

COMPUTER ANIMATION OF QUADRUPEDAL LOCOMOTION

A Thesis

by

THOMAS LANCE THORNTON

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2004

Major Subject: Visualization Sciences

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ABSTRACT

Computer Animation of Quadrupedal Locomotion. (December 2004)

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A discussion of the theory and methodology for creating believable quadrupedal locomotion for computer animation applications. The study focuses on a variety of issues related to producing realistic animal gait animations and includes a case study for rigging and animating the various gaits of a horse. Visualization of unnatural gaits for the horse will also be discussed and animated. The process of rigging involves setting up the character control system in a high-end 3d computer animation program such as Maya which is used extensively by the computer graphics industry.

DEDICATION

This thesis is dedicated to the billions of animals killed each year for the sake of human greed and gluttony. I hope that as a society we will soon begin to treat all animals with compassion and respect.

ACKNOWLEDGEMENTS

I am thankful to the Texas A&M University Horse Center for allowing me to film horses on their equine treadmill and for discussing horse locomotion with me. The reference from that film shoot was extremely valuable to my work.

I would also like to thank my advisory committee for their patience and support. Their encouragement and enthusiasm were invaluable to completing this research.

I would also like to thank the Houston Zoological Gardens for working with me to film large animals at their facility in Houston for reference. Especially Maryanne E. Toci dlowski for her support of the project and taking the time to work with the animals for filming.

TABLE OF CONTENTS

	Page
ABSTRACT.....	iii
DEDICATION.....	iv
ACKNOWLEDGEMENTS.....	v
TABLE OF CONTENTS.....	vi
LIST OF TABLES.....	viii
LIST OF FIGURES.....	ix
1. INTRODUCTION.....	1
1.1 Statement of Purpose.....	3
2. BACKGROUND AND REFERENCE MATERIAL.....	4
2.1 Ancient References.....	4
2.2 Modern Locomotion Research.....	5
2.3 Computer Graphics and Animation References.....	6
2.4 Video Research.....	7
3. DEFINITIONS.....	9
4. CHARACTER SETUP.....	14
4.1 Building the Skeleton.....	14
4.2 Rigging Inverse Kinematics.....	16
4.3 Manipulation Handles.....	17
4.4 Scripted Controls.....	19
4.5 File Referencing.....	21
5. ANIMATION METHODOLOGY.....	22
5.1 Understanding Animal Locomotion.....	22
5.2 Gait Animation Methodology.....	24
5.3 Unnatural Gaits.....	29

	Page
5.4 Application to Other Species.....	32
6. FUTURE DIRECTIONS.....	33
7. SUMMARY.....	35
REFERENCES.....	36
APPENDIX A DESCRIPTION OF ANIMATION CLIPS.....	38
APPENDIX B MEL SCRIPTS.....	39
VITA.....	43

LIST OF TABLES

	Page
Table 1. Quadruped gaits and relative limb phases.....	21
Table 2. Average stride times in seconds and frames.....	25
Table 3. Adjusted frame ranges based on number of gait beats.....	27
Table 4. Relative offsets from hip for base and tip of head and tail joints.....	29

LIST OF FIGURES

	Page
Figure 1. Cave painting from Dordogne, France. 15,000 B.C.E.....	4
Figure 2. One full stride of a canter.....	9
Figure 3. One full stride of a single suspension gallop.....	11
Figure 4. Two points of suspension in the double suspension gallop.....	11
Figure 5. One complete stride of a trot.....	13
Figure 6. One half of a walk stride.....	13
Figure 7. The skeleton of a horse.....	14
Figure 8. Virtual quadruped rig representing major skeletal bones.....	15
Figure 9. IK setup (highlighted in red).....	17
Figure 10. Perspective and side views of the manipulation handles.....	18
Figure 11. Frames one and eight of the double suspension gallop.....	31

1. INTRODUCTION

This thesis describes a methodology for rigging a quadruped for computer animation applications, and a method for animating many of the natural and unnatural locomotion gaits. The process of rigging involves setting up the character control system in a high-end 3d computer animation program such as Maya which is used extensively by the computer graphics industry. The animation section shows the rig in use and discusses techniques for producing a variety of gait motion cycles.

Computer animation and special effects are becoming increasingly popular in the film and entertainment industry. The growing popularity of virtual creatures in film and video games increases the demand for methods to produce believable looking animation. Virtual creatures are normally based on real world animals or a combination of animals. While these synthetic creatures may have their own unique look or behavior, the motion must ring true in order for an audience to suspend disbelief. That is, the movement must resemble or caricature something an audience member can identify from the real world. For example in the film *Jumanji*, the computer animated elephants, rhinos, and other large animals needed to move like their real life animal counterparts. The dinosaurs in *Jurassic Park* were artistic representations of extinct species, but many moved like large elephants. This idea extends to completely make believe animals like those in *Star Wars* movies. These imagined creatures must also move in a manner that an audience can identify in order to invoke a sense of realism.

This thesis follows the style and format of the *ACM Transactions on Computer-Human Interaction*.

The goal of the rigging process will be to create a system that can be used to animate a quadruped efficiently and with enough flexibility for a variety of motions. The rig includes a bone and joint structure that represents the animal as well as manipulation handles to control the actions of the quadruped during animation. The animation process will focus on recreating many of the different gaits of quadrupeds using the developed rig. A discussion of gaits and how to animate them efficiently is included. Custom tools to speed up the gait animation process were coded and are included in the appendices of this thesis.

Many of the natural gaits of a horse are animated, such as the walk, trot, pace, canter, and gallop. Unnatural gaits are also discussed and animated, such as a skip and double suspension gallop. This shows the versatility of the rigging system and uses the technology to visualize actions that cannot be seen in nature.

The art of animation is more than an exact replication of what we see in real life. It is a stylized artistic interpretation of motion. It is a two dimensional medium representing a three dimensional action with a finite number of discreet time periods per second. All of the traditional principles of animation apply to animal locomotion to create an illusion of life. A discussion of some of these principles is included in the animation methodology section.

This thesis addresses many of the problems for creating believable motion in the relatively new artistic medium of computer animation. It addresses the technical and artistic concerns for animating the locomotion methods of quadrupeds. Though the rigging system and animation methodology discussed are primarily oriented toward animators, character technical directors will also benefit from the ideas discussed.

1.1 Statement of Purpose

The intention of the research presented in this paper is to produce a character rigging system and an animation methodology for animating the various locomotion gaits of quadrupedal animals. The rigging system should be easy to manipulate, extendible, and provide some automation for the especially tedious aspects of the animation process. The rig and animation methodology should be applicable to any quadruped, though a horse will be used as the primary test case.

2. BACKGROUND AND REFERENCE MATERIAL

2.1 Ancient References

Animal motion studies have been conducted for thousands of years. Some of the earliest examples of art could actually be animal locomotion studies. A cave painting found in Dordogne, France, that dates to about 15,000 B.C.E. depicts an ancient horse galloping (Figure 1).



Figure 1. Cave painting from Dordogne, France. 15,000 B.C.E. [French Ministry of Culture and Communication 1998]

Other paintings from around the same time depict cave lions walking and woolly mammoths ambling. Though the proportions are off, this appears to be a four-beat single suspension rotatory gallop. The intent of this painting and others like it may not have necessarily been to study animal locomotion gaits, but the painters would have

surely had to think seriously about how an animal moves in order to create such artistic expressions.

Greek scientists placed horses and other large animals on wooden decks to listen to their footfalls in an attempt to better understand how the animals moved and to test for lameness. Aristotle's book *On the Gait of Animals* written in 350 B.C.E contains a scientific philosophy of how and why animals move the way they do. Countless sculptures and paintings of horses and other animals throughout our history of art depict the full range of locomotion gaits. In many examples, it is clear which gait the artist is depicting with just a single image, however many works of art depict a pattern of footfalls that do not correctly describe any locomotion gaits.

2.2 Modern Locomotion Research

Scientists have also been studying this subject, especially recently. It was only in the last 120 years that advanced film tools were available to capture live animals in motion to aid scientific analysis. With his photographic work in the late 1800's, Eadweard Muybridge pioneered the study of recording how animals move. He photographed many species including horses, elephants, lions, and camels moving in a variety of gaits and performing many different actions. His black and white photography cataloguing a variety of animal gaits and actions was a huge leap for the science of analyzing animal locomotion. More recently, animals have been filmed with high-speed cameras in their natural habitat to capture faster movement at higher frame rates. Muybridge's photographic images and high speed video from a PBS series were used extensively as reference during animation and are referred to throughout this thesis.

A large body of material on the study of quadruped gaits can be found in the horse and dog training disciplines. Henry Wynmalen presents a breakdown of all horse gaits in *The Horse in Action: A Unique and Exact Portrayal of the Movements of the Horse*. He carefully describes the differences between ideal and actual gaits. Most animals have slight variations in timing for all the gaits that make them unique [Wynmalen 1954]. Show dogs and riding horses are trained to walk specific gaits, some of which would never be performed by those animals under natural conditions. The foxtrot and the Tennessee walk are examples of unnatural gaits that horses have been trained to utilize because they either look nice to us or are comfortable to ride [MFTHBA 2003]. Additionally, some horses have been bred over many generations to employ some of these gaits as their natural gait [Osborne 2004].

Extensive research into locomotion can be found in the modern field of robotics. Not only must locomotion be recreated by something we design, but it also must really work. The robotics industry analyzes animal gaits to find locomotion solutions for synthetic creatures to see how motion might be reconstructed [Oricom 2001]. An even more intimate understanding of biomechanics is required to achieve goals in this discipline.

2.3 Computer Graphics and Animation References

The animation medium has many great examples of gait locomotion. Classics like *Bambi* (1942) and *The Jungle Book* (1967) from Walt Disney Pictures were groundbreaking achievements in the art of animal gait animation. Live animals were brought into the studio to be used for reference during the animation process which

emphasizes how critical it is to use nature as reference even for very stylized art [Thomas and Johnston 1981].

As computers become involved in the medium of animation, much research was done to speed up the process of animating animal gaits. Algorithmic approaches have been developed to create movement based on the laws of physics and biomechanics. Sun and Metaxas presented an automatic gait generator for bipeds that deals with curved motion paths and uneven terrain. One goal of this work is to remove the task of animating tedious gaits from the animator or to automate the process of animating hundreds or thousands of creatures in a scene [Sun and Metaxas 2001].

Motion capture is another modern method of generating gait animation quickly. Motion can be captured using video cameras and computers and then applied to virtual creatures. However, this process can be difficult for untrained or wild animals which makes motion capture more useful for capturing human actions. Motion capture animation also is not stylized nor staged as clearly as traditional animation therefore it often has to be adjusted manually [Furniss 1999].

2.4 Video Research

Understanding how an animal is constructed and how it moves is central to creating a believable caricature of that animal's movements. Part of the background research for designing a rigging and animation system was to discuss locomotion with animal handlers and veterinary experts. Video reference was filmed on location at the Houston Zoological Gardens of various large animals. It was possible to discuss locomotion and anatomy with the trainers and veterinary staff as the animals moved.

This process allowed comparisons to be made concerning the same gaits for a variety of quadruped body structures.

Additional reference footage was taped at Texas A&M University's Horse Center. A horse in fit condition was exercised on the equine treadmill and filmed by the author. The animal handlers were able to encourage the horse to use the walk, trot, canter, and single suspension gallop gaits for filming. A variety of shutter speeds were used to capture the horse's motion to ensure quality reference material.

Another film shoot involved visiting an antelope reserve near Bryan, Texas to film antelope. The footage shot on location was not as useful as the orthographic views filmed at the zoological gardens and equine treadmill, but it was possible to film the rare "pronking" motion which is a gait involving only one beat.

3. DEFINITIONS

The following is a list of terms used in this thesis which may not be familiar to the reader.

amble – there is a good bit of inconsistency regarding this term in the literature surveyed. It is sometimes referred to as a pace or even a walk variation, but for purposes of this thesis, it is defined as a two-beat gait in which the lateral limbs are moved forward in unison. There are always at least two limbs touching the ground at once therefore there are no points of suspension.

canter – the only three-beat gait where a hind limb strikes the ground followed by one hind and one fore limb in unison followed by the other fore limb, then a brief period of suspension (Figure 2).

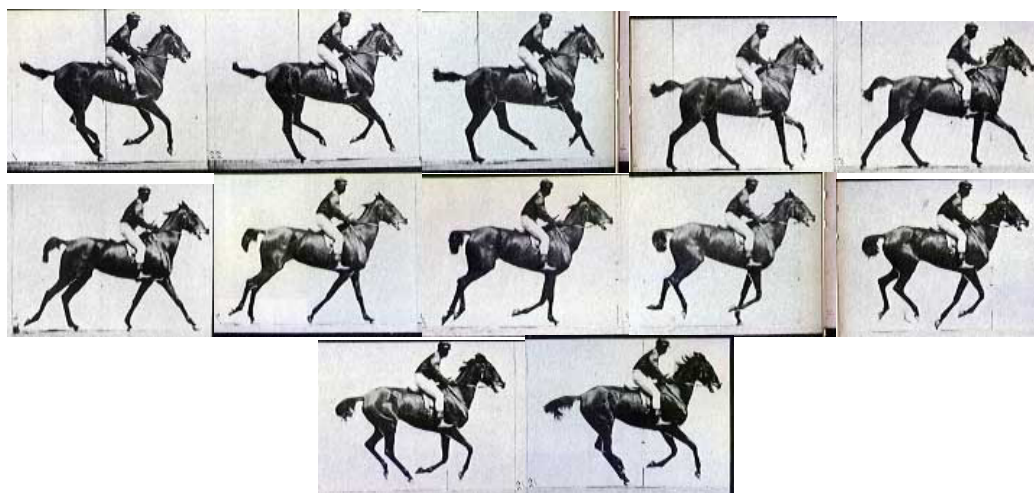


Figure 2. One full stride of a canter. [Muybridge 1957]

constraining – a technique used in computer animation whereby the motion and position of the constrained object is a direct reflection of the motion and position of the constraining object.

creep – the slowest form of quadrupedal locomotion. Three and sometimes four feet are always contacting the ground. The animal moves one foot at a time securing its position before moving another limb in the walk pattern of footfalls.

gait – gait is a pattern of locomotion characteristic of a limited range of speeds, described by quantities of which one or more change discontinuously at transitions to other gaits [Alexander 2002].

gallop – a four-beat gait with one or two points of suspension. A hind leg strikes the ground first followed by the other hind leg, then a fore limb followed by the other fore limb and finally a point of suspension (Figure 3). In the double suspension gallop, there is a second point of suspension after the hind legs lift off but before the fore limbs touch. This gait can be either right lead or left lead. One complete stride of a single suspension is pictured below as well as two pictures from a double suspension gallop showing the two distinct points of suspension (Figure 4).

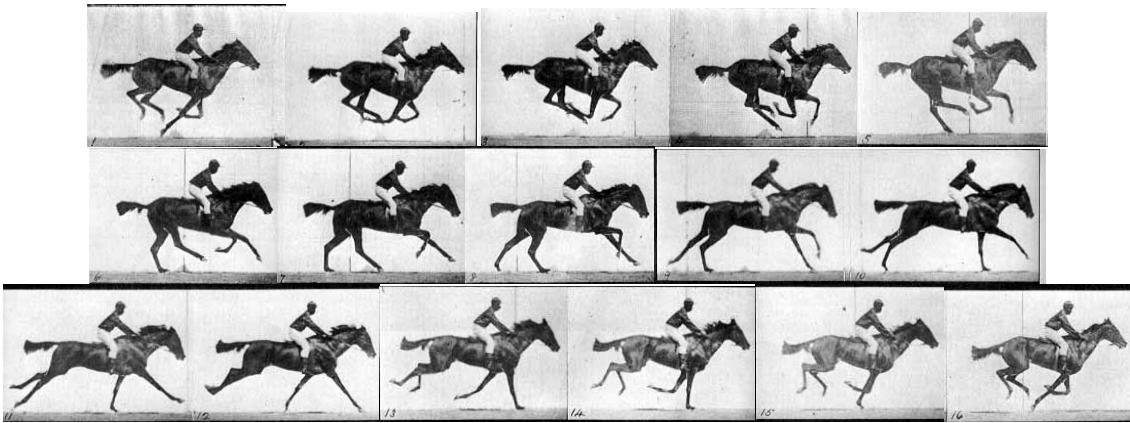


Figure 3. One full stride of a single suspension gallop. [Muybridge 1957]

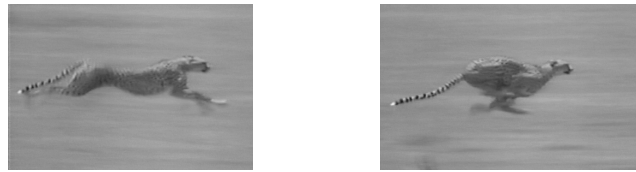


Figure 4. Two points of suspension in the double suspension gallop. [PBS 1997]

keyframe – a term originally used in classical animation, in computer animation it refers to setting the position of animated objects in space at various points in time. The computer then generates the in-between frames using linear or other forms of interpolation.

key poses – the drawing or drawings that show what is happening in the shot [Williams 2001]. These are the primary poses that best communicate the action being described.

pace – a two-beat gait similar to the trot except that instead of diagonal limbs touching the ground in unison, the lateral limbs touch in unison. This gait is sometimes described as a rack, or simply a variation of the trot.

pronk – a one-beat gait of locomotion where all four feet strike the ground in unison. Not normally employed by quadrupeds except by certain species of antelope.

step – the act of lifting one limb off the ground, moving it, and placing it back on the ground, normally forward in space from where it was lifted.

stride – the complete movement from the point of one foot striking the ground, leaving it, and then striking the ground again.

traditional animation – also referred to as cel or classical animation. This is the form of animation where pencil and ink drawings are created for each frame of animation and then inked with color on acetate film. Many of the founding principles of animation were defined with this medium and can be applied to computer animation projects.

trot – A two-beat gait where the hind and diagonal fore limb strike the ground in unison followed by a point of suspension, then the opposite diagonal limbs strike the ground followed by a second point of suspension. A trot is pictured below (Figure 5).

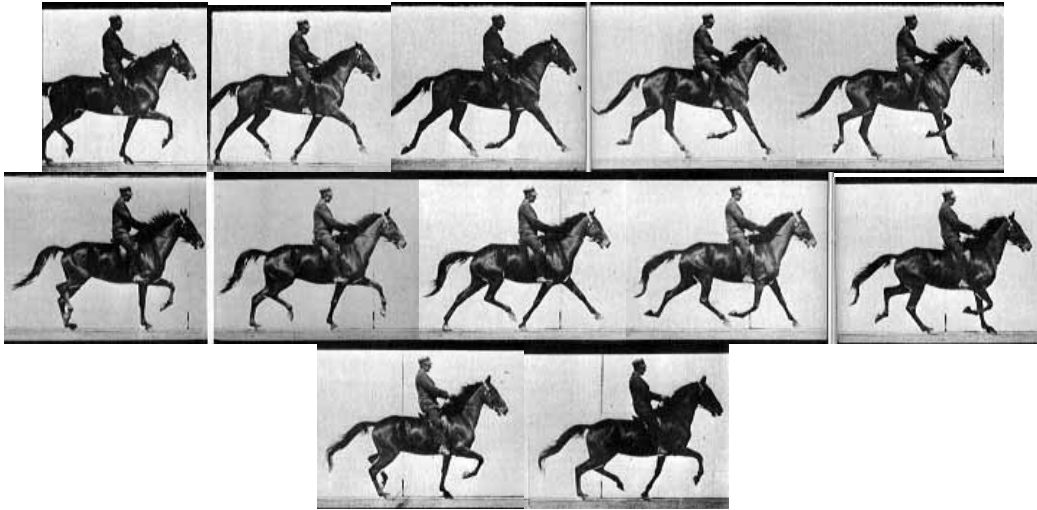


Figure 5. One complete stride of a trot. [Muybridge 1957]

walk – A four-beat gait where each foot strikes the ground independently of the other three. At a walking gait, the quadruped never has more than three nor less than two feet bearing weight at the same time. Half of a walk cycle appears below (Figure 6).

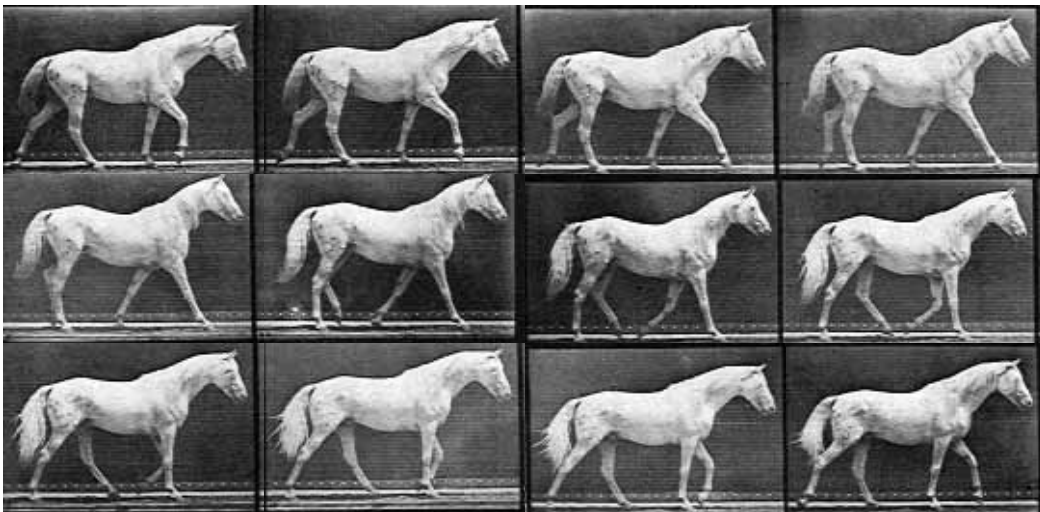


Figure 6. One half of a walk stride. [Muybridge 1957]

4. CHARACTER SETUP

This section discusses the character setup portion of the research including building the skeleton, rigging tools, manipulation handles, and scripts for simplifying animation.

4.1 Building the Skeleton

The process of animating a quadruped starts with a good character rig. The rig must be complex enough to work for a variety of actions, but also be simple and intuitive to manipulate. The rig is built with joints that represent the underlying skeletal structure of a horse. Figure 7 is a reference skeleton of a horse from *New Rider* that was used for constructing the rig.

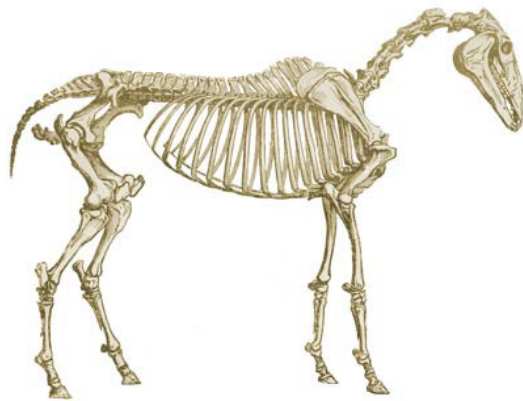


Figure 7. The skeleton of a horse. [New Rider 2004]

A certain artistic license must be taken when setting up the virtual skeleton. While it is straightforward to create 36 individual vertebrae for the spine and neck of the horse, it would be challenging to both rig and animate that many individual joints. The same is true for the average of 18 bones for the tail. Far fewer joints are needed to give an impression of flexibility in those regions which makes the animation process far simpler. Additionally, the rig is intended to be reused for a variety of quadrupeds that have varying numbers of spine and tailbones. Figure 8 shows the rig as constructed in the computer with Maya with the major bones represented and a reduced number of bones in the spine, neck and tail regions.

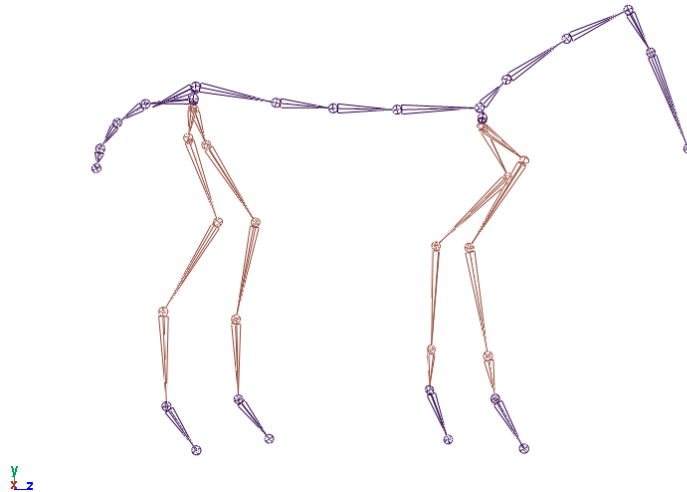


Figure 8. Virtual quadruped rig representing major skeletal bones.

Three neck, four spine, and four tail joints proved adequate for overlapping motion. This should be sufficient for other animals, with the exception of extremely disproportionate animals like the giraffe or perhaps the camel, which would need more bones for animating overlapping motion. Inserting additional bones in the quadruped rig

is simple and will not affect the manipulation tools or rig design. Further liberties are taken by eliminating the rib cage which is for all practical purposes inflexible and therefore not animated.

4.2 Rigging Inverse Kinematics

Inverse kinematics or “IK” is an invaluable tool in animation and is part of the rig design. A definition of Inverse Kinematics and IK Handles from Maya’s online documentation [Maya 2003]:

Inverse Kinematics: In animation, a method of posing a joint chain by specifying the location in space you want the joint chain to reach. IK is the easiest way to position the end of a joint chain on a particular object or point in space, because you do not have to define how each joint needs to rotate.

IK handle: In animation, a tool for posing joint chains. An IK handle resembles a wire running through a joint chain, and enables you to pose the entire joint chain in one action. As you pose and animate the joint chain, its IK handle automatically figures out how to rotate all the joints in the joint chain using an IK solver.

IK handles are normally set up in virtual humans from the shoulder joint to the wrist joint and from the hip joint to the ankle joint. Though the metatarsal and metacarpus bones are much longer than equivalent bones in the hands and feet of bipeds, the IK handles should be placed in the same places as they would for rigging bipedal characters. This is true for all quadrupeds. The equivalent knee and elbow joints are constrained to the IK handles so animating the upper limbs is done by positioning the IK handles and setting keyframes. The IK handles are shown by lines connecting these joints in Figure 9. The rotation of the joint above the IK handle is computed

automatically. The position and orientation of the joint where the IK handle connects is determined automatically by the distance from that joint and the last joint of the chain (the end of the limb). The joint beyond the IK handle is animated manually.

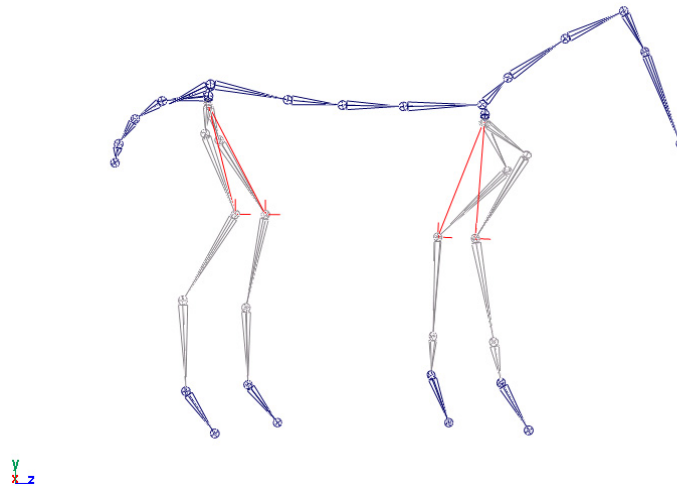


Figure 9. IK setup (highlighted in red).

4.3 Manipulation Handles

The quadruped rig could be animated as is, but a great improvement to the rig is to add manipulation handles. These are simple boxes, cones, and other shapes that correspond with parts of the rig that are intended to be animated. This is a widely used industry standard and an important part of the rigging process. From an animator's perspective, these handles are an extra layer of abstraction, simplifying the complexity of the model. The animator only need be concerned with the manipulation handles when animating, safely ignoring all joints and controls that have no handles. From a technical director's perspective, it is a way to communicate to whoever animates the character by assigning handles only to objects intended to be animated. Additionally, some joints

need to be protected so that expressions and other behind the scenes tools will work properly. Handles will also be the placeholder objects for all animation keyframes and the controller for some of the automated tools discussed below. The manipulation handles for the rig are shown in Figure 10.

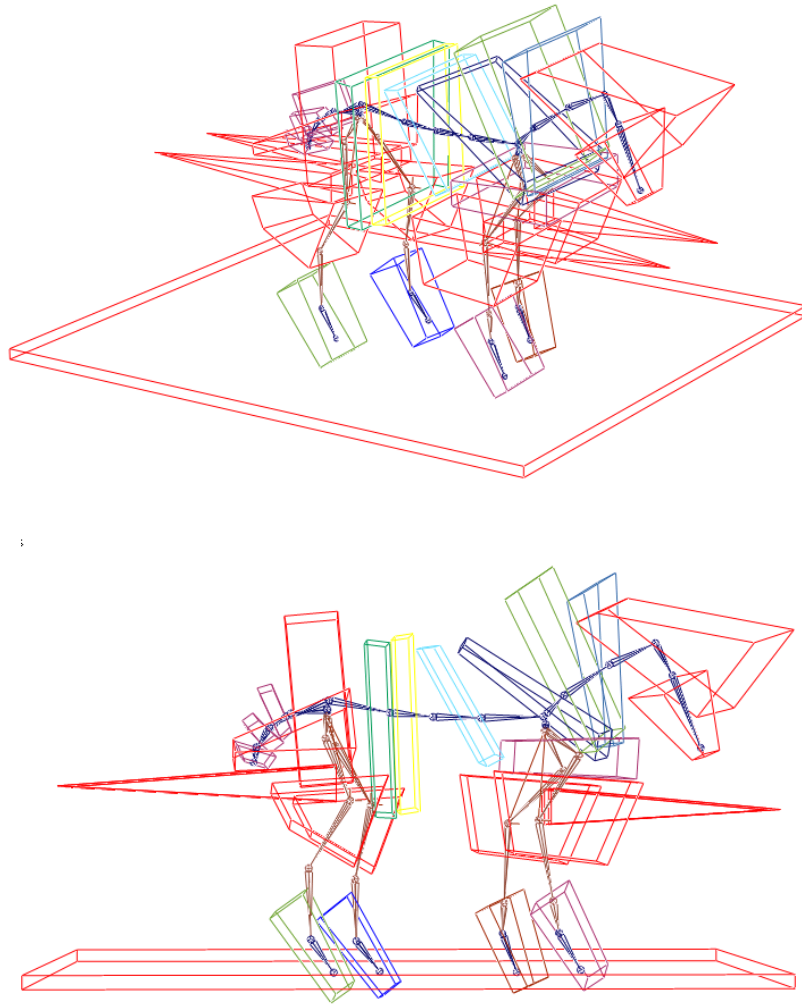


Figure 10. Perspective and side views of the manipulation handles.

The addition of manipulator handles clarifies exactly what is intended to be animated. Each spine, neck, and tail joint has its own manipulator handle. The hips, shoulders, fore and hind feet each have handles. The IK controls at the elbow and knee joints have a control handle, but since IK handles are not meant to be rotated, the rotation channels are locked so they cannot accidentally be animated and cause problems. The pole vector of the IK handle has its own cone shaped manipulation handle that determines the orientation of the shoulder or hip joint if it needs to be adjusted. This would only need to be animated if the orientation computed by the IK solver needed to be guided manually. An overall handle to move the entire character around without affecting joint animation is represented by the flat box below the character. If facial expressions were to be animated, additionally controls would exist in the head for the ears, eyes, mouth, etc.

4.4 Scripted Controls

To speed up the animation process, four scripts were created to be used as needed during animation. These scripted controls are only applied when desired via a button in the interface so that they do not interfere when not necessary. These are:

1. Center Hip
2. Center Shoulder
3. Copy Fore Limb Animation
4. Copy Rear Limb Animation

All of the scripts were written in MEL, a scripting style programming language in Maya, literally “Maya Embedded Language.” The first two scripts are used to center the hips and shoulders over the corresponding hind and fore limbs. This is useful for an animator to find the center point between the limbs in the X and Z-axis (where the positive Y-axis is pointing up and the character is positioned facing down the positive Z-axis) which aids in ensuring the animal’s weight is balanced properly above its legs. This is often cheated in the animation process for a variety of reasons but having a reference point can be valuable.

The scripts for copying rear and fore limb animation are intended to speed up the process of creating a gait animation cycle. Typically the right limbs will move in exactly the same way the opposite left limbs move, but offset in time. Table 1 shows the typical time offsets for some common quadruped gaits. The “relative phase” is defined as the “stage of the stride at which the leg is set down expressed as the fraction of the duration of the stride following the setting down of an arbitrarily chosen reference leg.” [Hardt and Stryk 2000] For example, Leg1 and Leg2 are fore limbs and looking at a trot gait where the offset of Leg1 is 0.0 and Leg2 is 0.5. It is possible to simply copy the animation of Leg1 to Leg2 with an offset of half the number of frames in the scene. The X-axis needs to be multiplied by -1 to keep the leg on the correct side of the body. The Y and Z-axis are copied without adjustment. Copying animation in this manner will ensure symmetric motion and increased animator efficiency. Of course, during the animation process, the symmetry can be broken if desired but this technique gives a good starting point for fluid motion.

Table 1. Quadruped gaits and relative limb phases. [M HARDT and O von STRYK]

Relative Phases of Legs				
Gait Name	Leg1	Leg2	Leg3	Leg4
Walk	0	0.5	0.25	0.75
Amble	0	0.5	0.5	0
Trot	0	0.5	0	0.5
Pace	0	0.5	0.5	0
Canter	0	0.3	0	0.7
Transverse Gallop	0	0.1	0.6	0.5

Code for centering the hip and shoulder joints and copying animation is available in Appendix B.

4.5 File Referencing

The final issue to set up with the character rig is the file referencing structure. Each animation cycle will be stored in a separate file, and it is desirable for all of these files to use the same model instead of having a local copy of the model in each file. This allows any refinements to the rig to be done in one place, rather than in many places. The phase of setup is a standard industry practice and should be included in the rigging process.

5. ANIMATION METHODOLOGY

This section describes factors for creating believable animal locomotion using the character rig presented above. Animation techniques used to animate the horse gait cycles are presented in detail.

5.1 Understanding Animal Locomotion

Humans have been studying how animals move for thousands of years. Computer animation is the next logical step in the modern research of understanding how animals move. To break down an action to a point where one can reconstruct it through drawings or computer images one frame at a time requires an intimate understanding of that motion. To animate an action, one must feel the movement, feel the forces at work, and understand the timing as weight shifts. Since people cannot actually perform the gaits of quadrupeds, careful observation in nature is required as well as studying photographs of the movement. The process of animation is one of the best ways to truly understand how a quadruped moves.

All four legged mammals and reptiles have the same potential locomotion gaits, with very few exceptions. These are the creep, walk, amble, trot, pace, canter, and gallop. The first three are slower paced movements with no points of suspension. That is, there is never a moment where the animal is unsupported by a limb. The trot and pace are symmetric two-beat gaits with 2 points of suspension as the legs change. The canter and gallop are not symmetric and can be led with either the left or right side. The canter is a three-beat gait with one point of suspension. The gallop is a four-beat gait

with one or two points of suspension. Both the canter and the gallop footfalls can be in either transverse order meaning a hind limb is followed by a diagonal fore limb footfall, or in rotatory order meaning a hind limb will be followed by a fore limb on the same side of the body.

Understanding the biomechanics of how gaits work for an animals is extremely valuable to the animation process. In order for an animal to go faster, either it must take more steps per unit of time or it must take bigger steps. Consider this explanation of a stride from Jamie Larsen (2000) for PBS:

A stride is a complete movement from the point of one foot striking the ground, leaving it, then striking the ground again. Stride length is the distance traveled in one stride. A horse has a maximum stride length of about seven meters, a stride rate of about 2.25 strides/second and a top speed of about 70 km/hr. A cheetah, which is much smaller than a horse, has a stride length that is about the same as that of the horse; but the cheetah has a stride rate of about 3.5 strides/second and a top speed of about 110 km/hr.

It is interesting to note that a cheetah's stride length is about the same as a horse which is a much larger animal. It does this by extending the scapula forward and bending at the spine to achieve a much longer stride length. When animating the gaits, this is an important idea to understand. Slower gaits do not show much motion in the upper limbs. Most of the reaching happens at the knees or elbows and below. Faster motions like the double suspension gallop require maximum stretching at the shoulder and hip regions and bending of the spine if possible.

5.2 Gait Animation Methodology

The character rig developed for this thesis was used to animate a selection of natural and unnatural gaits for a horse. In this section, the general techniques used are described as well as the specific problems for animating certain gaits are detailed. The animations for this thesis are included as separate movie files described in Appendix A.

The first step in animating each locomotion method is to study the reference material available for that gait. The Muybridge photographic reference plates and the video footage are extremely valuable in understanding where the weight is distributed and how it is transferred to each limb as the animal moves forward. The motions were studied by observing the relative positions of the limbs, head, tail, and spine as well as physically acting out the motions. Acting out a four legged animal gait can be done by either crawling or by swinging arms in the air to mimic the fore limbs of an animal touching the ground.

The next step is to work out the timing of the motion. The Muybridge plates have times associated with each plate but the first and last photographs do not always match exactly so a sequence may contain slightly more or less than one complete stride. The video reference footage is more useful for working out the timing. Using the time code from the video footage, it is possible to get an accurate average time duration for one complete stride. To find an average stride time, the time code at the beginning of the stride was noted for each gait. Then, the video was advanced while counting 50 complete strides and the ending time code was again noted. The total time was then divided by 50 to find an average stride time. This was done for each gait where video footage was available. In some cases, more than 50 complete strides were filmed and a

larger sample size could be used to determine average stride times. Table 2 shows average stride times for each gait and the corresponding frames necessary assuming thirty frames per second. Data for the pace is assumed to be the same for the trot since the gait is essentially the same with mirrored fore limbs. Data for the double suspension gallop is taken from a more limited frame range of a cheetah.

Table 2. Average stride times in seconds and frames.

Gait	Stride Samples	Avg. Stride Time	Frames
Walk	52	1.154	34.61
Trot	50	0.626	18.78
Pace (from trot)	50	0.626	18.78
Canter	60	0.518	15.55
Gallop	50	0.458	13.73
Double Susp. Gallop	20	0.386	11.58

Translating these times into frame ranges for animation presents a significant problem. When the images are output to video, only whole number frames will be visible. The key poses that are animated should be on whole frame numbers that will end up in the final pictures, not on fractional frames. The reason for this is that the computer will be interpolating the motion in between the key poses that are set for animation. Generally, these key poses will better communicate the spirit of an action than the interpolated poses. Squash and stretch techniques also rely on specific shapes at specific points in time such as an extreme stretch before ground contact, an extreme flattening on the frame of ground contact and another stretch offset from the ground after contact [Thomas and Johnston 1981]. An interpolation between these key poses will

destroy the squash and stretch effect. Therefore, we need to work with whole numbered frames that will show up in the final work.

Additionally, the frame range should be evenly divisible by the number of beats in the gait so that the action will appear smooth and symmetrical. For example, the trot averages 17.175 frames which would be rounded to seventeen whole frames. The trot is a two-beat gait with two phases of motion that are mirror images of one another. In the first phase, the near fore limb and off hind limb carry the horse forward and push off to propel the horse into the air for the first period of suspension. In the second phase, the opposite fore and hind limbs repeat this exact movement. If nine frames are given to the first phase and only eight frames to identical motion in the second phase, the horse will appear to speed up and slow down unnaturally when that animation is cycled. Using sixteen or eighteen frames allows the motion between both phases to be split evenly which will create smoother animation. This concept is true for the four-beat gaits like the walk and gallop. In these gaits, each of the four limbs moves independently in succession. Using a frame range that is evenly divisible by four will result in the smoothest animation so that each limb gets the same number of frames to complete its range of motion. The canter is the only three-beat gait and should be given a frame range divisible by three. Table 3 contains the adjusted frame ranges used based on this concept.

Table 3. Adjusted frame ranges based on number of gait beats.

Gait	Gait Timing	Avg. Frames	Adjusted Time in Frames
Walk	4-beat	34.61	36
Trot	2-beat	18.78	20
Pace	2-beat	18.78	20
Canter	3-beat	15.55	18
Gallop	4-beat	13.73	16
Dbl Susp. Gallop	4-beat	11.58	12

After studying the motion carefully and planning the frame range, the animation process will proceed more efficiently. The root joints of the character are animated first, then working down the hierarchy to the ends of the limbs, head, and finally the tail. All animation higher in the hierarchy will affect joints lower in the hierarchy so working top down reduces the amount of potential reworking to be done as revisions are made. For example, moving the shoulder joint will also move both fore limbs because they are children of the shoulder in the hierarchy. If the limbs are animated first and adjustments are later made to the shoulders, then the fore limb animation must be redone since the ground contact points and other relative positions will have changed. The up and down motion of the spine is the first priority. For a walking gait, the slight up and down motion of the hips and then the similar motion of the shoulders is animated. Next, the left to right rotation in the Z-axis when the legs will be directly beneath the hip or shoulders is added. The limbs are animated next by creating motion for one hind limb and one fore limb and then copying that animation to the other fore and hind limbs based on the relative phase offsets from *Table 4*. Using a frame range evenly divisible by the

gait beat type ensures every limb will use the same number of frames to complete its motion which simplifies the process of copying animation from one limb to another.

The gaits with points of suspension are more difficult because a sense of weight must be communicated to the audience. The animal lifts itself in the air briefly and then catches its weight on the appropriate limbs. Making the creature feel heavy as it lands is an important part of selling the animation. The root hip joint is animated as if it were a bouncing ball. This means a slow ease-in and ease-out from the high point in the air and a quick, but exaggerated cushion upon contact with the ground. The squash and stretch principles should also be used here to give the creature more life [Williams 2001]. Extending the limbs before impact stretches the animal out and exaggerating the body distance to be close to the ground for one frame will give a sense of squashing. This needs to be exaggerated more based on how high the animal is “bouncing” off the ground. A trot and pace change height much less than a canter or gallop and therefore needs less squashing and stretching.

The head and tail are animated after the limbs and should have believable overlapping motion especially for gaits with suspension. The head and tail should translate up with the body but should occur later in time. How much later depends on the speed at which the animal is moving up and down. *Table 4* shows the frame offsets for the head and tail versus the root hip joint for each type of gait. The head and tail consist of several joints in a chain that are again offset from one another in time. The tip or last joint of the head and tail joint chains are offset by more frames than the root joint of the chains.

Table 4. Relative offsets from hip for base and tip of head and tail joints.

Gait	Root Frame Offset	Tip Frame Offset
Walk	0	1
Amble	0	1
Trot	1	2
Pace	1	2
Canter	2	3
Gallop	1	3
Dbl Susp. Gallop	N/A	N/A

Note that though the canter is an overall faster mode of locomotion than the trot or pace, but the up and down motion is slower so the offsets are longer. This is because for each stride, there are two points of suspension for the trot and only one for the canter so the horse is moving up and down more slowly when cantering. In the double suspension gallop, the cheetah barely moves its head or tail at all so overlapping motion is minor if present at all.

To cycle the motion, all positional keyframe values at frame one are copied to one frame beyond the last frame of animation. This ensures the animal will return to its start pose at the end of the animation so looping the cycle will be seamless.

5.3 Unnatural Gaits

A double suspension gallop and skip were created for the horse as part of the animation process. This was done to show the usefulness of this rigging structure and computer animation in general for visualizing motion that cannot be seen in nature. A horse's spine is normally not flexible enough to perform a double suspension gallop.

This mode of locomotion is used only by the fastest moving creatures to maximize stride length and increase top speed. This is a very difficult motion to animate successfully for several reasons. First, a complete stride occurs in less than half a second so the poses must be easily interpreted to communicate the action clearly. It helps to ease in and out of key poses that clearly describe the action such as the points of maximum stretching and compression in frames one and eight in Figure 11 below. Second, even though the number of frames is less than half of the walk, about the same number of keyframes are needed to move the creature through the poses of the gait. The walk animated required 126 total keyframes in 32 frames counting all keyframes for all joints. The double suspension gallop required 116 keyframes in only 12 frames of animation. This is because the animal still has to move its limbs through the full range of motion and because the motion is so extreme, the interpolation between frames frequently requires manual cleanup.

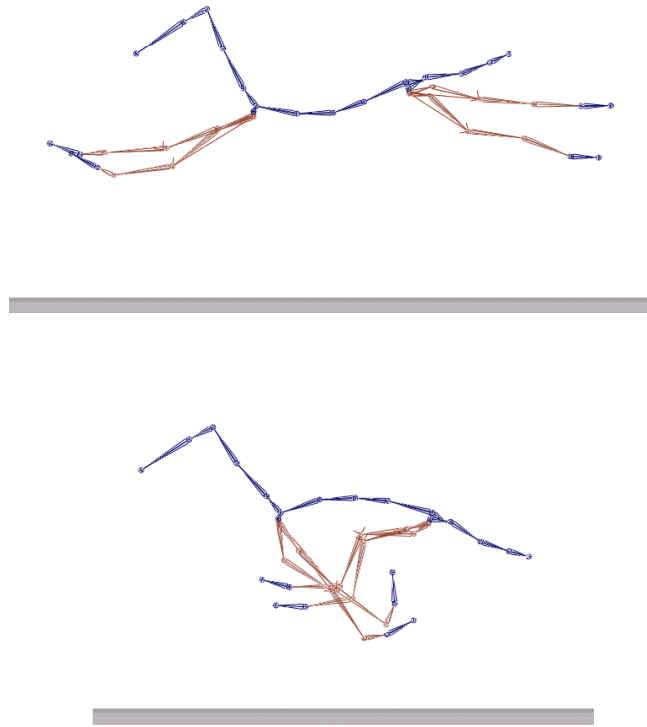


Figure 11. Frames one and eight of the double suspension gallop.

The skip gait is more challenging. Not only is the skip gait a type of motion that is unnatural to a horse, there are no quadrupeds ever recorded employing this type of motion. Only humans use this gait. Therefore, unlike the double suspension gallop where references from another species of quadruped can be used, the only reference for this comes from bipeds. Study of this motion reveals that it is based more closely on the walk pattern of footfalls than on a pace pattern as might be expected given its speed and lateral nature. It is a four-beat gait where the lateral limbs move in unison hopping once in mid step. The hop occurs after the limbs pass beneath the center of gravity but before

reaching their maximum backwards reach. The hop lands in front of the center of gravity but behind the maximum forward reach. These observations were collected from acting and filming the skip and were applied to the horse animation. Animation of the skip followed the process above, first animating the spine to achieve the up and down hopping motion, then proceeding to the limbs, head, and tail. The right limbs were animated first, and then copied to the left side using the MEL scripts described previously.

5.4 Application to Other Species

For any given species, a walk, trot, gallop, or any other locomotion method has the same pattern of footfalls and the same relative timing for each footfall. The principles discussed for each gait type apply to animating other types of creatures, including animals that are not unguligrade. If animating an animal that walks on the balls of its feet such as a feline, then the rotation of the last joint would need to be modified to align to the ground. All principles of weight transfer, timing, and balance would still apply. There would be no necessary changes to the character rig other than setting a new default rest position.

For creatures that are plantigrade such as brown bears, hedgehogs, and moles, some adjustments to the rig may be necessary. The IK setup would remain the same, but there would need to be a mechanism for rolling the foot off the ground so that the animal could contact with its heel for a while then roll to the ball of the feet as it lifts up. This could be manually animated but it would be tedious and time consuming so an automated tool added to the rig would be highly desirable.

6. FUTURE DIRECTIONS

There are many opportunities for additional research in the area of computer animated locomotion of quadrupeds. Two- and six- or more-legged creatures are out of the scope of this thesis but could be the focus of future studies. The discipline of robotics includes extensive analysis of insects such as six-legged arachnids. Six legs allow a body to move three legs at a time and still maintain a stable foundation. This is important to machines since they do not have stabilizing muscles to maintain balance on one or two appendages. The MEL scripts written for this project to copy keyframe animation to other appendages offset in time would work for any number of limbs as long as each limb were setup in a similar manner. The IK setup would be the same regardless of the number of limbs and limb to ground contact point. However, for plantigrade creatures, you would probably want a foot align control mechanism mentioned previously to automate contact with the ground.

The gaits presented are by far the most common, but there are theoretically twenty-two different possible footfall patterns. Six possibilities for four-beat gaits, eight possibilities for three-beat gaits (half of which are mirror images), eleven possibilities for two-beat gaits (including gaits where two or three feet strike the ground simultaneously), and one possibility where all four feet strike the ground at once (one-beat gait) [Bowling 1999]. All of these could be considered in the animation methodology section but there is no need to adjust the rigging system to accommodate these various gaits.

Other motion cycles could be analyzed and animated including more unnatural gaits for different species. Elephants galloping for example could be visualized with this rigging and animation methodology. Unusual horse gaits could be animated including rare gaits like the Icelandic pony's tlt, the various gaits of the Spanish Paso Fino, or the Tennessee Walk. All are of which are specialized versions of existing gaits but have distinct movement patterns that differentiate them. These gaits are the result of selective breeding and have become natural gaits for horses of those breeds.

The transitions between gaits could be looked at as well. Quadrupeds all seem to change gaits within a single stride. Looking at how the footfalls land during a transition period could be studied and the knowledge applied to techniques for animating such transitions smoothly. Jumping, standing up, and other motions could also be discussed from an animation viewpoint.

The art of character animation is only touched on briefly here. The performance of a character is something that could be discussed at length, however this thesis is particularly focused on animating the various locomotion methods. More techniques from traditional animation than those discussed could be applied to gait animation.

7. SUMMARY

The process of animating four-legged creatures in the computer involves many complicated processes and touches on many disciplines. It is crucial to look to nature for inspiration but not to be bound by it since animation in this medium is both an analytical and artistic endeavor. A combination of scientific analysis paired with an artist's eye will produce the strongest representation of animal motion.

During the course of this thesis, the animation process strongly influenced the design and redesign of the rig. The animation process also influenced the creation of the scripts to automate aspects of creating the gait cycles. Animating a character rig is one of the best methods for debugging and improving a character rigging system.

The animation cycles verify that the rig is successful for a variety of locomotion methods. Though the structure and gaits of a horse were used for rig development and animation, the goal was to produce a character rigging system and methodology for animating any quadruped at any gait.

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APPENDIX A

DESCRIPTION OF ANIMATION CLIPS

The following are descriptions of the Quicktime animation files included with this thesis.

Walk_side.mov – Side view of the horse rig walking.

Walk_persp.mov – Perspective view of the horse rig walking.

Amble_side.mov – Side view of the horse rig ambling.

Amble_persp.mov – Perspective view of the horse rig ambling.

Trot_side.mov – Side view of the horse rig trotting.

Trot_persp.mov – Perspective view of the horse rig trotting.

Canter_side.mov – Side view of the horse rig cantering.

Canter_persp.mov – Perspective view of the horse rig cantering.

Gallop_side.mov – Side view of the horse rig in a single suspension rotatory gallop.

Gallop_persp.mov – Perspective view of the horse rig in a single suspension rotatory gallop.

DoubleGallop_side.mov – Side view of the horse rig in a double suspension transverse gallop.

DoubleGallop_persp.mov – Perspective view of the horse rig in a double suspension transverse gallop.

Skip_side.mov – Side view of the horse rig skipping.

Skip_persp.mov – Perspective view of the horse rig skipping.

APPENDIX B

MEL SCRIPTS

These scripts, written in the Maya Embedded Language are used to make the animation process more efficient. They include tools to center the hip and shoulder joints over the hind and fore limbs and scripts to copy animation from one limb to another offset in time.

```

proc centerHip() {

    // +-----+
    // This procedure averages the positions of the left and
    // right hind leg joints and places the value in the root
    // hip joint.
    // The position change is done for both the X and Z axis.
    // +-----+

    float $pos_lbt[3] = `xform -query -worldSpace -t left_backLeg_Toe`;
    float $pos_rbt[3] = `xform -query -worldSpace -t right_backLeg_Toe`;
    float $pos_lbb[3] = `xform -query -worldSpace -t left_backLeg_Ball`;
    float $pos_rbb[3] = `xform -query -worldSpace -t right_backLeg_Ball`;
    float $pos_lba[3] = `xform -query -worldSpace -t left_backLeg_Ankle`;
    float $pos_rba[3] = `xform -query -worldSpace -t right_backLeg_Ankle`;
    float $pos_lbk[3] = `xform -query -worldSpace -t left_backLeg_Knee`;
    float $pos_rbk[3] = `xform -query -worldSpace -t right_backLeg_Knee`;
    float $pos_lbh[3] = `xform -query -worldSpace -t left_backLeg_Hip`;
    float $pos_rbh[3] = `xform -query -worldSpace -t right_backLeg_Hip`;

    setAttr Hips.translateX (
        ($pos_lbt[0] + $pos_rbt[0] + $pos_lba[0] +
         $pos_rba[0] + $pos_lbk[0] + $pos_rbk[0] +
         $pos_lbb[0] + $pos_rbb[0] + $pos_lbh[0] +
         $pos_rbh[0]) / 10
    );

    setAttr Hips.translateZ (
        ($pos_lbt[2] + $pos_rbt[2] + $pos_lba[2] +
         $pos_rba[2] + $pos_lbk[2] + $pos_rbk[2] +
         $pos_lbb[2] + $pos_rbb[2] + $pos_lbh[2] +
         $pos_rbh[2]) / 10
    );
};

```



```

proc centerShoulder() {

    // +-----+
    // This procedure averages the positions of the left and
    // right fore legs and places the value in the shoulder joint.
    // The position change is done for both the X and Z axis.
    // +-----+

    float $pos_lft[3] = `xform -query -worldSpace -t left_frontLeg_Toe`;
    float $pos_rft[3] = `xform -query -worldSpace -t right_frontLeg_Toe`;
    float $pos_lfb[3] = `xform -query -worldSpace -t left_frontLeg_Ball`;
    float $pos_rfb[3] = `xform -query -worldSpace -t right_frontLeg_Ball`;
    float $pos_lfa[3] = `xform -query -worldSpace -t left_frontLeg_Ankle`;
    float $pos_rfa[3] = `xform -query -worldSpace -t right_frontLeg_Ankle`;
    float $pos_lfk[3] = `xform -query -worldSpace -t left_frontLeg_Elbow`;
    float $pos_rfk[3] = `xform -query -worldSpace -t right_frontLeg_Elbow`;
    float $pos_lfh[3] = `xform -query -worldSpace -t left_frontLeg_Arm`;
    float $pos_rfh[3] = `xform -query -worldSpace -t right_frontLeg_Arm`;

    setAttr Shoulder.translateX (
        ($pos_lft[0] + $pos_rft[0] + $pos_lfa[0] +
         $pos_rfa[0] + $pos_lfk[0] + $pos_rfk[0] +
         $pos_lfb[0] + $pos_rfb[0] + $pos_lfh[0] +
         $pos_rfh[0]) / 10 + 8.27

        // Constants 8.27 above and -20.26 below are the offsets in world
        // space of the joint positions relative to their parent joint.
        // This offset is unnecessary for the hips since it is the
        // root joint.
    );

    setAttr Shoulder.translateZ (
        ($pos_lft[2] + $pos_rft[2] + $pos_lfa[2] +
         $pos_rfa[2] + $pos_lfk[2] + $pos_rfk[2] +
         $pos_lfb[2] + $pos_rfb[2] + $pos_lfh[2] +
         $pos_rfh[2]) / 10 - 20.26
    );
};

proc doCopy (int $startFrame, int $endFrame, string $node, string $dest, int
$flip)
{
    // +-----+
    // This procedure copies keyframe data from "node" to "dest".
    // Translation values are multiplied by -1 if "flip" is set
    // to 1. Tangent angles are preserved.
    // +-----+

    string $animNodes[];
    string $timeString = $startFrame+"-"+$endFrame;
    float $keytimes[];
    print ("\nNode: " + $node);

    // Copy these channels:
    $animNodes = {"translateX", "translateY", "translateZ", "rotateX",
                 "rotateY", "rotateZ"};
    for( $ac in $animNodes ) {
        print ("\nAnimCurve: " + $ac );
        // Find which frames have keyframes on them
    }
}

```

```

$keytimes = `keyframe -at $ac -time $timeString -query -timeChange
            $node`;
print ("\n" + size($keytimes) + " keys: " );
for( $keyt in $keytimes ) {
    $keyv = `keyframe -at $ac -time $keyt -query -valueChange $node`;
    print ( " [" + $keyt + ", " + $keyv[0] + "]" );

    // Get tangent information for copying
    $keyinT = `keyTangent -at $ac -time $keyt -query -inTangentType
            $node`;
    $keyoutT = `keyTangent -at $ac -time $keyt -query -outTangentType
            $node`;
    $keyinA = `keyTangent -at $ac -time $keyt -query -inAngle $node`;
    $keyoutA = `keyTangent -at $ac -time $keyt -query -outAngle $node`;

    // multiply translate by -1 if flip is set.
    if ($flip == 1) {
        if ($ac == "translateX" || $ac == "translateY" ||
            $ac == "translateZ")
            $keyv[0] = $keyv[0] * -1;
    }

    // Set the keyframe data on the other limb
    select -r $dest;
    setKeyframe -at $ac -time $keyt -value $keyv[0];
    keyTangent -at $ac -time $keyt -inAngle $keyinA[0] $dest;
    keyTangent -at $ac -time $keyt -outAngle $keyoutA[0] $dest;
}
}
};

proc copyLimbAnimation( int $startFrame, int $endFrame, int $left, int $hind)
{
    // +-----+
    // This procedure copies animation from one limb to another.
    // "left" specifies if left or right side, "hind" specifies
    // fore or hind limb.
    // +-----+

    if ($left == 1) {
        if ($hind == 1) {
            doCopy($startFrame, $endFrame, "backLeftLeg_thighIkHandle2",
                "backRightLeg_thighIkHandle", 0);
            doCopy($startFrame, $endFrame, "backLeftLeg_footIkControl",
                "backRightLeg_footIkControl", 1);
        } else {
            doCopy($startFrame, $endFrame, "frontLeftLeg_thighIkHandle1",
                "frontRightLeg_thighIkHandle", 0);
            doCopy($startFrame, $endFrame, "frontLeftLeg_footIkControl",
                "frontRightLeg_footIkControl", 1);
        }
    } else {
        if ($hind == 1) {
            doCopy($startFrame, $endFrame, "backRightLeg_thighIkHandle",
                "backLeftLeg_thighIkHandle2", 0);
            doCopy($startFrame, $endFrame, "backRightLeg_footIkControl",
                "backLeftLeg_footIkControl", 1);
        } else {

```

```
doCopy($startFrame, $endFrame, "frontRightLeg_thighIkHandle1",  
      "frontLeftLeg_thighIkHandle", 0);  
doCopy($startFrame, $endFrame, "frontRightLeg_footIkControl",  
      "frontLeftLeg_footIkControl", 1);  
    }  
  }  
}
```

VITA

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