ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

SEMESTER PROJECT

BIOINSPIRED LEG DESIGN FOR A SALAMANDER ROBOT

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Abstract

Deducting movement from video is never easy and several methods have proved there limits. Here the main goal is to understand, deeply, the movement of the skeletal structure of a salamander hind limb in walking gate. The idea is to use a fully linked three dimensional model of the hind limb with its kinematic chain. This structure allows to deduce the bones positions when visual information is missing. Moreover, fitting over every single frame of the video would be too tedious, this structure allows the program to automatically interpolate the bones position between two defined time steps. The results are exactly as expected, they support actual .understanding of salamander's locomotion. The described method is based on x-rays videos, from top and side view of a walking salamander. It is a general method applieable to different animal in different situations.

Contents

1 Introduction

For almost a centuries now, scientists have been studying salamanders. This animal is part of the few spices witch are believed to have the same walking gate as the first terrestrial tetrapod. Therefor a detailed analysis of their locomotion brings a lot in the general understanding of the chain of evolution regarding locomotion.

This text is an overview of one method helping understanding a vertebrate's locomotion. This thesis goes through a brief biological introduction, just to have the reader at its ease with some names, following with a little analysis of the information source, passing by the three dimensional model created for a very particular purpose and its usability to finally extract the results and confirm what was established earlier in history by many scientists.

2 Salamander's morphology

2.1 General anatomy

The Pleurodeles waltl salamander is a special species that is now declare as threatened. But it is also a kind of salamander who was sent into space for experimentation. The Pleurodeles waltl salamander is a specific kind of salamander who likes to spend most of it time inside clean and calm water, but as it has lungs, it periodically come back to the surface to breath. This is important to understand because the main discussion in this text is about its ability to walk, while it is not its favourite way of locomotion. So his body is designed primary to swim, then to walk and later in the text, this aspect takes importance.

The salamander walks by coordinating its spine coverture, which laterally oscillate with a standing wave, and the movement of its limbs. This lateral oscillatory movement will cause some problems regarding the recordings; they will be discussed later on.

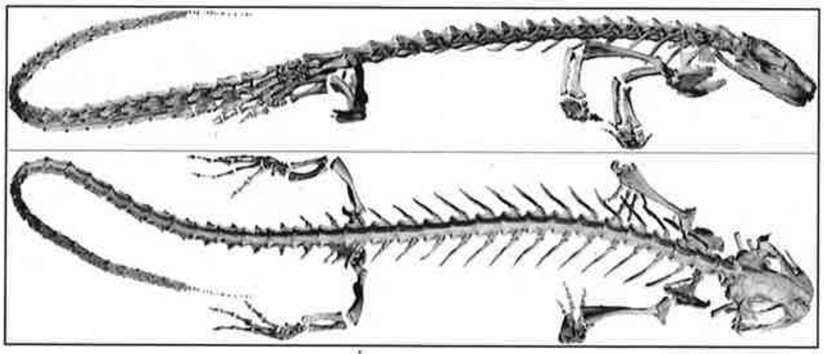

Figure 1

2.2 Hind limb anatomy

In this work, the target is to understand the walking cycle of the salamander, more specifically, the importance of the hind limb's morphology in parallel with its effect on the salamander's propulsion. Figure 2 describes the structure of the hind limb, with the femur, the crus composed of the Tibia and the Fibula, the tarsus formed by the tarsals, the metatarsus separated into five metatarsals and finely the phalanges.

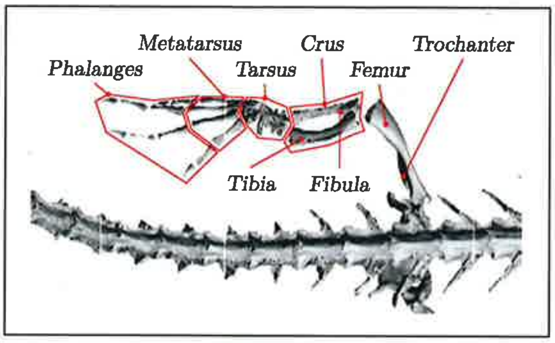

Figure 2

This bones names will be used throughout this text, getting familiar with them will most certainly ease the reading.

The next important part is the information source, from whom this thesis is based on and it is discussed in next chapter.

3 Media

3.1 Characteristics

The videos have been filmed at the Jena University in Germany. The technology used was a biplanar high-speed cineradiographic camera taking 500 x-ray scans per seconds. The original file size is 1536 by 1024 pixels.

The record is composed of two videos, a medio-lateral and a dorso-ventral view; they are both presented in Figure 3, in the respective order.

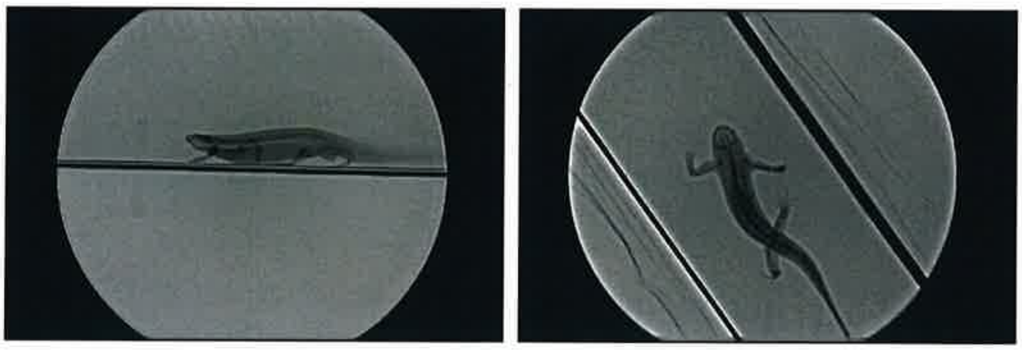

Figure 3

3.2 Deformations

From the top view of the video, it is clear that the salamander doesn't walk parallel to the rail, which might cause the salamander's size to appear smaller.

The first method in order to measure this deformation is to track the position of the head of the salamander along the top view video. The dashed and black line in Figure 4, gives an angle of -8,334°, heading toward the wall on the right. This means that for each 10 cm the salamander is going forward, it was also getting 1.47 cm closer to the right wall, which is quite important.

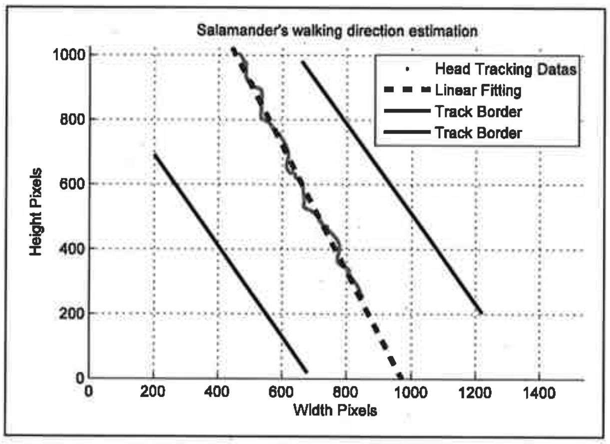

Figure 4

The length difference is about 24 pixels throughout the half of the side video, which corresponds to approximately 9mm. On a size of 190mm it represents an offset of 4.8%. It might seem little and negligible, but when it comes to fitting the bones, it gets very noticeable that they don't actually overlap on both views. The top view also has distortion but it is, this time, with less than 1.6%, insubstantial.

3.3 Measurements on salamander's size

The salamander's approximate length is 190mm and here are the salamander's lengths in pixels in both views.

Top View (Rotation of -54.5°):

1285 - 900 = 385 @ time 0:00:06:13
1120 - 737 = 383 @ time 0:00:18:03
958 - 567 = 391 @ time 0:00:29:17
808 - 418 = 390 @ time 0:00:41:12
653 - 262 = 391 @ time 0:00:56:05
⇒ Mean Pixel Size: 388 +3/-5

Scale in Top View :

~940 px @ time 0:00:50:13
⇒ 4.95 px/mm

Left View (Rotation of -1.1°):

1324 - 903 = 421 @ time 0:00:06:13
1146 - 732 = 414 @ time 0:00:18:03
967 - 555 = 412 @ time 0:00:29:17
817 - 408 = 409 @ time 0:00:41:12
649 - 252 = 397 @ time 0:00:56:05
⇒ Mean Pixel Size: 410.2 +10.4/-13.6

Scale in Left View :

~955 px @ time 0:00:50:13
⇒ 5.03 px/mm

Based on these approximate measurements, an adapting scaling factor can be deduces as below.

Table of size adaptation:
385 / 421 = 0.9145 @ time 0:00:06:13
383 / 414 = 0.9251 @ time 0:00:18:03
391 / 412 = 0.9490 @ time 0:00:29:17
390 / 409 = 0.9535 @ time 0:00:41:12
391 / 397 = 0.9849 @ time 0:00:56:05

Rescaling factor from Top over Left approximately in middle of the video is 940/955 = 0.9843 = 98.43%

Figure 4 provides the evaluation of the deformation due to perspective from side to top view, with linear fitting tendency and extrapolation to the complete video time range.

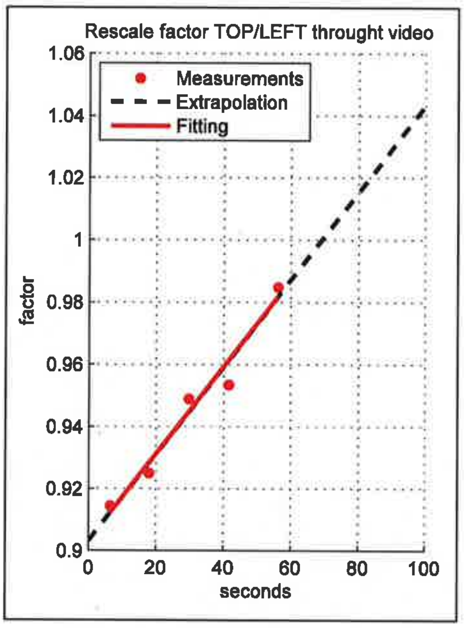

Figure 5

Rescaling the video through time was only a part of the solution; the lens effect was not corrected. Also the oscillatory movement of salamander was not taken into account as the hind limbs stay almost in the same plan during one walking cycle.

3.4 Walking cycle

Because of the discussed distortions, the only walking cycle that fits best on both top and side view is the one happening in the middle of the field. The lens effects are at their minimum and the error over the slope of the linear fitting is also less relevant in this particular region. The X-Ray recordings have been cropped, mirrored and properly rotated in order to have a sequence with on the top half the top view and the bottom half the left view, both at the same size and focused on the hind limb's cycle. This gait is being represented in the Figure 6, the interval between each frame is about 2.5 seconds. It is not the most regular one, but it is the definitely the most usable.

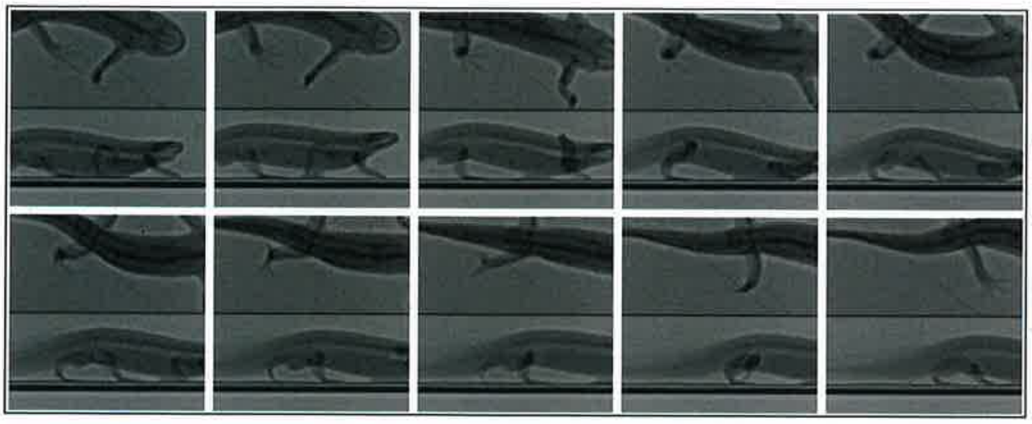

Figure 6

This gate is characteristic to this kind of salamanders walking cycle. We can see on the first image of Figure 6 that the middle finger of the hind limb is aligned to the direction in which the amphibian was traveling. Moreover, the last image shows the direction taken during this cycle; it is parallel to the body alignment at frame 8 of this figure.

This sequence is 26.5 seconds long, at 25 frames per seconds, it gives 662 frames; the next chapter discusses how the fitting method is structured to copy the motion given by these frames.

4 Three dimensional Model with inverse kinematic

The cinematic of the model is composed of ball joints at every junctions, apart the knee and the degree of freedom between the two sets of tarsals, which are pivots. Figure 7 demonstrates this hierarchy.

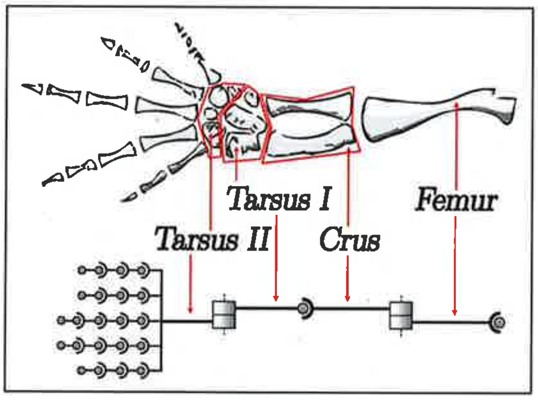

Figure 7

All the controllers presented below act as magnets. They define the position and/or rotation of a joint. But when the joints can't be at the exact place or angle given by the controllers, the solver returns a solution that minimizes the offsets, to be a close as possible to what is expected. The hierarchy of the inverse kinematic is very important. In this case it was necessary to go from the tip of each finger to the head of the femur. This is mainly because the fingers positions where almost always the most relevant visual information that could be used. Therefor positioning the known element allows finding the position of the others, more uncertain. Moreover, the fingers are still during most of the stance phase, so this hierarchy let us move what is actually moving in the recording.

The next figures give an illustration of the controller and the inverse kinematic.

The first controller is presented on Figure 8 by the red box. It is defining the position of the head of the femur, which is the hip's ball joint. The angle of the femur is not defined by this controller, but by the one on Figure 9.

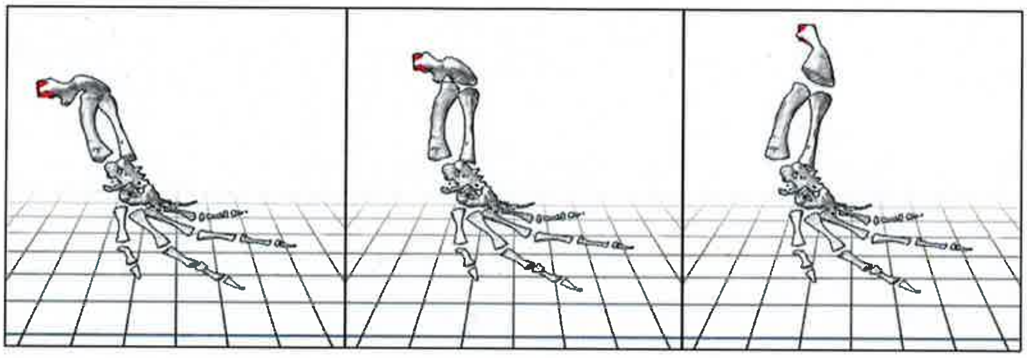

Figure 8

Figure 9 presents the femur and crus rotation's controller. The femur head and the tarsus are not affected by this controller. As the inverse kinematic has multiple solutions due to the ball joints, this controller allows fitting around the most appropriate one.

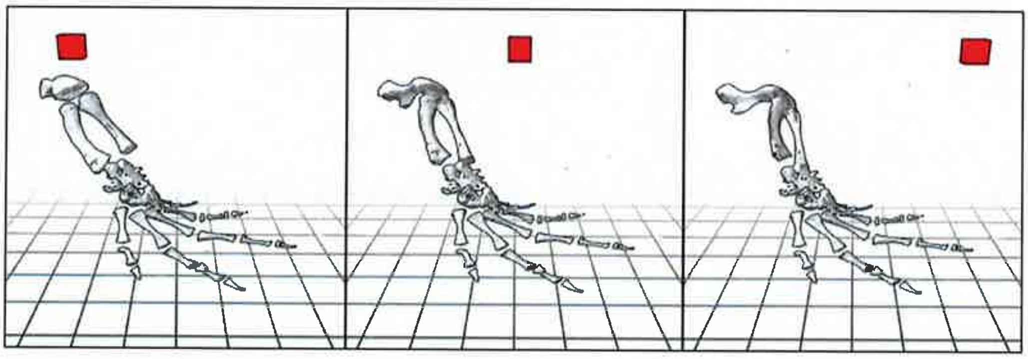

Figure 9

A controller was created also to control the entire feet, it acts as the ankle in human. It is presented in Figure 10, but was mainly used to define the feet position in top view.

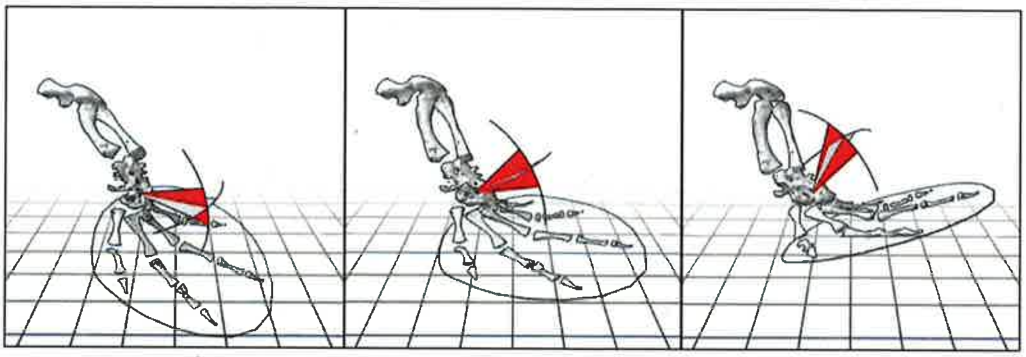

Figure 10

As mentioned at beginning of this chapter, there is a degree of freedom between the two rows of tarsals. After some tries on the video fitting, it became clear that an element was missing in order to reproduce the correct movement. When moving the limb of a dead salamander, whose skin was chemically set transparent and the bones set to pink such as they were clearly visible, it appeared that this degree of freedom was actually possible. After updating the model it became clear that it was a necessary and used degree of freedom. As visible on the Figure 11, it only affects the upper part of the limb, the second row of tarsus, the metatarsals and the phalanges are kept the same; it is due to the phalanges to femur hierarchy discussed previously.

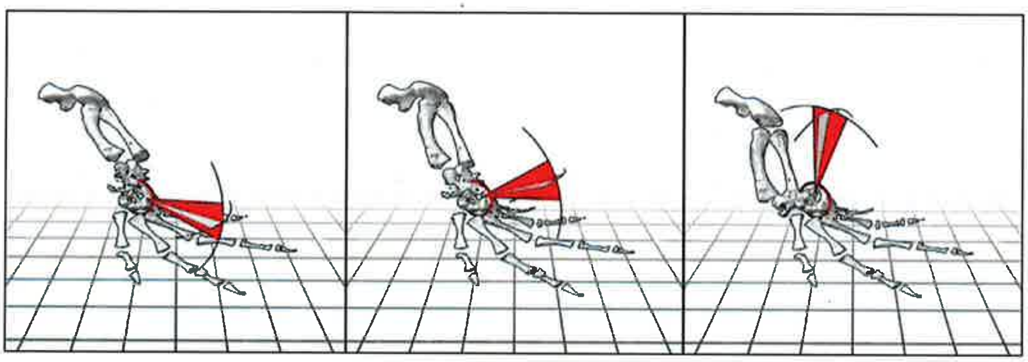

Figure 11

The next controller is probably the most critical, complex and important of the model. Figure 12 to Figure 15 illustrate the ball joint kinematic and its effects in rotation and position regarding the bone structure. As said, the finger position, more specifically their connections to the tarsals, gives from the video's top view a very clear idea of the position and rotation of the Tarsus II shown in Figure 7.

This first rotation is local pitch or rotation in the sagittal plan. Figure 12 shows its effects on the position of the tarsus, when metatarsals and phalanges are kept still.

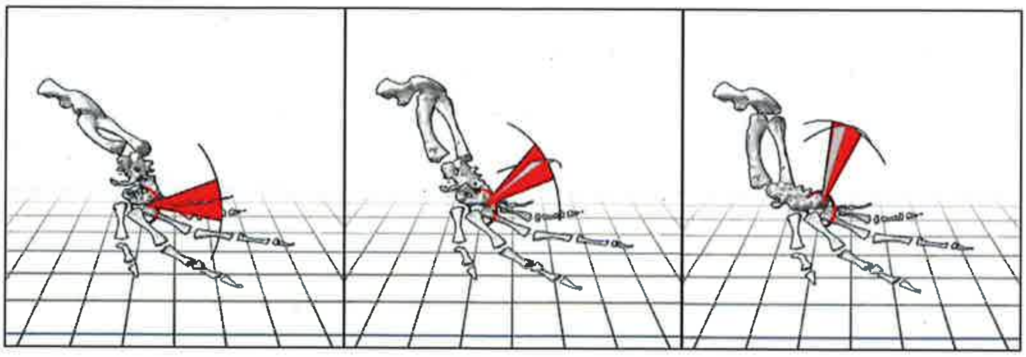

Figure 12

Figure 13 provides the yaw rotation, or more physiologically, the rotation in the transverse plan.

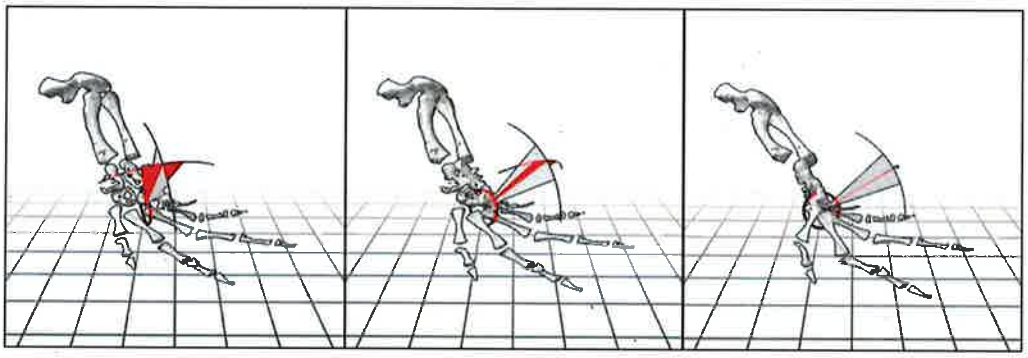

Figure 13

And Figure 14 demonstrates the results of a rotation on the coronal plan, or a roll angle.

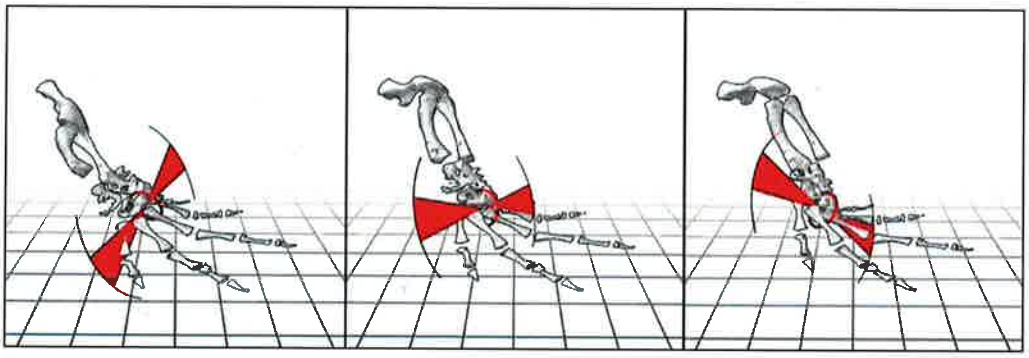

Figure 14

To complete the description of this controller, Figure 15 show the bones in three different configuration, where on the left the controller is moved to the side, and on the right it is moved forward and up.

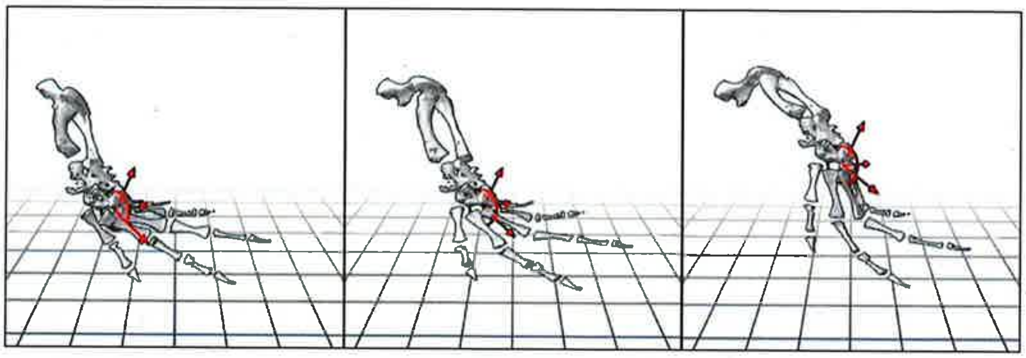

Figure 15

Finally, the last controllers are the position and rotation controller set at each phalange's joints. As visible on Figure 16, the fingers can be set freely, but moving them will not affect the position of the metatarsus.

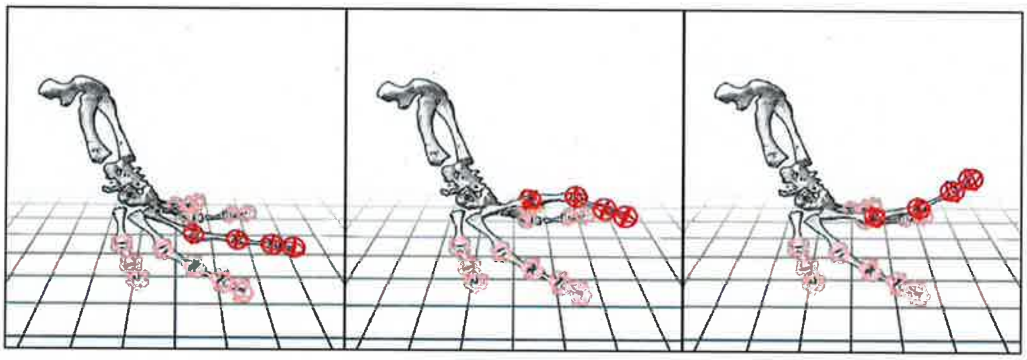

Figure 16

For the reader to get a clearer view of how it looks like in the environment used for the fitting, the Figure 17 presents a screenshot of the layout, which is composed of a top view, a front view and a perspective view. They all have their purpose and they will be discussed in chapter 5.

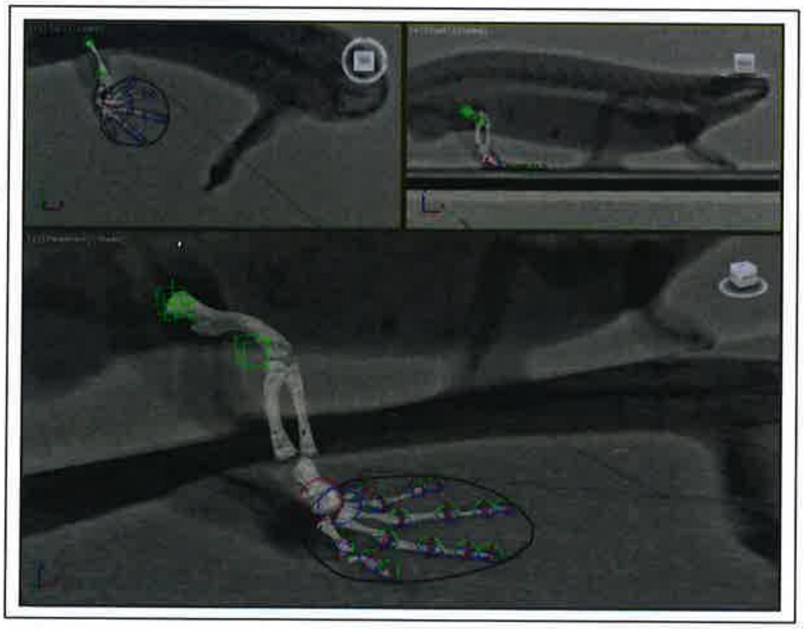

Figure 17

5 Fitting procedure

The video fitting, or the cinematographic overlapping, is based on two specific tools. The first one is the most scientific; it is based on the video. And the second one is a bit less rigorous, but gives excellent results if used correctly, it's the human mind. Let's define more specifically what each of them does.

5.1 Visual information

The video have a sufficient quality to sometimes see some parts of some bones. But most of the time there is a lake of information. The next figures will try to illustrate this.

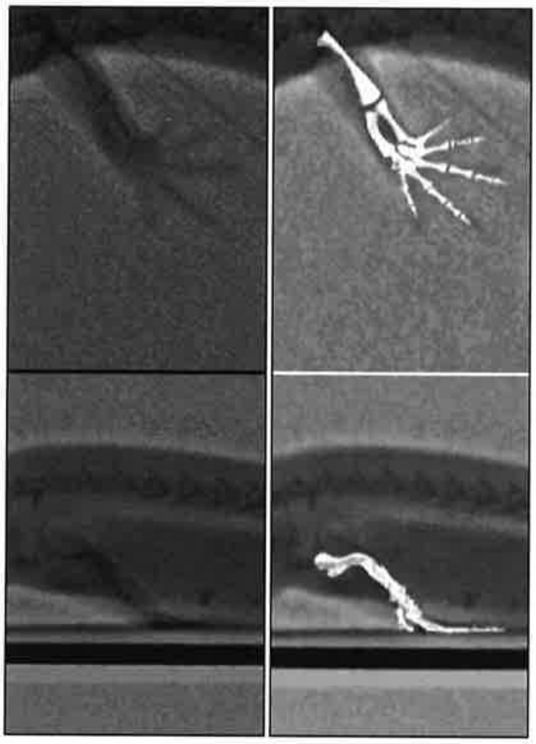

Figure 18

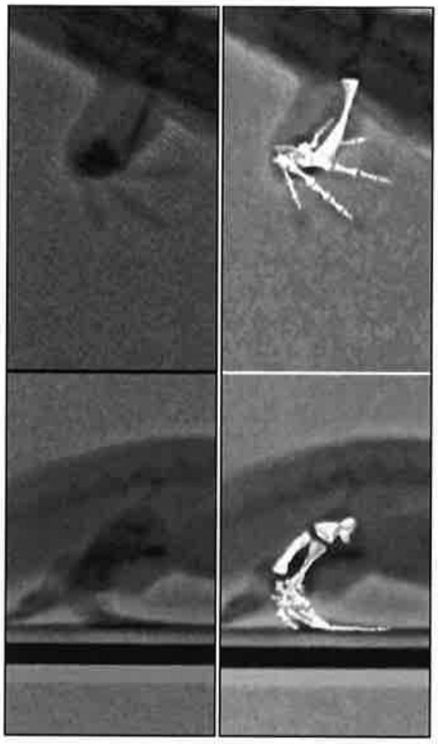

Figure 19

On the left, Figure 18, on the top view, the femur, the crus and the fingers are pretty visible, when it is not the case for the front view, but in both case, the tarsus is not visible at all. The front view still gives us important information, which is height of the knee above the level of the fingers. It is interesting also to note that on the left frame of Figure 18 we cannot see the bones of the pinky, which when reconstructed are very visible and could not be somewhere else.

Figure 18 is even critical. In neither the top, nor the front view can we see the crus. Viewing back from the reconstructed frame, we guess where it is, but a first there are no way to be sure.

In both examples, we have no view at all of where the tarsals are and it's also the case much of the time. But it was possible to interpolate there position and rotation from the metatarsals and the crus, which himself was also deduced from the femur's position and a bit from the front view. But when visual information are really missing, like the position of the head of the femur in the front view, which height can't be read from the top view, then the second method, the "Mind reconstruction", becomes helpful and necessary.

5.2 Mind reconstruction

This tool is actually the most efficient one. The human mind is really good a reconstructing movement, at finding patterns and anticipate. The trick to help the mind is simply to play the video back and forth around the frame missing visual information. Doing these several times help the mind to read the movement of the desired bone. Moreover, the mind is also trained to differentiate between a natural movement and a non-natural one; therefor an optimisation can be done. The reader is invited to try it on its own to get the feeling. The good thing is the more the process is repeated, the stronger the mind becomes at interpolating bones positions.

Like presented on Figure 19, going forward and backward through the frames allows the mind do recreate the illustrated walking cycle.

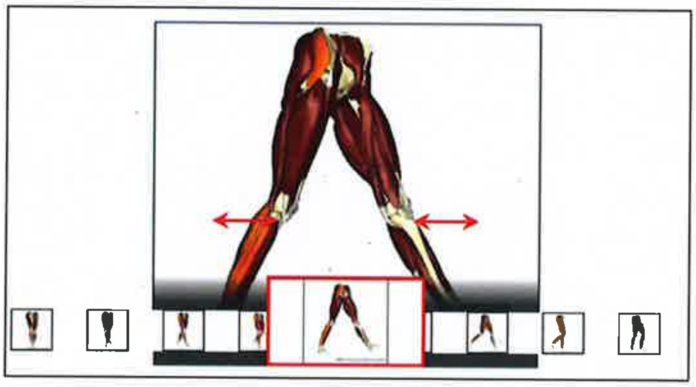

Figure 20

5.3 Key frame animation

Getting these two tools into use over the 662 frames represents a lot of work and a lot of time, and is probably not the way to get the best results.

In this case, the inverse kinematic of the model was really useful. The first key frames, which are the frames at which we manually set the position of the controllers, are set every 100 frames during the stance phase, 1 at the transition and every 50 during the swing phase. Then a second pass on the swing phase gets more into detail and sets key frames every 25 frames, which during the stance phase where not necessary as the inverse kinematic was interpolation the position quite correctly.

After this, the additional added key frames where set only because there where absolutely necessary. During the transition phase, between the stance and de swing phase, the fingers, specially the middle one, have non-linear movement and therefor had more attention during the animation. Here is a visualisation of the density of key frames set regarding the frames of the recording. The black boxes represent all the key frames given to all the controllers.

Figure 21

After all this work set and done, comes to analysis of the movement, or the results, which are discussed in chapter 6.

6 Results

The first important information we can get out this animation is the duration of the stance phase. For this specific type of salamander, the Pleurodeles waltl, the forward walking stance duration is approximately 77%, to whom this cycle is really close, with about 76%, as presented on Figure 22. What is called transition phase here is when the fingers are touching the ground but the salamander is not putting weight on them, they are basically part of the swing phase.

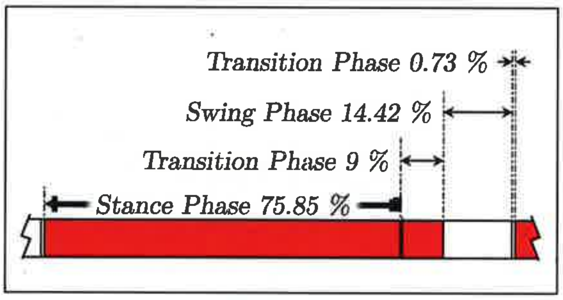

Figure 22

With the bones reconstruction, it is very visible that only the phalanges of the salamander are in contact with the ground. At no point do the metatarsals touch the ground. This characteristic of the salamander is known for more than 60 years. They do at least have an angle 20° with the floor, as shown on Figure 23, measured on the middle finger. This angle is believed to add a damper effect to the leg.

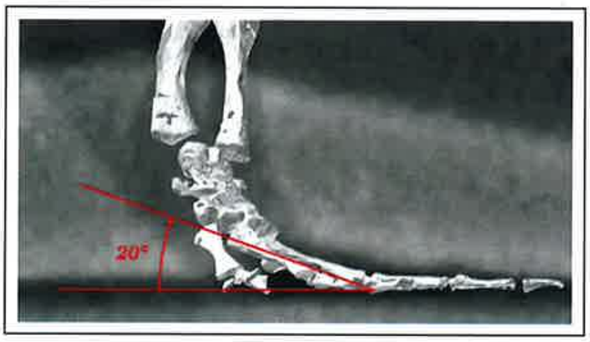

Figure 23

This angle might seem not very important, but it's one more difference with the lizard, whose metatarsals and tarsals are flat on the floor.

The assumption that was made, at the very beginning of this text, that the crus was one solid block, and the Tibia and the Fibula did not cross each other, implies that most of the rotation is done between the crus and the tarsals. The 3d model reconstruction gives us a value of almost 90°, as presented on Figure 24. Trying to reproduce this on the human wrist would dislocate it, as the almost 180° rotation capacity is only due to the ulna and the radius crossing. This is also why salamanders are studied; so much flexibility at this particular joint is characteristic to these early amphibians tetrapod.

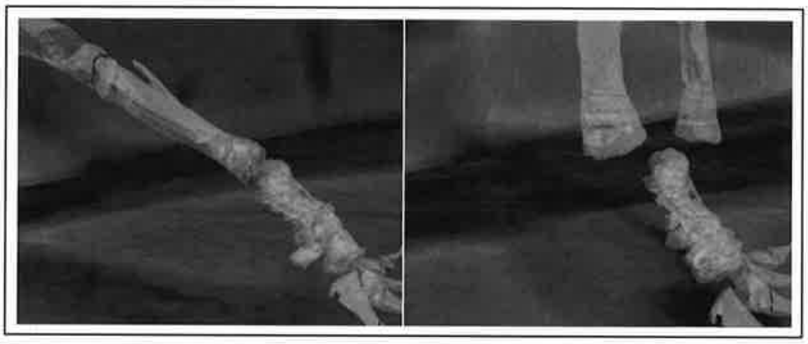

Figure 24

From this reconstruction work, there are several things that can be kept as design ideas for a salamander's robot leg. First the wrist should be a ball joint, flexibly, allowing a large degree of movement and it should also be coming back to its rest position. This can be done passively. Second, even though it has been shown that a ball point contact can be as efficient as a leg in a robotic salamander for propulsion, having a hind limb based on the real animal one would add damper, stability as the contact surface is larger and also a better grip on the floor. While moving on a flat and known floor, adding a full limb would just add more weight, but if there are needs of adaptability regarding the terrain, then a salamander's hind limb like design would be more efficient.

7 Conclusion

The main first goal of this project was to propose a design for a robotic leg based on the salamander's morphology. However, going into the very details of the bones movement is a project on its own and comes with a massive amount of work especially if the method does not exist and need to be created, which was the case here. I truly believe that the steps which I have been trough and detailed as clearly as I could in this text are identical no matter the species. This methodology is a robust way of confirming the actual knowledge and to bring some new ideas. Adding muscle afterward on such a model gives it opportunity also to verify the muscle activations patterns.

8 Bibliography

[1] K. Karakasiliotis, N. Schilling, J.-M. Cabelguen and A. J. Isjpeert, *Where are we in understanding salamander locomition: biological and robotic perspectives on kinematics.* 2012.

[2] M. A. Ashley-Ross, *Patterns of hind limb motor output during walking in the salamander Dicamptodon tenebrosus, with comparisons to other tetrapods.* Feb 2005.

[3] A.P. Russell,V. Bels, *Biomechanics and kinematics of limb-based locomotion in lizards: review, synthesis and prospectus.* January 2001.

[4] M. A. Ashley-Ross, *The Comparative Myology of the Thigh and Crus in the Salamanders Ambystoma tigrinum and Dicamptodon tenebrosus.* JOURNAL OF MORPHOLOGY 1992.