for every time one of the fish changed direction.

The *Thoracosaurus* was a bit of a challenge in this particular shot as well. The most important moment in the shot was when it strikes to catch a fish. This key event needed to have an incredibly quick and effective timing. This was strenuous because the animal would, naturally, not anticipate the snap. In typical animation production, there are a number of ways to emphasize an action. One of the most widely used enhancements is the animation *principle of anticipation*. If one wants an action to stand out, the most obvious thing to do is surround the action with contrasting motion(s). If one sees something contrasted by what is around it, visual attention is drawn toward what is different. This is how anticipation works as a common tool to give motions more impact.[22] There is definitely anticipation in the real world, but since the *Thoracosaurus* was relying on a surprise attack, any anticipation that would actually be there would not be extreme enough to be visible to the human eye. This is because the slightest vibrations in the water would give its position away to the fish, resulting in the fish scattering before the *Thoracosaurus* could catch anything.

Instead of heightening the anticipation of the snap, the shot's action was simply made quicker and the swim away slowed down a bit. A couple frames were added to let the *Thoracosaurus* linger after catching its prey before swimming away. This was another technique to emphasize the motion by surrounding it with contrast, while also maintaining realism. This moment's timing had to be adjusted to find the right balance between snap and swim away. Originally, the animal snapped up the fish and swam off rather quickly. The actions flowed into one another and read as one motion, creating a less than satisfactory result; the snap could not be easily and effectively perceived. Striking a balance for this pacing was eventually achieved through continued experimentation.

It was also noticed that the snap tended to be strongest if the viewer watched the fish about to be caught during the snap. With this in mind, some of the motions and positions of the fish were adjusted in a way that pushed the entire composition to direct the eye toward the fish being eaten. The diagonal line of the open jaw of the *Thoracosaurus,* as well as the positions of the smaller fish were arranged to create an implied line, to direct the eye toward the largest fish immediately before the snap (Fig. 63).

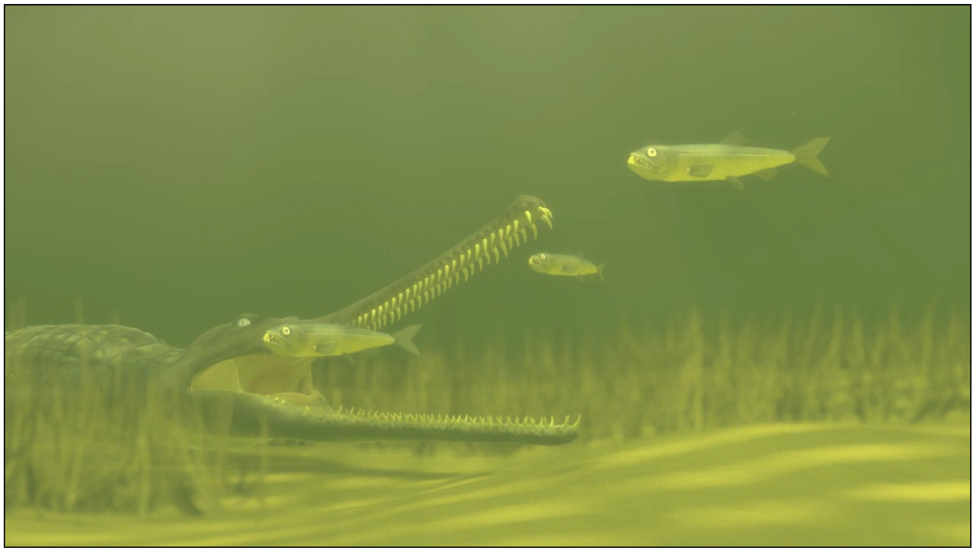

Figure 63 The composition was set up to direct attention to the largest fish

Another element of animating the *Thoracosaurus* for this shot involved having to hold back on over-animating. This was particularly challenging for the portion of the shot before the snap, when the animal is waiting to strike. Normally, with idle characters, it has become a bit of a habit to go in and add just enough motion so that they do not look dead in the background. Adding a blink here or there, or including some amount of chest movement to simulate breathing is usually all it takes for this. In the case of the *Thoracosaurus* catching a fish, secondary action was avoided for the first half of the shot, for similar reasons to why the snap could not be anticipated. After completing an animated draft of this shot, when motions were not reading quite as well as was expected, a recess was taken away from the computer to reassess what was going wrong. During this brief hiatus, a day trip was taken to visit the Philadelphia Zoo. While there, special attention was paid to the crocodylians that were there. After viewing a number of caimans, crocodiles, and both living species of alligators, it was decided to remove any sort of secondary action from the first part of the shot. While the animals were sitting in their enclosures, absolutely no movement was perceptible. When lizards or frogs sit still, movement can still usually be seen in their throats or rib cages, but this was not true with the crocodylians. They appeared to be completely motionless. This was the final bit of observational information needed to commit to *not* adding any sort of secondary motion in the *Thoracosaurus* as it was waiting to strike.

The final shot to animate was the *Thoracosaurus* surfacing to swallow the fish. This shot progressed relatively quickly since only the head and neck were visible above the surface of the water for the duration of the shot. This meant that only the head, neck, and jaws of the *Thoracosaurus* had to be animated, since the rest of the animal was underwater. Excellent reference imagery of a gharial swallowing a fish was also available. This reference footage was a close-up shot as well, so it was much more easily analyzed. The small nuances of the gharial motion that were incorporated into this shot significantly enhanced the animation. Movements such as the lateral wobble in the head as it threw the fish up in the air, and the way it tilted and turned its head, compensating for the large beak helped make for a very convincing simulation. Adding a bit of neck and upper back motion while the croc was tossing the fish into the air also subtly enhanced the action.

Along with animating these details in the *Thoracosaurus*, secondary motion was also added in the dead fish's tail. The fish was not too mobile, considering the needle-like teeth of the *Thoracosaurus* would have killed the fish on impact, so it would have been dead at the time of consumption. The movement added to the fish was physically residual, resulting from the tossing motion. Effort was put into making sure that each toss was not identical. Whenever the jaws threw the fish backwards, the *Thoracosaurus* head wobbled in a different way. Also, each toss was not evenly timed, so that the motion would not feel robotic.

After all of the animation was completed, the animation transfer process had to be used to incorporate the muscle rig into the shots in order to set the scenes up for rendering. When working with the full muscle rig, the reference footage had to be reviewed to set up initial jiggle values for all of the muscles via the master muscle control. A number of observations were noted when reviewing the reference footage: 1) The muscles attached to the vertebrae as a whole were found to be pretty stiff and tightly packed to the skin. This gives crocodylians a rather rigid neck and back. 2) The other areas of the body that were relatively stiff, and did not contain much, if any, muscle jiggle were the tail, and the lower limbs. 3) The most extensive skin sliding and jiggle was found in the belly, neck, and throat area. Especially in gharials, the undersides appeared to be particularly flexible and moved quite a bit as the animals carried themselves about. 4) The upper arm, shoulders, and thighs featured some significant skin sliding also, but only a modest amount of muscle jiggle. In short, anywhere where there was a lot of skin deformation depicted skin sliding and muscle jiggle, and any muscle groups that were attached to many bones, like in the spine, appeared to be stiff.

Values were given to the master muscle control object based on these observations before the muscle rig was incorporated into the final shots. Once brought into a shot, the animation had to be transferred with the method described earlier. The transferring worked flawlessly, other than one minor hiccup. When importing the .XAD file storing the animation data, the current frame of the timeline had to be set to the first frame, or else the animation would be offset in the timeline. The animation came into the program starting at whatever frame the timeline was set to at the time of import.

After transferring animation, the next step to setting up the muscle jiggle was to export a quick sequence from the viewport of Maya, called a *playblast*; to be able to see the motion in real time. The muscle jiggles were then evaluated by looking at these sequences on a shot by shot basis. Even if jiggle values were setup to work well for one shot, in other shots a quick motion could easily cause the dynamic forces applied to the muscles to be amplified, creating unnatural and inaccurate results. Once problems like this were detected, muscle jiggles were adjusted accordingly. This usually required subduing muscle jiggle in the shoulders and upper arms. Overall, the master muscle object became an incredibly useful rig control. Spot checking of muscle attributes was the final step to be taken in each shot for the motion to be officially completed.

4.6. Environmental Generation

With the motion of both the schematic and narrative animation complete, there was still a lot to do before the final project would be finished. In particular, there was a decent amount of environmental work in queue, which included some visual effects work, as well as scene lighting, rendering, and final compositing. Most of the environment was to be generated in the compositing process. The three main components to the environment were the environment models, the water simulations, and the background plates.

In order to focus completely on the animal and its motion, there would not be any environment included for the schematic portion of the animation. The idea was to have the *Thoracosaurus* moving in a sterile, pristine environment. Because of this, it was decided to only render cast shadows on the ground, so that the animal's contact with the ground planes used for animation would be implied by the direction and shape of the shadow, rather than having an actual textured ground distracting from the *Thoracosaurus*.

In the narrative, there were two simple sets that were created. They both consisted of subdivided planes that were sculpted to represent uneven terrain. The first set piece was incredibly simple, and was shaped into a sandbar for the opening shots of the narrative. The sandbar was sculpted and texture painted. The majority of the sandbar was textured to look dry, while the edges were darkened to look wet, since the surrounding water would run up onto the sandbar. Other details were added to the sandbar texture as well, such as tracks from seabirds, crocodylians, and turtles. All of these trackways were added to the texture in Adobe Photoshop, and were sampled from photographic reference. The main complication to the texture of the sandbar was the issue of generating animated tracks from the *Thoracosaurus* when entering the water. After much thought on the problem, a solution was found by returning to Side Effects Software's Houdini. This was the software program used at the start of the reconstruction in order to position the original fossils before transferring to Maya. Houdini, thanks to its procedural tools, allowed for a solution involving a node that allows attributes to be transferred from one object to another. This *Attribute Transfer* node, as it is called, was used to generate the tracks for the *Thoracosaurus*.

A couple steps were involved to get this to work: 1) The ground plane geometry, complete with the proper UVs that were used to texture it, was exported as an .OBJ file and imported into Houdini. 2) The animation of the *Thoracosaurus* also had to be brought into Houdini. Animation transfer between packages is always tricky, so a MEL script was employed that was written by a Drexel Digital Media colleague, Daniel Letarte, and adjusted by another colleague, Dan Bodenstein. The script allowed Maya to export an .OBJ file containing the geometry of the *Thoracosaurus* model for each frame of the animation. In Houdini, these files could be read in as a sequence, which would transfer the fame-by-frame animation data into Houdini. Once the files were read into Houdini, they were re-exported as a sequence of ".BGEO" files. This was because .BGEO is Houdini's native file format for geometry, and Houdini would use the computer's memory more efficiently with .BGEO files, therefore speeding up the workflow.

Simple flat colors were applied to the *Thoracosaurus* and the ground plane. The ground plane was assigned the color black, and the *Thoracosaurus* was assigned a bright green. The *Attribute Transfer* node transferred the color attribute from the animal to the sandbar. Any time the *Thoracosaurus* model came in contact with the sandbar model, the color from the *Thoracosaurus* would transfer to the surface of the sandbar, and only in the areas where the two models were touching, thereby creating a colored trackway over a number of frames. One beneficial aspect of this technique was that color transferred any time *any part* of the animal touched the ground. This allowed for tracks to be generated not just for footprints, but also for the belly, tail, and neck, where needed. The transferred color was then applied to the UV space of the sandbar object, and an image file was generated for every frame of the animation, at the same resolution as the sandbar's texture map.

The next step required bringing the sandbar texture map and the trackway image sequence into Nuke, a high-end compositing program designed to combine elements from multiple images. This is also the software with which all of the final shots of the animation would be completed. Once in Nuke, the color green from the tracks was extracted, and the shape was used to darken the same area on the sandbar texture map. This then put what looked like tracks in the sand texture. The same technique was used to generate the displacement of the tracks, so that the footprints would actually change the shape of the ground plane along with the color. The last part of this process required a *Frame Blend* node in Nuke, because the tracks that were generated from Houdini actually re-updated for every frame. This meant that on each new frame, instead of the new tracks adding to the previous tracks, they would replace them. The *Frame Blend* node allowed Nuke to take all of the existing frames from the trackway sequence, and have them simply layer on top of one another so that a complete path was visible by the end of the sequence. Then image sequences for the color, and the displacement of the sandbar texture were generated and brought into Maya to be used as image texture sequences (Fig. 62).

There was only one small mishap when bringing these files into Maya. In order to save on drive space by not generating hundreds more images than were needed for the sequence, only the frames of the image sequence where change in topology occurred were generated. The problem with this was that there was time before and after the *Thoracosaurus* enters the water, where the tracks needed to stay on screen. By default, since there were no frames available in the image sequence before and after the motion, the texture would disappear. A MEL script had to be written in order to hold the first frame of the texture sequences until the motion started, and then hold the last frame of the texture sequences after the motion ended. The script that was written consisted of the following:

```
$animationFrame = frame;
if ($animationFrame < 273) {
$animationFrame = 273;
} else if ($animationFrame > 775) {
$animationFrame = 775;
}
file46.frameExtension=($animationFrame);
```

This script essentially says if the current frame of the timeline is before the frame range of the image sequence, use the first image of the sequence as the file texture, and if the current timeline frame is after the sequence, use the last frame as the texture file. After this was finished, an animated trackway was successfully and accurately generated from the actual animation in the shot.

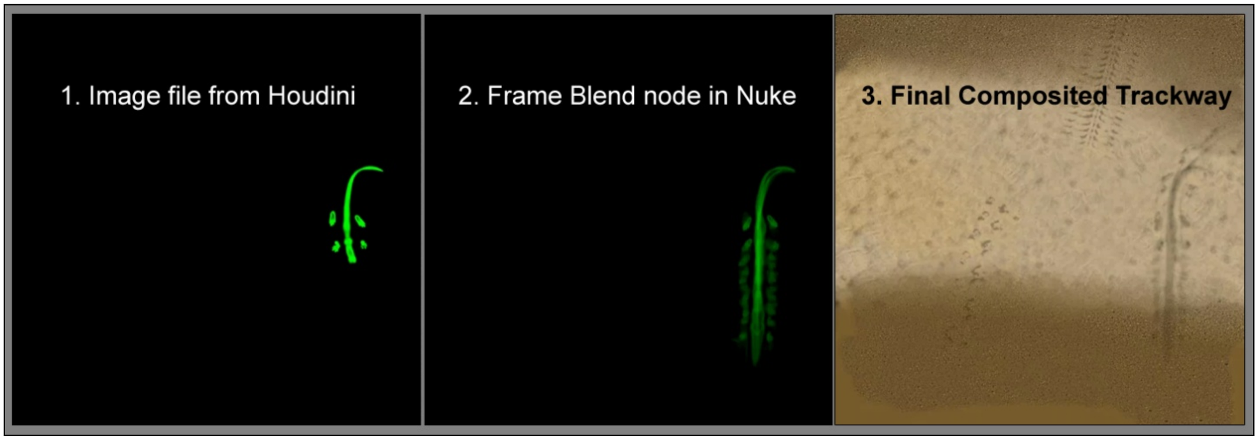

Figure 64 Steps of compositing the sandbar texture file sequence

The second set piece that had to be created was for the underwater shot where the *Thoracosaurus* catches the *Enchodus*. The initial setup was similar to the sandbar. It required building a geometric plane that was then adjusted into uneven terrain, painted, and sculpted to look like the ocean floor. This environment required more preparation due to all the dynamic systems that were used in the shot. There was seaweed to be created, as well as bubbles in the water, and a cloud of dust to brush up from the seafloor when the *Thoracosaurus* strikes.

The seaweed was created through a dynamic hair system which was connected to a fur object for shading. The hair system consisted of dynamic curves that were generated from the ground around the *Thoracosaurus*. The seaweed used as a way of framing the main action by being around but not directly in the way of the creatures in the shot. The motion of the dynamic curves was defined by dynamic forces in the environment, with the look being defined by the fur system. The fur system was essentially the default system used for grass, but it was altered significantly in order to depict taller, flatter, and scragglier plants. The seaweed was given a slightly transparent, murky greenish-brown color, and included variation in size, shape, and look across all of the plants.

The motion of the plants was created by controlling values on the magnitudes of dynamic forces used to simulate the ebb and flow of the water's current. These forces included a gravity field. The magnitude of the gravity field was toned down from the default value in order to simulate the damping effect of objects in motion underwater. There was also a turbulence field and an air field added. These forces were animated in order to create a wake caused by the snap and swimming away of the *Thoracosaurus.* Once the motion was working correctly, the look of the seaweed had to be adjusted significantly. Rendered images of individual strands of fur are typically more effective when they are far away from the scene camera. The fur object in this case was being used for larger plants that were more spread out than a patch of grass, hence, the test images tended to look flat and artificial. Many aspects of the images were adjusted in the composite, which ultimately helped blend the seaweed into the background, and achieve a much more believable and aesthetically pleasing result.

The dust that kicks up from the *Thoracosaurus* movements was created with a particle system. The particles were controlled by a number of different forces, and were animated to rush upward and slowly dissipate at the right moment in the shot. When rendering the particles, they looked even less convincing than the seaweed did in its render. This was partly because the animation as a whole was being rendered with the RenderMan for Maya rendering engine, and the particles would not appear with RenderMan. They needed to be rendered in another renderer, and so were generated with Mental Ray. The lighting of the shot was already set up based on RenderMan features, though, and therefore could not be used with the other renderer. Because of this, the composite once again had to be used to drastically adjust the shape and look of the dust. The dust was then subdued significantly, so attention would not be drawn directly to it. It was meant to simply add subtle detail to support the rest of the shot action.

Setting up the dust to accurately collide with the *Thoracosaurus* was consistently unresponsive. Since the *Thoracosaurus* was to be immersed in the dust cloud, and the dust was to be transparent, parts of the *Thoracosaurus* were supposed to appear in front of the dust, while other parts had to appear behind it. Since the dynamic collision was not working, it was attended to in the composite, by using the shape of the *Thoracosaurus* combined with a soft gradient to work as a mask; preventing the dust from appearing in front of the rendered *Thoracosaurus* image in the areas within the shape of that mask. The dust outside of the mask shape, however, would be able to appear on top of the animal. This was essentially a cookie-cutter type of workflow used to properly simulate a volume of the particles, by making it appear as if the *Thoracosaurus* was moving *through* them as opposed to in front or behind them.

There were a few other remaining elements that were added to make the setting more convincingly a murky marine environment. The look and feel of these shots was greatly inspired by a trip to Maine during the project. The underwater environment, seen when swimming in the lakes there, was the primary influence on the aesthetic of the underwater sequences.

The first element of depicting this underwater vision involved generating green fog to give a sense of depth and atmosphere to the water. After this, efforts were invested in finding a method of simulating the caustic light that is cast on the surfaces of objects when the sun shines through water; e.g. this phenomenon is responsible for the glimmering on the bottom of a swimming pool. To actually calculate the reflections and refractions of light coming through the surface of moving water would have been incredibly time consuming and processor intensive, so a method of imitating it was used instead. The solution involved projecting a procedurally animated noise texture onto the objects in the scene from a directional light that represented the sun. Once this texture was projected onto the environment, it appeared as if it were the result of refracted caustics coming from the surface of the water. This was a much cheaper solution to actually calculating the light transmissions of caustics, and did not require any water simulation to be done.

Aside from the caustic reflections on the seafloor, there was also an element to be created depicting the caustics that occur when sunlight is transmitted through a volume. Light is broken up into what are known in computer graphics terms as volume rays. They are particularly noticeable when cracks of light penetrate water, or shine through dust-borne air. This effect was generated entirely in the composite, thanks to a workflow used by a Drexel Digital Media colleague, Nate Shaw. The technique went beyond simply using the *Volume Ray* node in Nuke to generate the effect. It required the use of a number of these nodes. First, there were the golden volume rays used to simulate the sunlight travelling through the water. Then, there were caustics that were generated from other elements in the scene, darkened, and faded out. This set of darkened light rays was used as the shadow of the *Thoracosaurus*, which would trail with the light in the water. Since the animal would be blocking parts of the water from the sun, those portions of the water would become darker, creating the effect of a long trailing shadow (Fig. 65).

In one of the underwater shots, an up-tilted camera angle reveals the surface of the water from below, as the *Thoracosaurus* swims by overhead. The surface of the water had to be generated to depict the sunlight shining above, as refracted through the surface. Even this element was largely created in the composite. An image sequence of a geometric plane, textured with an adjusted version of the noise used to generate the underwater caustic pattern, was rendered from Maya. The black and white image sequence was then used as a mask in Nuke to create highlights that simulated light coming through the surface of the water. This technique worked just as well as the other forms of simulating caustics (Fig. 65). The last element of the underwater shots involved creating bubbles throughout the environment.

Figure 65 Light at the water's surface, as well as the caustics were created in the composite

Bubbles were created sparingly throughout the environment so that they added atmosphere without becoming too distracting. In trying to keep scientific integrity, it was decided to return to the underwater reference footage of alligators and crocodiles before deciding how to go about adding bubbles. There were actually very few points where bubbles would appear underwater, depending on the activity of the environment. The most that were seen were individual bubbles rising from the ocean floor sporadically.

There really would not be bubbles surrounding the tail and feet of the *Thoracosaurus*, or the fins of the fish while swimming, as was originally conceived. Since bubbles are the result of diffused air rising to the surface, most objects that are normally underwater would not be emitting bubbles, since there is no air to diffuse.

There was one video, where suddenly a stream of bubbles emitted from a crocodile's nostrils, but this was when it was surfacing to breathe. Crocodylians have a valve that covers their nostrils when underwater. In this particular video, the valve must have been released so the animal could exhale before surfacing to take another breath. This footage differed from the underwater shots of the animation, where it was considered to add a bubble trail coming from the *Thoracosaurus*'s nose. In the most tempting of the underwater shots, the animal swims toward the camera. This happens soon after it dives, however. Since the animal just recently dove, there would not be a reason for it to start exhaling. The valve above the nose would likely stay shut since it was only diving deeper.

The bubbles that did make it into the shots were created with an instanced particle system. Transparent spheres with a bubble shader were attached to a particle object. Randomized sizes were then applied to individual particle bubbles for variation. The bubbles were then slowly and periodically emitted from a geometric plane at the bottom of the scene. The bubbles had to be rendered in Mental Ray due to the issues with Maya particles and their compatibility with RenderMan. The bubbles were then composited into the final images, and subtly blended in.

Despite all of these smaller details, the most prominent step for environmental generation required simulating the surface of water. There were a number of shots that would not only require there to be open, flowing water, but these shots also required the *Thoracosaurus* to interact directly with it, which would require splashes and ripples to be generated by the animal's motion. This process was created in yet another software program, Next Limit's RealFlow. RealFlow is a program that specializes primarily in liquid and gas simulation. For open bodies of water, there is a feature in RealFlow called the *Real Wave*. The *Real Wave* is essentially a high resolution geometric plane that has adjustable attributes to simulate waves and turbulence on the surface of water. After setting up the parameters, the geometry of the wave had to be increased significantly so that the surface could show enough detail in the flowing waves. Then, all of the geometry that the wave would interact with, namely the *Thoracosaurus* and the sandbar, had to be imported into RealFlow. There is functionality for transferring information between RealFlow and other 3D applications, including Maya, which is made available by Next Limit.

To transfer models and animation to RealFlow, all geometry in Maya was converted from quad surfaces to triangles in order for RealFlow to calculate the interactions correctly. All the required geometry was then exported as an .SD file, which contained not only the geometry, but all the motion as well. Before exporting, however, any unnecessary objects had to be removed from the scene. All geometry that was not going to be used as a collision object, such as all the underlying skeletal geometry of the *Thoracosaurus*, was removed, along with anything that would have just taken too much time to calculate, such as with teeth and toenails. For one shot in particular, when attempting to simulate the wave interactions without removing some of this extra geometry, it took a complete eight hours to simulate the wave for only fourteen frames. The simulation would theoretically have been more accurate if some of that dense geometry was kept in the scene, but in practice it was not worth the time it was taking to simulate. Optimizing the scene by removing unnecessary objects and reducing the complexity of other geometry made it much more efficient.

After the Maya scenes were optimized, exported, and imported into the RealFlow scenes, water interactions and collisions could be calculated automatically. The only elements that had to be added in order to get this to look right were the splashes that were spawned by collisions between the objects and the *Real Wave*. After enough settings were tweaked so that the *Real Wave* and the splashes were working correctly, the simulations then had to be exported out of RealFlow. The export process resulted in RealFlow creating a “.BIN” file for the geometry of the *Real Wave* at every frame of the animation.   It also generated a separate file for the splash particles on each frame.

After one shot was exported, the next could be set up. Thankfully each shot needed the same elements, and the same basic *Real Wave* object could be used as a starting point, only having to change the size and shape of the *Real Wave,* and having to re-set up the splash particles once the new collision geometry was added. All the shots requiring water simulation took place in the same type of water, and the camera angles were at about the same distance from the water. This allowed the same basic *Real Wave* settings to be used across all the shots that depicted water.

When it came to incorporating the simulated water with the rest of the scene, another RealFlow tool inside of Maya allowed for importing the .BIN files into Maya. These were brought in as sequences of dense geometry. Working with the RealFlow generated geometry was incredibly slow inside of Maya, since simply changing a frame required a new .BIN file to be loaded in. Only lighting and shading had to be done after importing the RealFlow geometry, though, and nothing that required manipulating the timeline slider extensively was needed. The geometry from RealFlow behaved as any other type of geometry in Maya, and could be lit and shaded just like any other object. This allowed for a bluish shader to be applied to the water, and for reflections to be generated on its surface to help integrate the *Thoracosaurus* into its environment.

In the last shot of the animation, where the *Thoracosaurus* emerges from the water to swallow its catch, another shading detail had to be augmented to better integrate the animal with the water. Since the animal was emerging from the water, a separate shading model had to be created for the skin to make it look wet. This was done by creating another version of the skin shader that had a bumpy noise assigned to the specular channel, to simulate the glisten and gleam of wet skin. In trying to replicate this effect, the only time it actually looked wet, was when the lights hitting the skin were only casting specular light, and not diffused or ambient light. The specular highlights looked correct with this lighting method, but the contrast and shading was too intense to be believable in the context of the environment. The solution ended up being rendering out a sequence of the wet croc skin texture as well as a sequence for the regular skin texture, and combining them together in Nuke, to use the successful elements of both passes to contribute to a single image. This was the final step to believably integrating the other scene elements with the RealFlow simulations.

After the necessary set pieces, effects, and water simulations were created, the final element to restoring a 65 million year old New Jersey was to add the mangroves in the distance. It was planned, when reassessing the layout of the environment, to use photographic image planes as backdrops to create the mangroves. While in Costa Rica, where the American crocodile reference footage discussed earlier was captured, one day of the trip consisted of visiting a mangrove estuary in the western province of Guanacaste. The estuary is known as the Estero de Tamarindo in Las Baulas National Park. This estuary system contained all types of tropical wildlife, and the banks of the water were densely packed with many species of mangroves. A plethora of detailed photographs of this estuary were captured in order to take full advantage of this fantastic opportunity.

Once back in the United States, the photographic reference had to be manipulated into a form so that it could actually be used. All of the mangrove images where both the water and the skyline were visible were composited together into a massive 7,953 x 1110 pixel panorama image. This image was created in Photoshop, and required hours of manually stitching mangrove photographs together. The final composited image resulted in an image of a newly invented version of the estuary sampled from a multitude of images of the actual estuary (Fig. 66).

Figure 66 The full composited mangrove estuary with a close-up to display details

The panorama was to be used for two purposes: 1) For background plates, and 2) For generating the lighting of the computer generated elements. As background plates, the panorama was simply brought into Nuke and placed as the backgrounds of the necessary shots. It was resized and cropped appropriately, and different sections of the panorama were used in separate shots. Since the mangroves were depicted in the distance, the background plates were defocused slightly and given a bit of an overexposed bloom effect, to make it appear as if the images were captured imperfectly with a video camera in a humid environment. This was done to add a sense of cinematographic realism. For shots where the camera was moving, slight movement was added to the background plate as well. An offset between the plate and the main camera move was maintained to simulate parallax. This is the phenomenon responsible for the perception that objects in the foreground (of equal speed) appear to move faster than objects in the background.

The second use of the panorama was for lighting the animation. This environmental lighting approach was used to help blend together the elements in each shot by having naturalistic environmental lighting, rather than trying to fake the look with an unnatural studio lighting setup. In order to achieve this, the panorama image had to be converted into an ".HDRI" file to use as an environment map within Maya. This environment map was then plugged into a RenderMan Environment Light in the animated scenes. This light, along with creating the proper colors of the bounced reflected light, also had options to create soft occlusion based shadows; similar to what was generated for the ambient occlusion maps used in the *Thoracosaurus* and *Enchodus* textures. The environment map was also used for the reflectivity of various surfaces in the scene, such as the corneas of the eyes. This would ensure that any reflective surface would show the mangrove environment in their reflections, despite the mangrove plates never actually being brought into the Maya scene files.

The RenderMan Environment Light technique was the primary form of lighting for the entire project. The mangrove environment map was only used for the above water shots and for the fossil introduction shots. Its use in the fossil introduction was purely aesthetic. A very slight reflection on the fossil shader was added, which would allude to the restored environment. This was included as a way of tying in the beginning of the piece with the narrative sequence, as well as subtle hinting that the fossils are the gateway into the ancient world.

The RenderMan Environment Light was also used throughout the schematic, but a solid white color generated the lighting instead of the mangrove environment map, since the schematic was to take place in a white void. The underwater shots used a similar technique, but with a greenish color to simulate the murky depths of the estuary.

During the rendering process, single frames took anywhere between one minute per frame for some shots, to fifteen minutes per frame for other shots. Setting up render layers aided this process, so that elements could be split into specific passes, to be later adjusted individually in the compositor. These separate passes included character, ground, water, and reflection passes. The only major issue that appeared when rendering, was the problem that RenderMan for Maya was having with rendering the incredibly dense fossil geometry, the reconstructed skeleton geometry, and the muscle geometry simultaneously. By simplifying the settings on the lights to reduce unnecessary shadow calculations, both the fossils and the full reconstructed skeleton rendered without issue. The only continued problem was rendering the full skeleton in the same image as the muscles.

The solution to this was to render in separate passes, so that the full skeleton was rendered, with the muscle image sequence to be later combined with it in the compositor. It would only work correctly if the muscles were given a use background shader, which essentially makes an object (and anything that it is overlapping) transparent, conformed to the shape of that object. This way the full skeleton was rendered in an image sequence that had all of the muscles “cut out” from it. This image sequence was then overlapped onto the image sequence of just the muscle geometry. Since the muscles would show through the “cut out” transparent shapes in the skeletal image sequence, it appeared as if the muscles were in the proper places, overlapping the skeleton in some areas, and being overlapped by the skeleton in others.

After this rendering issue was fixed, and all of the required image sequences were successfully rendered, the rest of the project was finished by tweaking the multiple image layers in Nuke; adjusting colors and using other techniques to combine the images into aesthetically pleasing, cohesive wholes. The sequences were then exported and brought into Adobe After Effects, where the editing of the final piece was done, complete with the addition of text and end credits. After this final composition was exported, it marked the end of production on the reconstruction, restoration, and animation of NJSM NH 2005.2: *Thoracosaurus neocesariensis.*

IV. FUTURE APPLICATIONS

With the completion of the project, a considerable amount of groundwork is now in place to further explore themes in digital paleoart. There are vast possibilities in this field, and the concepts and issues discovered in the reconstruction and restoration of *Thoracosaurus neocesariensis* can be used as starting points for a number of different projects. The restoration of *Thoracosaurus* could always be revised in the future based on more accurate data or more streamlined production pipelines, but there are also a host of other projects that could be explored, based on information learned from this restoration.

An incredible amount of detail was put into the reconstruction and restoration of *Thoracosaurus neocesariensis*. Despite all the efforts, the intricacies of nature are infinitely more complex than what could be created with mere artist tools. Even with the techniques and scientific oriented eye used for this restoration, there was an incredible amount of room for errors to be made. Even if the pipeline was revised and perfected, the amount of time and resources it takes to create a scientifically accurate restoration are incredibly limiting factors. Despite all of these hurtles, it does not mean a scientifically accurate restoration attempt is a lost cause. It merely opens room for further exploration to constantly improve upon previous work, and continue to strive for perfection in the spirit of the great traditional paleoartists.

There were a number of elements in the *Thoracosaurus* restoration that were less than optimal, and hold the potential to be improved upon in the future. Everything from having a more automated and stable scanning process; to having better orthographic imagery from which to model; to finding a way to more accurately limit the mechanics of the rig could instantly bring the restoration to a new level. There were plenty of compromises that had to be made due to the current state of the technology and limited available resources. The most obvious way to improve the restoration would be to find more complete fossil material, and to substitute hand modeled bones with new scans. Accurate scan data, after all, was the fundamental concept to creating a more successful restoration in this process.

When in the final stages of the muscle system, an email was received from a man named Dr. Jesper Milàn, who discovered information about the digital *Thoracosaurus* online. Jesper is the curator of geology at the Østsjællands Museum in Denmark. He was interested in helping the restoration by providing imagery of a *Thoracosaurus* skull he had been working with in Denmark. Although it was not a *Thoracosaurus neocesariensis*, the skull looked like a great reference of an early gavialoid that could have been incredibly helpful to the restoration. It looked rather similar to *Thoracosaurus neocesariensis,* despite being much flatter. Unfortunately at the time this resource was revealed, the project was already far into the skinning process, and it would have caused a lot of re-building to be done if this new data was incorporated. Nonetheless, just as how other bone scans could be introduced to the restoration, the same is true for new comprehensive research and better reference imagery.

This restoration could even be taken further with the current state of digital technology. Since the majority of the project consisted of building the rig, the bulk of the animation did not become completed until much later in the project. Unfortunately, not all of the muscles were affecting the rig quite as was hoped, due to a great deal of them being skinned to the skeleton. Even though these muscles retained their muscle properties, since they were skinned to the joint chains, the vertices were connected to the joints and did not behave as dynamic muscles. This prevented certain muscles from becoming useful for any sort of deformation effects. At the point in the project that this was finally discovered, there was little room for experimenting with alternate ways of rigging these effects. There are a number of ways these problems could have been solved if enough research and development efforts were put toward finding solutions. Other deformation tools could have been used so the entire creature was not reliant on the limited muscle system.

More intricate control mechanisms could also be incorporated into the rig. There were some controls that were not built into the rig since they were not needed for any of the shots in the final animation. Such controls could possibly be helpful for other animation in the future. Blink controls were not added to the rig. This would have added a lot of realism if it was implemented effectively, but the complexity of a crocodylian blink guided production efforts toward more essential tasks. Whereas with humans, a blink is achieved by simply closing the eyelids, a lot more is involved in the blink of crocodylians. Not only does the eye close, but the physical position of it on top of the head changes. The entire eye rotates and practically recedes into the head. While this is happening, there is also the nictitating membrane that wipes across the eye sideways. This is an incredibly intricate action that was omitted from the rig. Other controls that could be added include functionality to expand the rib cage to mimic breathing, and perhaps even tongue functionality. If the rig were to become this detail oriented in the future, it might also be useful to build a mobile epiglottis and trachea into the mesh, opposed to simulating them in the texture map.

Aside from the anatomical shortcomings of the project, the *Thoracosaurus* restoration could be used as a starting point for the research and development of other, more specific projects. The first of these possible future projects that comes to mind is the development of a more accurate muscle tool to integrate into Maya, or any other 3D application. A great deal of work could be done to build a more advanced, and biologically accurate muscle system, specifically for these sorts of projects. The Maya muscle system is great for the entertainment purposes that it is designed for, but other muscle solutions should be investigated in order to create a truly anatomically accurate muscle system. This is no simple project, and would require a great deal of research in both biology and computer science. If factors such as connective tissue, tendons, and ligaments could be incorporated, as well as the ability to create more complex muscle shapes, it would already be much more conducive to paleontological restoration.

Another project that could be attempted would be to use the now-existing *Thoracosaurus* rig, and put much more focus on locomotion, without concerns about building and shading an entire creature. One idea of incorporating more accurate motion, which was actually discussed briefly as a possibility during this restoration project, was in using a motion capture system to record the actual movements of alligators. The institutions involved in this project could positively realize this, considering the Drexel

University Digital Media Program maintains motion capture technologies, and there are live alligators, and staff trained in handling these animals at the Academy of Natural Sciences of Philadelphia. Granted, because of the incredible size difference between the young alligators at the Academy and the *Thoracosaurus*, the motion would not be directly applicable for *Thoracosaurus*, but it could provide interesting research by further analyzing crocodylian locomotion with much more physically accurate data.

Another interesting way of testing locomotion could be to start with trace fossils, such as trackways. The trackway generation technique used for the restoration could be used as a way to test the accuracy of an animal’s motion. If an animal was animated doing a specific action, and known tracks of that action could be photographed or collected, the attribute transferring technique used for generating a trackway could then be used to test the results of the animation. It could validate the animation by seeing if the generated trackway correlated with the fossil trackway.

There is also the possibility of attempting to remove human error altogether, by using strict mathematical and biomechanically-based physics to generate the motion of animals, as opposed to an animator replicating it by hand. For example, GaitSym is a software system that uses forces of muscles on bones to calculate the walk cycles of different types of vertebrates. This could offer a great way to incorporate even more biology to generate heightened accuracy of motion. Although this would be less accurate than the motion capture possibilities for crocodylian locomotion, perhaps a project using this system could be used in conjunction with motion capture techniques for comparison purposes. The GaitSym system is commonly used for other types of extinct organisms, such as dinosaurs, where motion capture would not exactly be an option.

This brings us to the most applicable future possibilities of this project. Having completed the reconstruction and restoration of an extinct crocodylian, a lot of work and research is in place to move forward and to attempt use of similar techniques, to improve upon them, and to restore other types of extinct species. It would be particularly interesting to explore the various gaits of extinct animals with no modern analogue, which would have more experimental and theoretical aspects to their biology. Considering most of the organisms that have ever lived on the planet are extinct, there are practically endless possibilities. With the crocodylian research in place, this thesis project sets up an extremely useful body of research for restoring dinosaurs. Since crocodylians and birds are the only remaining members of Archosauria, and the closest living relatives of the dinosaurs, this project represents one half of the puzzle needed for a solid grounding in restoring Dinosauria.

V. CONCLUSION

As a whole there were some rather successful results from this project. The blending of an artistic vision, critical scientific research, and state-of-the-art digital tools helped to build an animal from the inside out, and bring it to life through animation with an incredible amount of detail; all based on hard science. Attempting to restore an entire animal from the inside out is no easy task, as anybody working in paleoart would agree. The new techniques involved to take this legacy art tradition into the future can even complicate the restoration process further. Access to high-tech tools aids in achieving results with an unprecedented amount of accuracy, yet also continues to raise the expectation and authenticity requirements for such projects. Paleoart is ever evolving and becoming increasingly more important to the science in which it stems from, which further increases the standards of quality.

Even with all the success of the reconstruction and restoration of *Thoracosaurus neocesariensis*, it has only opened the gates to a much larger world, with endless possibilities to explore. The project was by no means perfect in creating a perfectly accurate depiction of an extinct animal, as there were many factors that limited this goal, even with the availability of newer digital tools. The compromises that had to be made to finish the project ranged throughout all parts of production, from the fact that the fossil data had to be stitched together by hand, to the unknowns and estimates of the skeletal model, to the inaccuracy of digital muscle systems, to the fact that it is often incredibly difficult to create anything that is completely photorealistic.

The muscle functionality was a significant factor in some of the problems with the restoration. The problems with using the fat offset options on a project like this were particularly harmful. Because of how it did not work as expected, the proportions of the *Thoracosaurus* ended up looking more like a much smaller crocodylian than a sixteen foot one. As a whole it should have been bulked up, and it should not have relied on the muscles to do this. This was, in part, the result of poor information that was provided when discussing Maya muscle functionality with informed colleagues. The only muscles that really ended up being useful for the final skinned animal were the *pterygoideus* muscles of the jaw, the *pectoralis* muscles, the upper arm muscles, the *latissimus dorsi*, and most of the muscles of the lower leg. The remaining muscles, despite providing a visually accurate muscle system, did not provide much functional success. Other than muscular related issues, there were also animation issues that were still not perfected at the end of the project, including the lack of jiggle on the creature's simulated underbelly. There were also problems with basic animation intuition, compounded by less than ideal reference footage that was used for the swimming motions.

There was also the issue of the practicality of the production. It takes a great deal of effort and multi-disciplinary research to execute a project like this, particularly when only one person is ultimately responsible for all aspects of the project. The project was largely impractical from a production standpoint. It would be much more helpful to undergo future projects of this nature with a full team of digital artists. This would also be best motivated if everyone working on the project had an equal dedication to science, such that each team member could be entrusted to not cut corners, unless it was fully justifiable.

Despite all of the production issues, this project stands as a significant step forward with this type of work, and provides a great deal of documented knowledge for anyone who is willing to restore any sort of anatomically accurate animal. Besides the extended limits of the production pipeline to adapt to a scientifically based restoration, another major success of the project was the established methods of working closely with scientists. Each step of the production process went through extensive review from many qualified experts. Paleontological approval was required for each task before moving on to the next portion. This was also the greatest folly of the project planning phase. It was known that scientific critiques were going to exist throughout the entirety of the project, but it was not realized initially how much work was going to have to be redone as a result.

A large amount of rework was done throughout multiple steps of the project, in order to try to achieve heightened scientific accuracy. This was also a major factor in how long the project took to complete. The skull was essentially built twice, along with a couple other bones. The muscles had to be altered once or twice based on feedback from mentors, as well as new reference material that was acquired during the process. Animation was also adjusted multiple times. The project was extremely fortunate to have been under the supervision of so many leading experts in the field of paleontology. These experts were not afraid to critique the work, either, which really helped push the quality of the restoration to another level. Some of the known issues in the project probably could have been avoided by referring to these experts much more frequently. Overall, a strong working relationship was established throughout the project, which helped strengthen the final results.

Another positive aspect of this production was the believability of the final look of the piece. Most current educational paleoart based programs rely on trying to create more realistic dinosaurs by setting them in real-world environments that were filmed with a camera. The result is usually restorations of animals that do not completely feel natural in their surroundings. This common shortcoming was known from the start of the project, so most elements were intentionally created digitally, so that the piece could avoid this issue. There were definitely photographic elements used in the background plates, but both photographic and computer generated image sources were adjusted and composited in a way to bring them closer together, aesthetically. The final *Thoracosaurus* restoration does not look exactly real to the trained eye, but it does look well fitted to its environment.

As previously discussed, there are countless possibilities for future attempts at this type of research. Paleoart is going to continue to evolve throughout the years. It may never become perfect, but that does not mean that perfection should not be attempted. Projects like the restoration of *Thoracosaurus neocesariensis* can be used to help further paleoart, by attaining results based on hard science that could not have been achieved with the techniques and knowledge of the Paleoart Reformation period, or the Dinosaur Renaissance. These types of projects can be used to set a higher standard for future paleoartists. In undergoing these projects, new capabilities and functionalities are ultimately discovered and invented, which make room for even more possibilities. It is important that no matter how wild, intricate, or convoluted the techniques get, the essential mission of paleoart stays the same. In inspiring times like the present digital paleoart movement, it is easy to become excited by the new tools, but the fossils themselves must remain central to the art form. After all, people could not even begin to imagine the world of prehistory if it were not for nature allowing for bones to become fossilized, so that they could be rediscovered millions of years later. It must always be remembered when undergoing this type of work that the new tools of the future will ultimately allow for the discovery of the wonders of the distant past.

BIBLIOGRAPHY

[1] A. H. Turner, P. J. Makovicky, M. A. Norell. (2007) Feather Quill Knobs in the Dinosaur Velociraptor. *Science* 317:5845, 1721-1721.

[2] Brinkman, D. 1980. The hind limb step cycle of Caiman sclerops and the mechanics of the crocodile tarsus and metatarsus. Canadian Journal of Zoology, 58:2187-2200.

[3] Brochu, C. A. 2006. Osteology and phylogenetic significance of Eosuchus minor (Marsh, 1870) new combination, a longirostrine crocodylian from the Late Paleocene of North America. Journal of Paleontology 80(1):162-186.

[4] Brochu, C.A. 2004. A new Late Cretaceous gavialoid crocodylian fromeastern North America and the phylogenetic relationships of Thoracosaurs. Journal of Vertebrate Paleontology 24: 610–633.

[5] Brochu, C. A. 2001. Crocodylian snouts in space and time: phylogenetic approaches toward adaptative radiation. American Zoologist 41:564–585.

[6] Chiasson, Robert B. *Laboratory Anatomy of the Alligator*. Dubuque, Iowa: W. C. Brown, 1962. Print.

[7] Cong, L., Hou, L., Wu, X., and Hou, J. 1998. The gross anatomy of Alligator sinensis Fauvel [in Chinese]. 388 pp. China Forestry Publishing House, Beijing.

[8] Debus, Allen A., and Diane E. Debus. *Paleoimagery Evolution of Dinosaurs in Art*. Boston: McFarland & Company, 2002. Print.

[9] Endo, H., R. Aoki, H. Taru, J. Kimura, M. Sasaki, M. Yamamoto, K. Arishima, and Y. Hayashi. 2002. Comparative functional morphology of the masticatory apparatus in the long-snouted Crocodiles. Anatomy Histolology and Embryology 31: 206–213.

[10] Figgins, S., "Graphics in computational paleontology," *Computer Graphics and Applications, IEEE*, vol.21, no.6, pp.6-13, Nov/Dec 2001.

[11] Frey, E., J. Riess, and S. T. Tarsitano. 1989. The axial tail musculature of recent crocodiles and its phyletic implications. American Zoologist 29:857–862.

[12] Futuyma, Douglas J. Evolution. Mahwah: Sinauer Associates, 2005.

[13] *HD Video Stock Footage, Stock Video Footage - BBC Motion Gallery*. Web. January-August. 2010. <http://www.bbcmotiongallery.com/>.

[14] Hutchinson, John R., and Stephen M. Gatesy. "DINOSAUR LOCOMOTION Beyond the bones." Nature 440 (16 Mar. 2006): 292-294. Nature. 16 Mar. 2006. Nature Publishing Group. 27 Apr. 2009 <http://www.nature.com/nature/journal/v440/n7082/abs/440292a.html>.

[15] *Jurassic Park*. Dir. Steven Spielberg. Perf. Sam Neill, Laura Dern, Jeff Goldblum, and Richard Attenborough. Universal Pictures, 1993.

[16] *Jurassic Park III*. Dir. Joe Johnston. Perf. Sam Neill, Alessandro Nivola, William H. Macy, and Laura Dern. Universal Pictures, 2001.

[17] J. R. Hutchinson, F. C. Anderson, S. S. Blemker, and S. L. Delp.
Analysis of hindlimb muscle moment arms in Tyrannosaurus rex using a three-dimensional musculoskeletal computer model: implications for stance, gait, and speed
Paleobiology, December 1, 2005; 31(4): 676 - 701.

[18] Kallick-Wakker, Ingrid. "Science Icons: The Visualization of Scientific Truths." Leonardo 27 (1994): 309-15.

[19] Kane, Georgann. Walking with Dinosaurs. BBC. 16 Apr. 2000.

[20] Kardong, Kenneth V. *Vertebrates Comparative Anatomy, Function, Evolution*. 5th ed. New York: McGraw Hill Higher Education, 2008. Print.

[21] "Lanzendorf PaleoArt Prize." The Society of Vertebrate Paleontology. 2007. 13 June 2009 <http://www.vertpaleo.org/>.

[22] Lochhead, Jamie, dir. "The Crocodile." *Inside Nature's Giants*. Prod. David Dugan. Channel 4. London, UK, 13 July 2009. Television.

[23] Martin, Anthony J. Introduction to the study of dinosaurs. Malden, MA: Blackwell Pub., 2006.

[24] Mayor, Adrienne. *The First Fossil Hunters Paleontology in Greek and Roman Times.* New York: Princeton UP, 2001. Print.

[25] McGowan, Christopher. *Dinosaurs, Spitfires and Sea Dragons*. Cambridge (Mass.): Harvard UP, 1992. Print

[26] Meers, M. 2003. Crocodylian forelimb musculature and its relevance to Archosauria. Anatomical Record, Part A 274:891–916.

[27] Oliver Bimber , Stephen M. Gatesy , Lawrence M. Witmer , Ramesh Raskar , L. Miguel Encarnação, Merging Fossil Specimens with Computer-Generated Information, Computer, v.35 n.9, p.25-30, September 2002 (doi>10.1109/MC.2002.1033024)

[28] Parris, D.C. 1986. Biostratigraphy of the fossil crocodile Hyposaurus Owen from New Jersey. New Jersey State Museum, Investigation Number 4. 16pp.

[29] Parrish, J. M. (1987). The origin of crocodilian locomotion. Paleobiology 13, 396–414.

[30] Reese, Albert M. *The Alligator and Its Allies*. New York: G.P. Putnam's Sons, 1915.. Print.

[31] Reilly, Stephen M. and Elias, Jason A. 1998, Locomotion in Alligator Mississippiensis: Kinematic Effects of Speed and Posture and their Relevance to the Sprawling-To-Erect Paradigm, J. exp. Biol 201,2559-2574

[32] Romer AS (1923) Crocodilian pelvic muscles and their avian and reptilian homologues. Bull Am Mus Nat Hist 48:533-552

[33] Schein, J. P., Lacovara, K. J., Gallagher, W., and Poole, J., 2006. A nearly complete *Thoracosaurus neocesariensis* from the latest Cretaceous-earliest Tertiary Hornerstown Formations of New Jersey, U.S.A. Journal of Vertebrate Paleontology, 26(3): 120.

[34] Scott, Karen D., and Anne M. White. "Unnatural History? Deconstructing the Walking with Dinosaurs Phenomenon." Media, Culture & Society 25 (2003): 315-32. SAGE Journals Online. 2003. SAGE Publications. 27 Apr. 2009 <http://mcs.sagepub.com/cgi/content/refs/25/3/315>.

[35] Shubin, Neil. Your Inner Fish A Journey into the 3.5-Billion-Year History of the Human Body. New York: Pantheon, 2008.

[36] Taylor, M.P., Wedel, M.J., and Naish, D. (2009). “Head and neck posture in sauropod dinosaurs inferred from extant animals”. *Acta Palaeontological Polonica* 54 (2), 2009: 213-220.

[37] Thorbjarnarson, John B. 1990. *Notes on the Feeding Behavior of the Gharial (Gavialis gangeticus) under Semi-Natural Conditions*. *Journal of Herpetology* 24: 99-100.

[38] Whitaker, Romulus. 2007. The Gharial: Going Extinct Again. Iguana 14: 24-33.

APPENDIX A: NOTES

1. The procedural nature of Side Effects Software's Houdini was used for the quick positioning of low resolution geometry. After positioning the low resolution versions of the fossils adjacent to one another, a *switch* node could then be created that automatically swapped out the geometry of each bone for higher resolution versions, all with the ease of dragging a slider in the Houdini interface.

2. The data was more efficient to work with in Maya opposed to Houdini since Houdini was referencing external .OBJ files for each and every bone, whereas Maya keeps this geometry recorded internally in its ".MB" file.

3. Unfortunately, word was that the reason this important bone was missing from the specimen when scanning, and was only available in the form of images, was because it was given away to a child a few years earlier, sometime after the fossils were excavated.

4. The whole purpose of joint labeling is so that when weights that are painted to determine how much of the skin is influenced by what joint, these influences can be mirrored to the other side, greatly decreasing the time it takes to set up a character. The joint requires the input for a "Side" value, which includes a dropdown menu with the options "left," "right," or "center." It then requires the user to determine which joint it is, by providing a list with commonly used joint names. In order to keep the labels consistent with the rest of the naming conventions, each joint on this rig was labeled with the type "Other." This then required a custom name to be typed in. It is important that when inputting a custom name, not to indicate right or left, since the previous "Side" option is there to make this distinction. Otherwise, when mirroring joint influences, the program may run into a predicament where it cannot find the joint labeled, "Right_Femur" on the left side, for example.

5. Within the parameters for the IK spline handles, there was apparently an "Advanced Twist Controls" menu within the "IK Solver Attributes." Within this menu, there were a few options. The first step for the fix was to enable the twist controls. Then, the "World Up Type" dropdown menu had to be set to "Object Rotate Up." The default for this is for the positive y-axis to be the "up" direction, but the twisting problem would continue when rotating the body. In order to fix this, an option labeled "World Up Object" with a blank text field was noticed. At this point the solution became obvious. A locator object was created and positioned above the skeleton. This was then named appropriately as "World_Up_Vector", and the name of this object was input into the "World Up Object" text field. The locator was then parented under the full rig control object, so that it would rotate relative to the rig at all times. This fixed the issue, since the locator acted as an object that defined what "up" was for the joint chain. This way, even though the positive y-axis was the default up direction, when the rig was rotated upside down, the top of the joint chain would aim toward the locator, keeping the splines oriented correctly. This had to be set up for all three spline IK handles, but was a relatively quick fix, despite the number of hours of debugging it took to figure out.

   When making extensive use of clusters and spline IK handles like this, the hierarchy of the rig is incredibly important. When using this setup, the curves created through the spline IK handles, the IK handles themselves, and all the clusters cannot be in the same hierarchy of the full rig. For this rig, all of these pieces were separated outside of the full rig controller, and were put into a separate group node labeled "Splineik_Pieces." If any of these parts were parented underneath the main rig control object, double transformations would have occurred. This means that the control objects that were affecting the clusters would move as a result of their parent, *and* the clusters would also move if they were parented under the same parent object, causing the clusters to move twice as much, resulting in a double transformation, which essentially breaks the rig.

6. There are two tabs on the muscle creator interface, *Create* and *Edit*. The *Create* tab requires a couple of inputs before a muscle is created. A user must define the name of the muscle, and the number of cross-sections and segments in the muscle, which will ultimately determine how much control over the shape of the muscle the user will have. The more cross sections, the more control over deformation properties along the length of the muscle there will be. The more segments, the more specific the shape of the muscle can become. For most muscles, three segments and cross sections were adequate. More segments were added for muscles that needed very specific shapes. The create tab also has two fields for the user to define the origin and insertion joints that the muscle is to be attached to.

7. At the top of the *Edit* tab of the interface, there is the "Sculpting" tab, which allows the user to determine the thickness of the muscle at any point along its length. In order to sculpt the shape of the muscle, there is a "Location" sliding bar which determines where along the muscle the sculpting will affect. The length of the sliding bar represents the length of the muscle, so sliding the handle toward the end of the bar lets one know that the affected area will be closer to the insertion point of the muscle. Once deciding where along the muscle to sculpt, there is a second sliding bar that determines the radius of the muscle at that point. Moving the slider to the right increases the radius, and moving to the left decreases it. The amount of falloff of the growing or shrinking of the muscle is a result of the "Strength" slider at the top, as well as the number of segments and cross sections determined at the time of muscle creation. The fewer segments and cross sections, the smoother the drop-off will be. One can think of the segments and cross sections like values on a gradient. The further apart they are the more room there is for smoothing between the two values, creating a more even transition.

   In the "Sculpting" tab, there is also an "Affect" option that has a number of buttons related to it. This determines what the sculpting will affect. The user has the option to grow or shrink the radius of the muscle only along the directional axes he or she chooses. Along with a button for each axis, there are also buttons for each state of the muscle. This lets the user determine which muscle states the sculpting will affect.

   The next important menu was the "Poses" tab, where the user informs the system of what to use for the rest, squash, and stretch states. This typically works by adjusting the rig to a pose where the muscle is in a neutrally stressed position and selecting the "Rest" button next to the label, "Set Current State As." Then after determining what the rest pose is, one would adjust the rig to a pose where the muscle would be most extended or flexed, and then select the appropriate "Squash" or "Stretch" button.

Under this section of the “Poses” menu is a list of all the controls and attachment points. The user selects the attachment point he or she would like to adjust from the list, and the program selects it in the viewport so that it can be interactively adjusted with the typical Maya interface. Adjusting the end locators allow the user to select where along the length of the bone the muscle will start and end, as well as determining the orientation of the muscle (something that is determined by the relationship between the distances and positions of the attachment points relative to one another). The other attach points control the position of the muscle between the end locator attach points. The position of the attachment points can then be adjusted for all of the muscle states. This is extremely useful, since the radius of the muscle will change based on the level of squash and stretch, occasionally changing what appears to be the position of the muscle as well. For example, with a muscle that must lay flat against a bone it is attached to, although it may be correct in the rest pose, when squashing, it will most likely intersect the bone, and when stretching it will most likely pull away from the bone, since the radius is changing, but the position of that attachment point (which registers from the center of the muscle) does not change. This is fixed by adjusting the positions of the attach points for each muscle state. The muscles and controls along the muscles also have jiggle and fat attributes which can be enabled and adjusted.

8. Even though the gharial is a highly specialized crocodylian, both animals occupied a similar ecological niche as a fish eating, highly aquatic crocodylian. This means that the *Thoracosaurus* musculature should have been incredibly similar to that of the modern gharial.

9. To mirror muscles, one simply has to go back to the “Create” tab of the muscle creator interface. There is the menu for mirroring on this interface, which requires the user to select the muscle to mirror, set the proper axis to mirror across (in this case, x), and enter inputs for the “search” and “replace” fields, to create the proper naming convention for the mirrored muscles. Since each muscle included “_L_” in its name as previously mentioned, “_L_” was entered into the search field, and “_R_” was entered in the replace field. After selecting the mirroring button, everything was copied over correctly, and the process appeared to work.

10. This was another process that was not particularly difficult, but since it had to be completed for all 68 muscles, it was quite tedious.

11. After all of the individual muscle controls were selected, the “<<<” button on the *Controls* field of the “Setup Master Muscle Control” window was selected to input all the selected controls into that field. The master muscle control object was then selected, and another “<<<” button was selected next to the *Master Control* field to designate where the attributes would be created. A name was then specified for the muscle group being assembled, and the “Setup Master Muscle Control” button was pressed.

12. This should have probably been done to a greater extent in other areas, most notably in the arms and legs, but the edge flow ended up working pretty well for the most part.

13. This was decided after some failed attempts in Autodesk Mudbox. Mudbox was originally going to be used since it is also an Autodesk program, and the interface is very similar to Maya. Because of this, it has a smaller learning curve for those familiar with Maya. After sculpting about a quarter of the *Thoracosaurus* in Mudbox, the computer started to run out of memory when attempting to add more detail. ZBrush was ultimately a better solution since it was more efficient at working with high-resolution geometry.

14. There were even times where muscle weights were adjusted for hours with little to no progress, only to discover that the problem was ultimately with the original skin deformer weights, and not with either set of muscle weights.

15. After hours of debugging, the Maya muscle documentation was consulted.\

16. The script was even free-to-download, making it easy to acquire.

17. During the shooting of these first couple shots, the smaller 9 foot female alligator scurried into the water. She was the quicker and more aggressive of the two.

18. Aside from one camera operator being in the alligator cage, further pressure was added since the footage could only be captured in one take. Once the animal made it to the water, there was no way of getting it to do anything else.

19. The staff of Reptiland could not be thanked enough for allowing this footage to be shot, which proved to be an incredibly useful reference.

20. The fall of the *Thoracosaurus* was one spot where there was a strong desire to push things further, and make the fall faster, with a greater rebound, in order to create more of a visual impact.

21. Such possible drama-enhancing flourishes were resisted.

22. If one were to perform a longer, drawn out wind up to pitching a baseball, the pitch would end up being more effective.

APPENDIX B: GLOSSARY OF TERMS

Adobe Photoshop – An industry standard painting and photographic manipulation application

Allometry – The idea that different structures from the same body grow and develop at different rates over time

Ambient Occlusion – A lighting method that simulates subtle and naturalistic shading, shadowing, and reflected color in 3D computer graphics

Animatic – A form of previsualization used to plan a sequence of shots. It is essentially an animated sequence of storyboards used to help plan the framing, pacing, and timing of a final movie. Animatics allow filmmakers to fine-tune how their story is told before production starts

ANSP 10079 – The catalogue of the holotype specimen of *Thoracosaurus neocesariensis* from the Academy of Natural Sciences of Philadelphia

Antebrachium – Anatomical term referring to the forearm

Anterior - Anatomical directional terminology referring to the front of the body

Autodesk Maya – An industry standard 3D modeling and animation software application

Basal – A feature found in older species, evolutionarily speaking

Basioccipital – The bone of the skull immediately ventral to the foramen magnum (the hole where the spinal cord exits from the braincase) that articulates with the first vertebrae

Belly Crawl – A crocodylian gait used to slide across the ground for short distances. It is characterized by the sprawling limb posture common to most reptiles and amphibians

Brachium - Anatomical term referring to the upper arm

Carbonization – Process of fossilization where elements such as oxygen, nitrogen, and hydrogen leave and are replaced by a carbon film. This commonly outlines soft tissues of organisms

Caudal – Anatomical directional terminology referring to the tail

Cavity Map – An image in UV space to be combined with a texture file to emphasize the displacement details in the color channel of a shader

Centrum – The main central body of a vertebra

Cervical – Anatomical directional terminology referring to the neck

Child – A lower level node in a hierarchy that inherits properties from parent objects above it

Cloaca – Also known as the vent, it is a single posterior opening that functions for the processes of urination, defecation, and reproduction

Cluster Deformer – A deformer that acts as a selectable handle to ease the selection of points, faces, or vertices of a surface

Control Object – A part of a control rig that is manipulated and animated to control a character, creature, or object

Cranial - Anatomical directional terminology referring to the skull

Crurotarsal Joint – A type of ankle joint that can pivot between the calcaneum and astragalus

Deep - Anatomical directional terminology referring to something that is further inside the body

Deformer – A tool used to change the shape of an object in animation production

Derived – A more recently developed trait not found in the last ancestor of a species, evolutionarily speaking

Dinosaur Renaissance – A paleontology movement sparked by the discovery of *Deinonychus*, which lead paleontologists to see dinosaurs as more dynamic and active animals

Displacement Map – A black and white image in UV space that simulates depth based on the grayscale value of the image. It is used to provide more detail in a three-dimensional model by appropriately displacing the surface of the model at render time.

Display Layer – An organizational feature within Maya to easily allow the visibility of objects to turn on and off

Distal - Anatomical directional terminology referring to something that is further away from the torso of the body

Dorsal – Anatomical directional terminology referring to the back

Double Transformation – An affect that occurs when an object is being controlled by more than one of the same type of input simultaneously, creating undesirable results in a rig

Duty Factor – The percentage of a stride that a foot is planted on the ground

Enchodus – An extinct genus of fish from the late Cretaceous and early Paleocene of the eastern United States. It is also known as the “saber-toothed herring”

External Mandibular Foramen – The outer opening in the jaw of a crocodylian, found at the connection between the dentary, angular, and surangular bones

Foramen – An opening in a bone

Forward Kinematics – FK is a way of controlling a joint chain by progressively positioning each joint down the chain

The Foundry’s Nuke – A high-end compositing software application

Fur Object – A fur object is used to create and determine the look of fur, hair, grass, or other such systems within Maya. Fur objects are often linked to dynamic hair systems in order to add motion.

Gastralia – Abdominal ribs that provide structural support for the area of the torso between the sternum and the pelvis

Gavialoid Crocodylian – A member of Gavialidae, a group of crocodylians that includes the modern gharial

Geomagic Studio – The primary software used in this project for the scanning of objects, compiling of point cloud data, and conversion of cloud data into geometric objects for use in animation production

Glauconite - A green mineral that is responsible for the color of the green sand known as marl. Green sands are interpreted as being former areas of highly productive marine environments

Hair System – A system of curve objects commonly used to drive the shape and motion of a collection of filamentous objects in computer graphics. They are commonly used to simulate elements such as blades of grass, hair follicles, or even tentacles. This is achieved through the use of dynamic forces acting upon the hair system's curves.

Headus UV Layout – A software application that specializes in tools for UV mapping

High Walk – A crocodylian gait used to travel across long distances. It is characterized by an erect limb posture

Holotype – The specimen of a particular species which defines the characteristics of that species, and which all other members of the species are based

Igneous Rock – Rock formed as a result of cooling magma

IK Spline – A method of controlling a joint chain based on the control points of an underlying curve, or spline object

Inverse Kinematics – IK is when controlling a joint at the end of a chain affects the orientations of the joints above it

Joint – The term in Maya for the basic skeletal unit in rigging. A joint is essentially a pivot point that can be attached to other pivot points to simulate the behavior of a skeleton

Lattice – A type of deformer that provides a geometric cage around an object, which can be manipulated in order to adjust the overall shape of the object contained within the cage

Longirostrine – A term describing crocodylians with long narrow jaws adapted for fish eating. This includes both gavialoid crocodylians and relatives of *Tomistoma*

Manus – Anatomical terminology for the structural equivalent to the human hand

Mask – An image that is used to create a "cutout" in another image, by rendering portions of the second image transparent according to the pattern on the mask image

MEL – Maya Embedded Language is Autodesk Maya's internal scripting language

Mental Ray – A high end rendering engine based on ray tracing

Mesotarsal Joint – A type of ankle joint where movement is possible between the ankle bones and the tarsal bones

Metamorphic Rock – Rock formed when heat and pressure turns one type of rock into another

Next Limit RealFlow – A software application that specializes in liquid, gas, and other dynamic simulations for computer graphics

NJSM NH 2005.2 – The catalogue number of the *Thoracosaurus neocesariensis* that was reconstructed and restored throughout the project

Normal Map – An image in UV space that uses the three red, green, and blue channels of an image to fake lighting on a surface in order to emphasize surface details

NURBS – Non Uniform Rational B-Splines are a way of representing perfectly smooth curves and surfaces in computer graphics

Orthographic Image – A flat, two-dimensional representation of a three-dimensional object to depict the shape of that object from a certain angle, without perspective

Osteoderm or Scute – The dermal armor of bony growths found embedded in the skin of many reptiles

Osteology – The scientific study of bones

PAIE - Python Attribute Import/Export is a custom python script built for transferring animation between rigs. The script is authored by Jakob Welner

Paleoart – The scientific or naturalistic rendering of paleontological subject matter pertaining to fossils

Paleoart Reformation Period – A period from about 1900-1910 where paleoart finally established itself as being a legitimate partner to science

Parallax – An appeared change in position of an object based on a change of perspective

Paraphyletic – A type of phylogenetic grouping that contains some but not all of the descendants of an ancestor

Parent – A higher level node in a hierarchy that passes properties on to the nodes underneath it

Parent Constraint – In Maya, a node that is attached to an object that allows for its position, rotation, and size to be determined by another object

Particle System – A dynamic system in computer graphics that allows for control over a large number of small similar objects

Permineralization – A fossilization process where ground water carrying dissolved minerals enters the remains of an organism and fills the empty spaces within

Pes – Anatomical terminology for the structural equivalent to the human foot

PET – Polygon Editing Tool is a software program used for scanning and stitching together point cloud data

Phylogeny – The evolutionary history of an organism

Pixologic ZBrush – A three-dimensional sculpting and painting application

Point Cloud – A set of vertices defined in three-dimensional (x, y, z) space that represent points on the surface of an object

Polygonal Mesh – A type of geometric surface comprised of a number of polygonal faces, known as polygons

Pose-to-Pose - An animation workflow that requires setting up all the “key” poses of a shot, timing them out, and letting the system compute what happens in between. It then requires systematically adding more poses in between (breakdowns) to help guide the computer’s interpolated motion.

Posterior - Anatomical directional terminology referring to the back or behind of the body

Proximal - Anatomical directional terminology referring to something that is closer to the torso of the body

Python – A commonly used programming language in many computer graphics applications. It is offered as an alternative to MEL within Maya

Reconstruction – A type of paleoart that involves reconstructing skeletons. This can be in the form of drawings, paintings, models, or even setting up display mounts. This also includes creating stand-ins for missing parts

Registration – The process of combining multiple scan data together so that they match up appropriately. There is both manual and global registration within Geomagic Studio

RenderMan for Maya – A version of Pixar’s award winning RenderMan rendering engine that is integrated into the Maya workflow. This was the primary rendering engine used for the project

Restoration – A type of paleoart that displays how organisms appeared in life

Rig – The underlying structure and control objects that are used to pose and animate a character, creature, or object in the production of computer animation

Rostral - Anatomical directional terminology referring to the nose

Sacral - Anatomical directional terminology referring to the pelvis

Sedimentary Rock – Rock formed from the deposition and consolidation of loose mineral and organic particles

Side Effects Software's Houdini – A high-end 3D modeling and animation application that is specialized for procedural workflows

Skin Deformer – A type of deformer that simulates skin by attaching geometry to multiple joints of a skeletal rig

Spinous Process – The dorsal structure on vertebrae used for muscle attachment

Spline – A curve whose shape is defined by smoothly interpolating between the positions of key controls points along that curve

Straight-Ahead – An animation workflow where an animator starts at the beginning of the shot, and animates each beat as it comes, chronologically. This allows the process of animating to help inform decisions and discover new solutions

Superficial - Anatomical directional terminology referring to something that is closer to the surface of the body

Surface Shader – A shading model that does not simulate the affects of light

Taphonomy – The study of the post-death processes that happen to an organism

Taphonomic Bias – The idea that some organisms preserve better than others due to morphology

Thoracosaurus neocesariensis – The species that is the focus of this project's reconstruction and restoration. It was a gavialoid crocodylian found in the late Cretaceous and early Paleocene deposits of New Jersey

Transverse Process – The structures on vertebrae where the ribs attach

Use Background Shader – A shading method that renders an object and anything it is overlapping as transparent. It is very useful when rendering multiple image sequences for use in the compositing process

UV Mapping – A geometric object has two sets of coordinates. There are the basic x, y, and z coordinates which define its position in space, and then there is the u and v coordinate system, which defines the surface of the model. Mapping UVs allows one to control the layout of the UV coordinates to make the texturing process more intuitive.

Ventral - Anatomical directional terminology referring to the belly

Vertex – A point that defines where two edges of a polygonal face meet

ZBrush Alpha – A black and white image that controls depth based on the grayscale value of the image. It is used to affect the shape of sculpting and painting brushes in ZBrush