Biomechanics Background

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Introduction

How do we create a bio-inspired salamander robot that can move through a granular media using foldable robotic techniques?

In order to answer this research question, a bio-inspired salamander robot must be designed, tested, and validated. The salamander was chosen to be the primary organism to focus on for research into its biomechanics.

Literature Review

First, a literature review was conducted into actual salamander biomechanics. Some of the keywords used for this were: salamander, ground force reactions, biomechanics. Below is a table of the references followed by an in-depth description of three of the sources.

Table 1. Literature review of salamander biomechanics

Article Title
Where are we in understanding salamander locomotion: biological and robotic perspectives on kinematics[7]
Axial dynamics during locomotion in vertebrates: lesson from the salamander[18]
Tiger Salamanders (Ambystoma tigrinum) Increase Foot Contact Surface Area on Challenging Substrates During Terrestrial Locomotion[19]
The Biomechanics of Tiger Salamander (Ambystoma tigrinum) Underwater Walking on Smooth and Rough Substrates[20]
**Propulsive Forces of Mudskipper Fins and Salamander Limbs during Terrestrial Locomotion: Implications for the Invasion of Land[9]
**Organization of the spinal central pattern generators for locomotion in the salamander: Biology and modeling[10]
**Patterns of Limb and Epaxial Muscle Activity During Walking in the Fire Salamander, Salamandra salamandra[16]
The effect of fiber-type heterogeneity on optimized work and power output of hindlimb muscles of the salamander Ambystoma tigrinum[11]

** Papers will be summarized in the next section

The paper, “Propulsive Forces of Mudskipper Fins and Salamander Limbs during Terrestrial Locomotion: Implications for the Invasion of Land,”[9] evaluated the ground reaction forces (GRFs) for the segments of appendages for mudskipper fishes and tiger salamanders. This includes the forelimb and hind limbs of the salamander. Experimental trials were done on salamanders using a multi-axis force platform and videoing the animal’s traversal of a plate. This paper specifically focuses on the ground reaction forces so this was extremely helpful in understanding these forces on the different limbs. This paper also gave the specifications of the actual 5 salamanders tested including body mass and length.

Another research group explores walking and swimming motions of a salamander[10] . The research divides the body into multiple segments and describes segments’ state and interaction over time. This will be helpful for translating to a foldable system. The researchers discuss a simulation in which a model of the CPG (central pattern generators) is coupled with a biomechanical model of the body in interaction with its environment. By incorporating and building off of generations of research, the paper provides a comprehensive understanding of the underlying principles of salamander locomotion.

Another paper discusses the muscle power output of the salamander at different frequencies for different muscle groups.[11] Work loops were obtained for ILTP (Iliotibialis Pars Posterior) and ILFB (Iliofibularis) muscles. The ILFB and ILTP differed significantly in the work per cycle and power generated at three levels of muscle strain and four cycling frequencies. The max power output of the ILFB muscle was found to be 56.7 W/kg and that of the ILTP was found to be 49.7 W/kg. Using this information, the power requirement of the robot can be estimated.

After this initial research, a literature review was conducted on salamander-inspired robots. The keywords in this search included: Salamander, Robot, Biomimicry, Amphibious Locomotion, Actuated Spine, Granular Media. Below is a table of the references followed by an in-depth description of three of the sources.

Table 2. Literature review of salamander inspired robots

Article Title
From cineradiography to biorobots: an approach for designing robots to emulate and study animal locomotion[15]
**From Swimming to Walking with a Salamander Robot Driven by a Spinal Cord Model[12]
**Salamandra Robotica II: An Amphibious Robot to Study Salamander-Like Swimming and Walking Gaits[13]
**Coordination of lateral body bending and leg movements for sprawled posture quadrupedal locomotion[14]
Where are we in understanding salamander locomotion: biological and robotic perspectives on kinematics[7]

** Papers will be summarized in the next section

The paper, “From Swimming to Walking with a Salamander Robot Driven by a Spinal Cord Model,”[12] demonstrated the capabilities of a salamander inspired robot to test different gaits and locomotion as it traversed sand to water. This paper addresses the mechanisms necessary for limb coordination and axial movements and gait transitions.It also compared actual salamanders with the bio-inspired salamander robot and made nodes to see how salamanders move its body for a desired motion/gait. This paper was helpful as it provided insight into the size and velocity of a salamander robot that has been successfully designed and tested. It also gives the number of actuators that was necessary to obtain this level of mobility.

Salamandra Robotica II[13] is an amphibious salamander robot that is able to walk and swim. The researchers investigate how the speed of locomotion and curvature of turning motions depend on various gait parameters such as the body−limb coordination, the type of body undulation, and the frequency. There’s tons of data provided by the researchers for us to draw design and actuation parameters for our robot. The robot created by the team can be translated to a foldable mechanism based on its design, leading to cheaper production, novel models for amphibious spines and legs.

Chong et.al[14] used a robotic model based on the fire salamander animal to demonstrate that back bending assists not only the forward motion, but also the lateral and turning positions. In order to model the animals' and robots' locomotion when in contact with granular media, the Granular resistive force theory has been used. For the experiment, a 3D printed servo-driven open-loop robot having four legs and an actuated back was used and the test bed was filled with 1mm diameter poppy seeds. Through the experiments, it was found that the rotational displacement is maximized when the frequency of back bending is twice as that of the leg movement.

Salamander Biomechanics Summary

Parameters describing a salamander's biomechanics were gathered from all the references mentioned in the previous section and put together in the following table.

Table 3. Salamander Parameters and Metrics

Parameter	Unit	Value Range	Reference
Mass	g	61.72 +/- 0.07	[17]
SVL (snout-vent length)	cm	10.2 - 11.5	[1]
TL (total length)	cm	18.5 - 21.3	[1]
forward swimming velocity	cms^{-1}	21.8 - 48.0	[1]
forward walking velocity	cms^{-1}	7.0 - 10.5	[1]
Power generation	Js^{-1}	4.9×10^{-4} to 99.5×10^{-4}	[2]
Stride Length	SVL	0.73 - 1.07	[3]
Pelvic girdle rotation	deg	38.5 - 73	[3]
Trunk flexion	deg	66 - 88	[3]
Net GRF	Body Weight(BW)	HL: 0.47 FL: 0.46 PF: 0.42	[4]
Max muscle power output	W/kg	115 ÷/x 2.97@ 20C	[5]
VO2 max	ml/hr	4.348	[6]
Metabolic energy consumption	J (peak)	$2.5 x10^{-4}$ (gravel) $12 x 10^{-4}$ (sand)	[6]

Ground reaction forces were found on the forelimbs and hind limbs for real salamanders in experimental test runs using a pressure plate. From the ground reaction forces, we can figure out where the highest forces are throughout a limb.

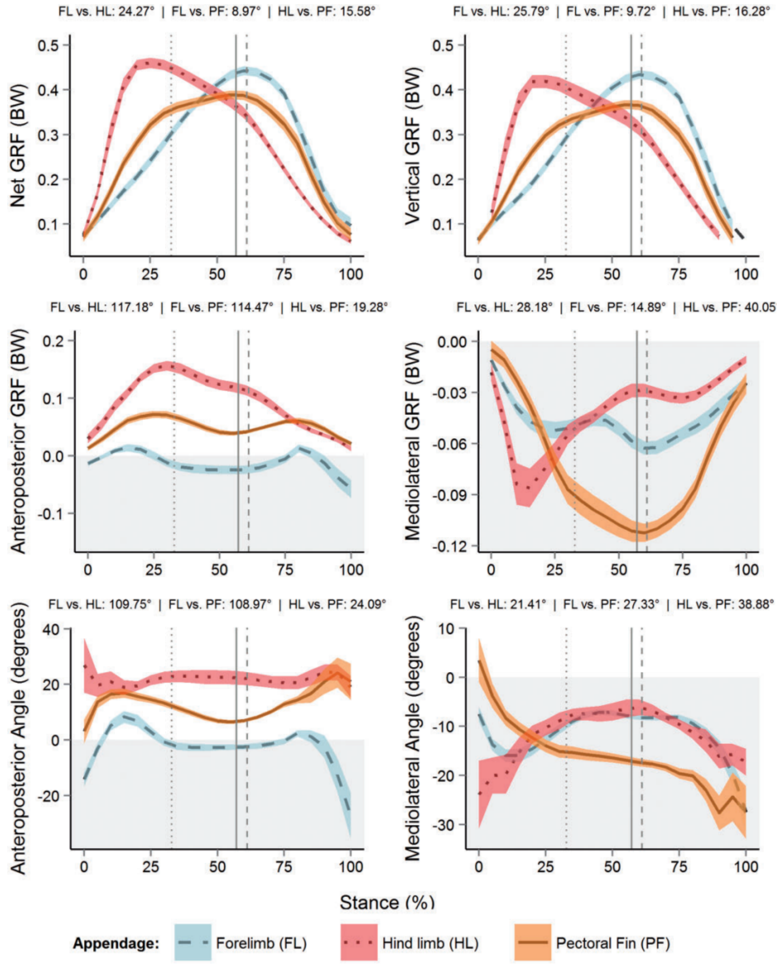

Figure 1. Shows dynamics of GRF parameters during stance. Salamander forelimbs are light blue, salamander hindlimbs are red, and the mudskipper’s pectoral fin is orange.

There are 3 major sections of muscles typically studied in salamander mobility. The axial muscles that allow the body to move side to side and the muscles in the forelimb and hindlimbs.

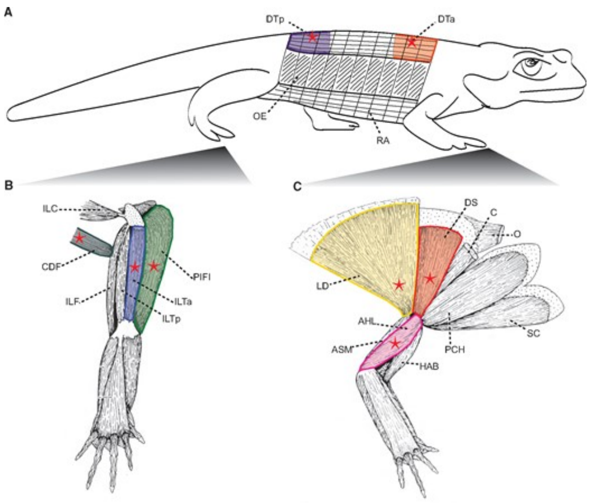

Figure 2. This image displays the postcranial muscular anatomy of a fire salamander. The axial muscles are m. dorsalis trunci anterior (DTa) and m. dorsalis trunci posterior (DTp). The hindlimb muscles are m. puboischiofemoralis internus (PIFI), m. extensor iliotibialis anterior (ILTa), and m. caudofemoralis (CDF). The forelimb muscles are m. anconaeus humeralis lateralis (AHL), m. dorsalis scapulae (DS), and m. latissimus dorsi (LD).

Electromyography, or EMG, was used to measure muscle response for these targeted muscles. For this particular study the rectified integrated area (RIA) /Duration is the normalized approximation of relative “force”.

Table 3 EMG summary variables measured for forelimb, hindlimb, and axial muscles of *S. salamandra*[14]

Forelimb	**(RIA) /Duration**	**Hindlimb**	**(RIA) /Duration**
DTa	0.64 (0.01)	DTp	0.62 (0.01)
AHL	0.52 (0.01)	PIFI	0.64 (0.01)
DS	0.58 (0.01)	ILTa	0.61 (0.01)
LD	0.65 (0.01)	CDF	0.23 (0.01)

Most information is known with regards to the energy usage of the salamander through our detailed research. Our research covers the the power of the legs in terms of W/kg but there is an assumption that part of that power is taking into account the undulating motion of the body

In order to learn about the biomechanics of salamanders, details figures/drawings of salamander skeleton and musculature were found.

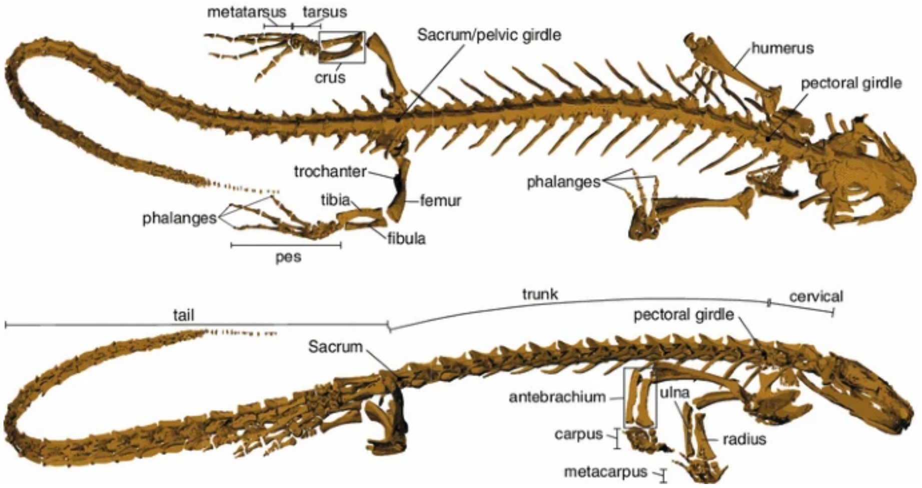

Figure 3. the skeleton of a salamander [7]

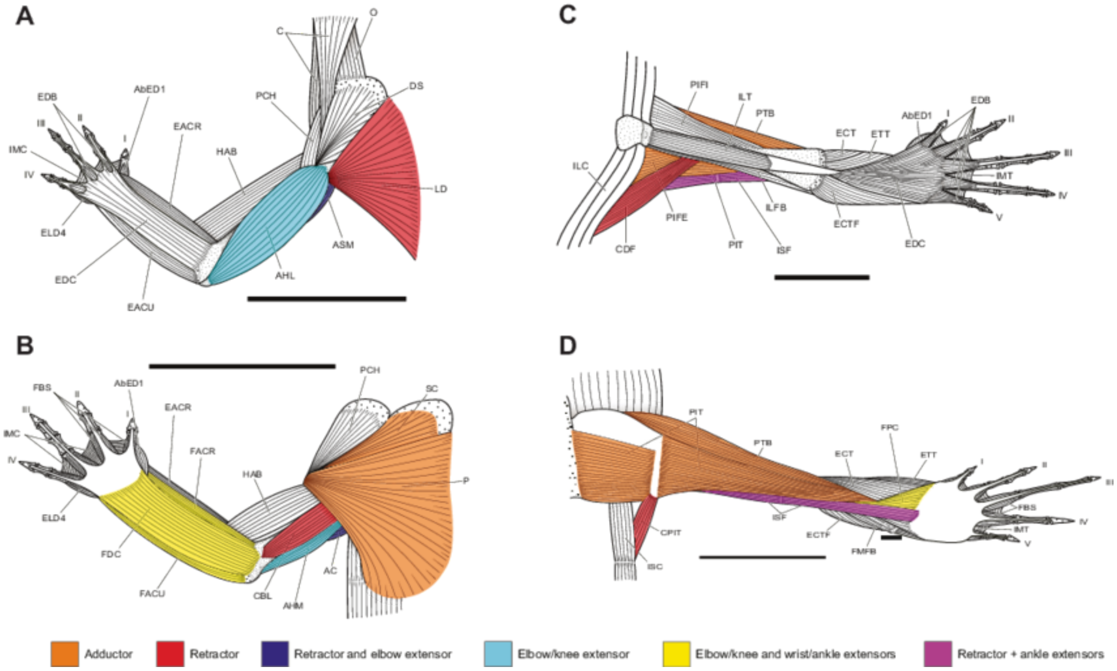

Figure 4. The musculature of the salamander limbs[8]

After learning about the muscles/structure of a salamander, then the motion of the was studied. In particular, freeze frames of gait cycles were found. This will help understand the actual movements of a salamander necessary for mobility.

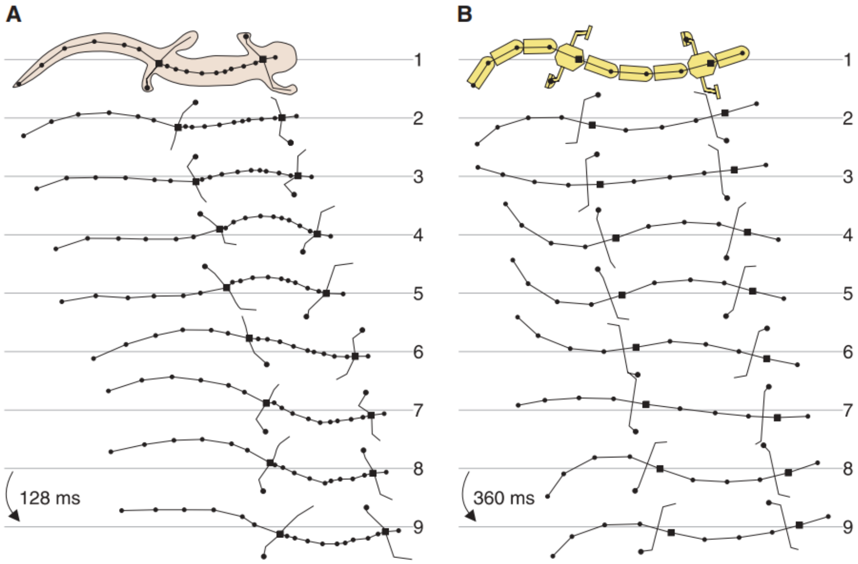

Figure 4 Salamander vs robotic framework during motion[12]

Figure 5 Salamander capture during motion[16]

Initial Bio-Inspired Salamander Robot Design

After studying the structure, constraints, and movements of real life salamanders; then this knowledge was applied to designing a simple representation of our system.

The simplest version of the system could be approximated as 3 rigid bodies. A front, a rear, and a body section with rigid legs built into the front and rear sections of the frame. The central body mechanism can control the undulation and trunk rotation motion. Each rigid body would be ~⅓ the weight of the overall robot.

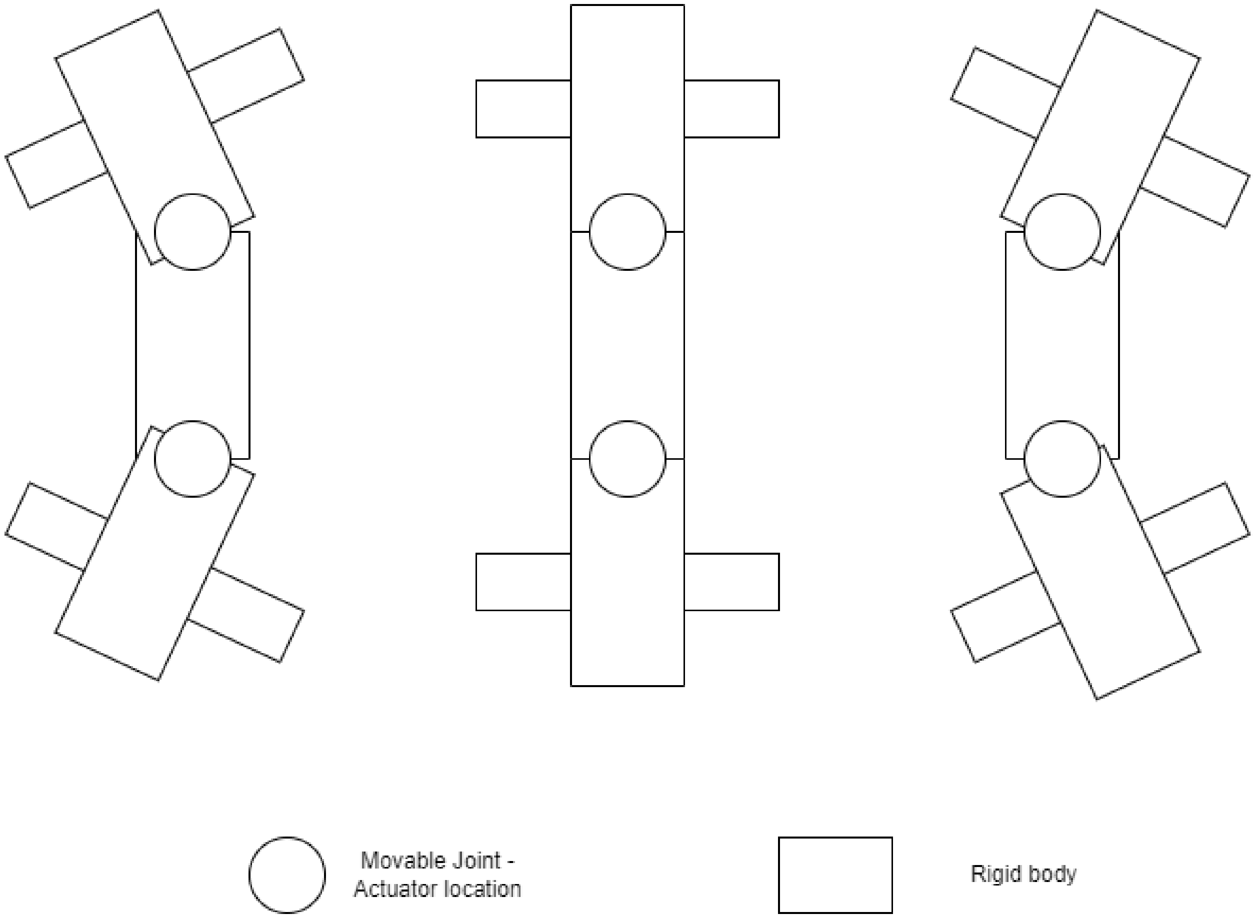

Figure 6 Simplified diagram of salamander body

Discussion

1. Discuss / defend your rationale for the size animal you selected in terms of your ability to replicate key features remotely with limited material selection.

The salamander is a relatively small creature with a manageable level of complexity in its movements. While we may need to scale the robot up slightly from the true size of a salamander it will not be as large as some of the current robotic designs that are nearly a meter long. This limit to our size helps keep weight manageable, reduces power transmission losses, and provides opportunities for simpler control. With the scale and budget we are looking at we will be able to acquire the parts necessary to control and power our design.

2. Find a motor and battery that can supply the mechanical power needs obtained above. Consider that motor efficiencies may be as high as 95%, but if you can't find it listed, assume you find a more affordable motor at 50-70% efficiency. Compare the mechanical watts/kg for the necessary motor and battery vs the animal's mechanical power/mass above? Which one is more energy dense?

If our design has near the same internal resistance and friction as a salamander then our design will have close to the same energy density as a salamander. We are looking at a 6v servo and 2 18650 batteries. This gives us 51.6 W/kg while the salamander has 49.7 W/kg. This calculation does not take into account the mass of our robot structure or any electrical/control components at the moment.

Motor 4.8 W (at stall) / (0.009 kg + 0.042*2) = 51.6

Salamander 49.7 w/kg [17]

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