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The Effects of Surface Feature Geometry on the Propulsive Locomotion of Tree-climbing Snakes

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An abstract of

a thesis submitted to the Faculty of Emory College of Arts and Sciences

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Abstract

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Being limbless, snakes face unique challenges when climbing trees, sometimes resorting to wrapping their bodies around the trunk to pull themselves up. However, corn snakes exhibit an alternative climbing technique that allows them to zig-zag up and down trees without wrapping. We model a large tree using a flat, vertical wall that utilizes a single vertical column of 22 force-sensitive pegs to record horizontal and vertical propulsive-force measurements as the snakes ascend or descend. On the wall, there are two types of 3 mm long pegs: the "normal" cylindrical pegs and the "tapered" pegs, which have a narrower tip, making them more difficult to grip onto. This study focuses on the force output over the body of the snakes through the combination of 3D-kinematic tracking data as well as time-resolved force data. Our findings reveal that the geometry of the pegs affects the snake's climbing ability differently when ascending versus descending. Given the probable challenges of upward climbing, the snakes were forced to utilize the tapered pegs. In these scenarios, we observed significant lateral forces exerted on the pegs, including the tapered ones, suggesting considerable effort exerted by the snakes to stabilize on the wall. On downward climbs, we observe reduced lateral forces in general, where the snakes are sometimes able to skip the tapered pegs altogether. This can indicate that downward climbs are less difficult and require less stabilizing forces. Future work will investigate how different snake species manage similar scenarios with different surface geometry.

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Chapter 1

Introduction

1.1 Motivation

When observing a snake climbing a tree, as shown in Figure 1.1, one may wonder how a limbless creature can perform a task that limbed animals are often observed doing. Snakes are not sticky, nor do they have claws – both of which are characteristic of several other climbing animals. Rather, this phenomenon has something to do with the texture of the tree, the microscopic structures of the snake's skin, and the forces the snake applies on the tree to climb up or down. Being limbless, snakes face an unusual set of challenges while climbing that most other species do not experience. Here, we aim to study the behaviors that have helped them overcome these challenges, and how these behaviors are affected by structures on the tree.

Currently, most of the research on tree-climbing snakes focuses on techniques involving wrapping around tree trunks (or cylindrical objects) to propel themselves upward. These findings show how snakes use constricting forces, reminiscent of how they constrict prey, to support their body weight on trees, as shown in Figure 1.2. This method requires extensive gripping forces, up to three times the force required to support their weight, and propulsive forces to spiral up around the tree trunk [2]. Another technique known as lasso locomotion is employed by arboreal snakes -snakes that live in trees- that use friction to grip around the tree to inch upward (see Figure 1.3). This technique is quite demanding, indicated by "slow speeds, slipping, frequent pausing, and heavy breathing during pauses" [3]. Both of these propulsive climbing techniques require a substantial amount of effort from the snake, yet fail if the snake's length falls short of the tree's circumference.

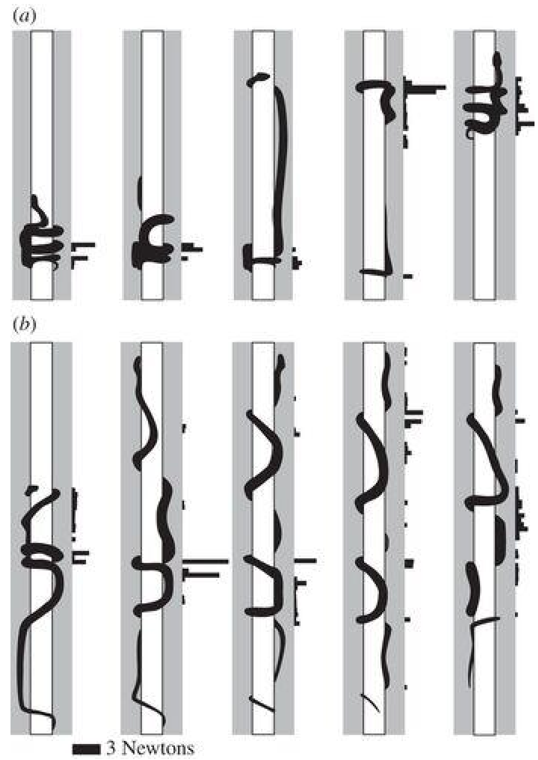

Figure 1.1 (left): A snake climbing up a tree without wrapping around it [1].

Figure 1.2 (right): Snake ascending a tree while wrapping and exerting constrictive forces [2].

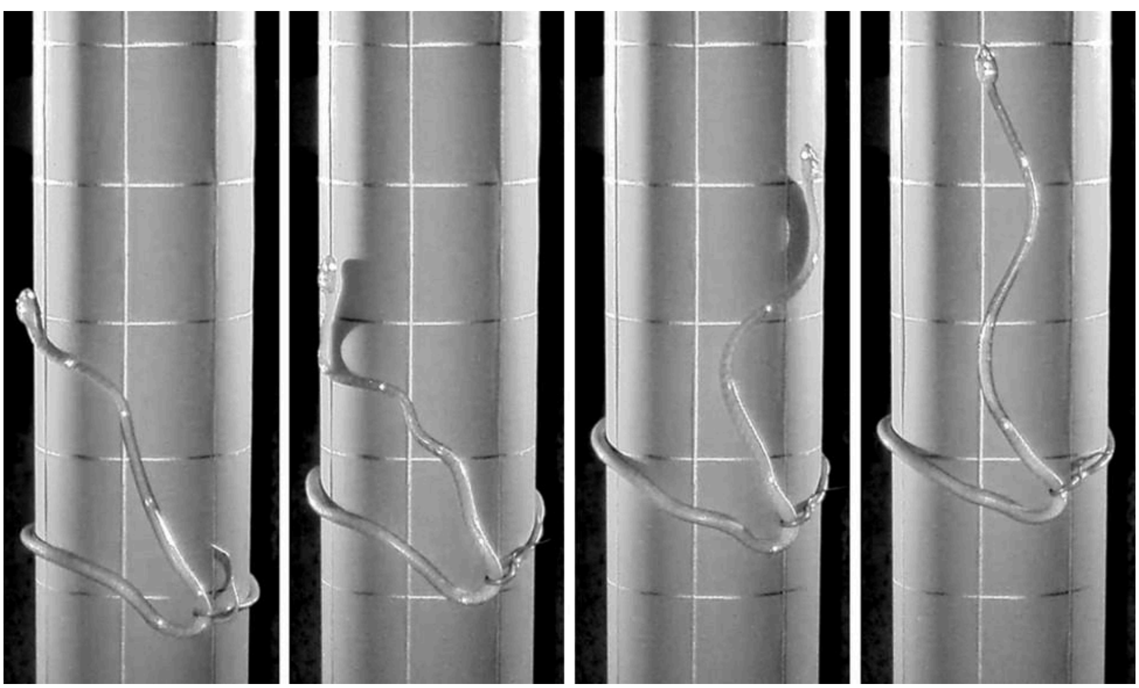

Figure 1.3: Brown tree snake utilizing lasso locomotion to propel itself up a cylindrical object [3].

What happens when a snake is unable to or chooses not to wrap around the tree? Some species of snakes, including the corn snake, possess the ability to ascend and descend a tree without coiling around its trunk. Utilizing the textures of the bark and other surface protrusions of the tree, the snakes demonstrate this wrap-less climbing technique. A study by Bruce C. Jayne et al.[4] examines snake climbing behavior on a pole with a diameter of 5 cm through a combination of different protrusion heights and inclines, including 90 degrees. This study analyzes the data through climbing speed and four-way analysis of variance to assess variability between climbs with cameras and code. Although this study introduces protrusions, the snakes all wrapped around the cylinder to climb when the incline was at 90 degrees, while using the protrusions.

1.1.1 Modes of Locomotion

I will introduce two types of terrestrial locomotion that will become relevant later (Section 3.1) while analyzing climbs: concertina and lateral undulation. Concertina is characterized by the snake pulling its body into alternating bends and straightening them out while pushing on these bends, as shown in Figure 1.4. This form of locomotion is known to be much more demanding, is remarkably slower than other forms of locomotion, and costs a lot of energy [5]. Lateral undulation, however, is the most common form of locomotion found in snakes and is also as energy-efficient as locomotive movement in limbed animals [6]. It is distinguished by the wave-like motion of a snake, following the curves made by its body, as illustrated in Figure 1.5.

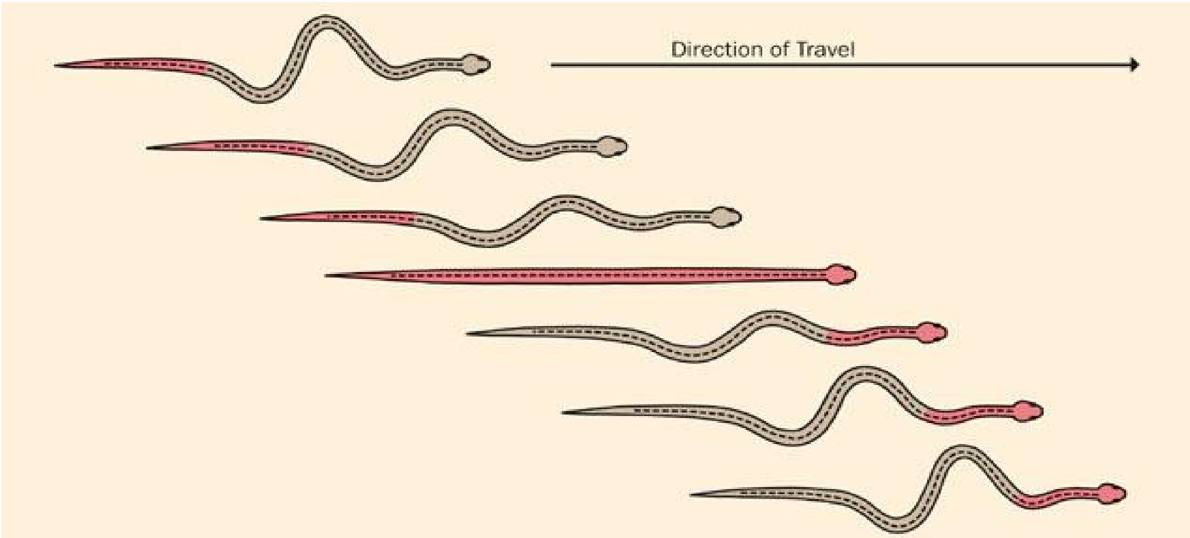

Figure 1.4: Concertina locomotion [5]

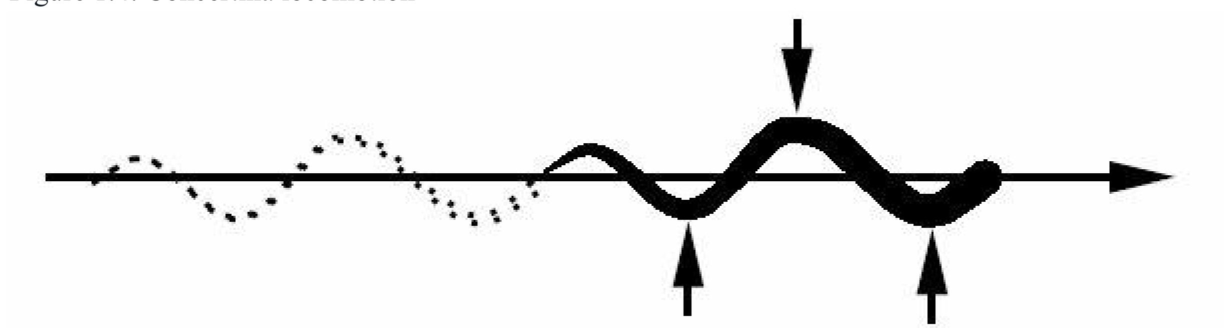

Figure 1.5: Lateral Undulation [7].

1.2 Subjects of the Study: Corn Snakes

Of the various tree-climbing snake species, corn snakes (*Pantherophis guttatus*), also known as red rat snakes, were chosen for this experiment. They are native to the southeastern states of the US, including Atlanta, Georgia. These non-venomous snakes are also semi-arboreal, meaning they often spend their time up in trees and are, therefore, excellent climbers. They are known for their distinct yellow/orange hue with red and brown spots that propagate down their body and a black and white checkered pattern on their bellies. Their eyesight is not as acute as humans [8]. The snakes in our lab weigh in between 90-110 g and are 71-81 cm long, with the height at the midsection of the snakes being 1.2-1.5 cm.

Figure 1.6: Photo of a corn snake [9].

1.3 Goals of Thesis

Although some forms of tree-climbing utilized by snakes involve wrapping around the tree, corn snakes exhibit an alternative climbing technique. This technique allows them to zig-zag up and down a tree without coiling around it, as the snakes are not long enough to do so or choose not to. We will examine how corn snakes rely more on the surface features and textures of the tree (modeled by short protrusions) rather than constricting forces, to ascend and descend trees in a controlled manner [3]. Furthermore, we will focus on the forces applied onto these protrusions, which have not been previously studied, rather than a visual analysis of the climbs. We will observe not just upward climbs but downward climbs as well, which have also been understudied. We aim to study the locomotive forces exerted onto such features and gain insight into the influence of surface features on snakes' upward and downward climbing abilities through a novel and profound way of force data collection.

CHAPTER 2

EXPERIMENTAL METHODS

2.1 Experimental Setup

2.1.1 The Climbing Wall Setup

Every tree in nature is unique, and so are the arrangements of various features and bark textures of the tree. Because of this, it is rather difficult to characterize this random assortment of features and it is also difficult to collect data on snake climbs in a controlled or repeatable manner. Since we are observing climbing behavior without wrapping around the circumference of the tree, the tree trunk can be simplified into a flat vertical wall. A smooth sheet of acrylic is used, held perpendicular to the floor with T-slot aluminum beams, as it has no textures or surface features the snake could use to climb. Without any additional features, the snakes are unable to climb up this vertical wall. Therefore, by adding some features, we know the snakes will completely rely on them to execute their climb. So, 22 pegs are added on this “climbing wall” for the snakes to grip and push off of. These pegs are relatively short, at 3 mm long, to resemble shallower protrusions found in bark, rather than larger features like branches.

The 22 pegs are free-floating and do not touch the walls, as they are held behind the wall and protrude through holes in the acrylic. As a result, the only forces measured will be the ones the snake exerts. These pegs lie in a vertical line from the bottom of the wall to the top (Figure 2.1). To measure the direction and magnitude of the forces exerted on the pegs, we made them force-sensitive both horizontally and vertically. On the tip of the pegs, two different kinds of peg sleeves can be attached to introduce varying peg geometries: **normal** (Figure 2.2b) and **tapered** at 27° (Figure 2.2c). Due to the shape of the taper, we believe it will be harder to grip than a normal peg. The pegs are spaced 50 mm apart and the sleeves are 3 mm long, compared to the 1.2-1.5 cm height at the midsection of the snake. The sleeves are 3D printed with resin and securely attached to the peg but also can be taken off or interchanged with other peg sleeve geometries. Along the bottom of the wall, there is a 3” thick foam pad to prevent any injury to the snake in case they fall.

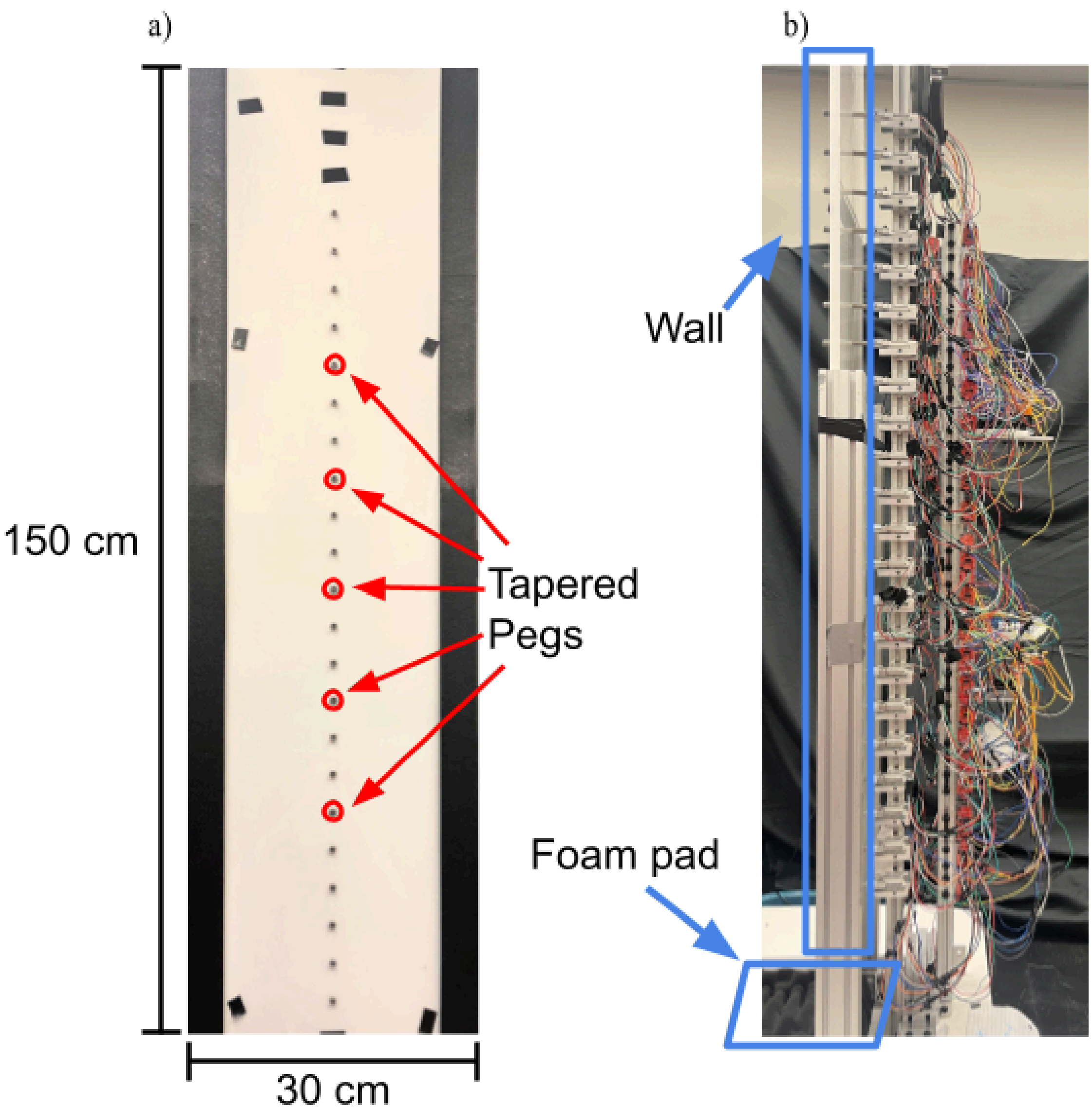

Figure 2.1: Front (a) and side view (b) of 150 x 30 cm vertical climbing wall setup with 22 force sensing pegs, with tapered pegs circled in red, and the foam pad and wall boxed in blue.

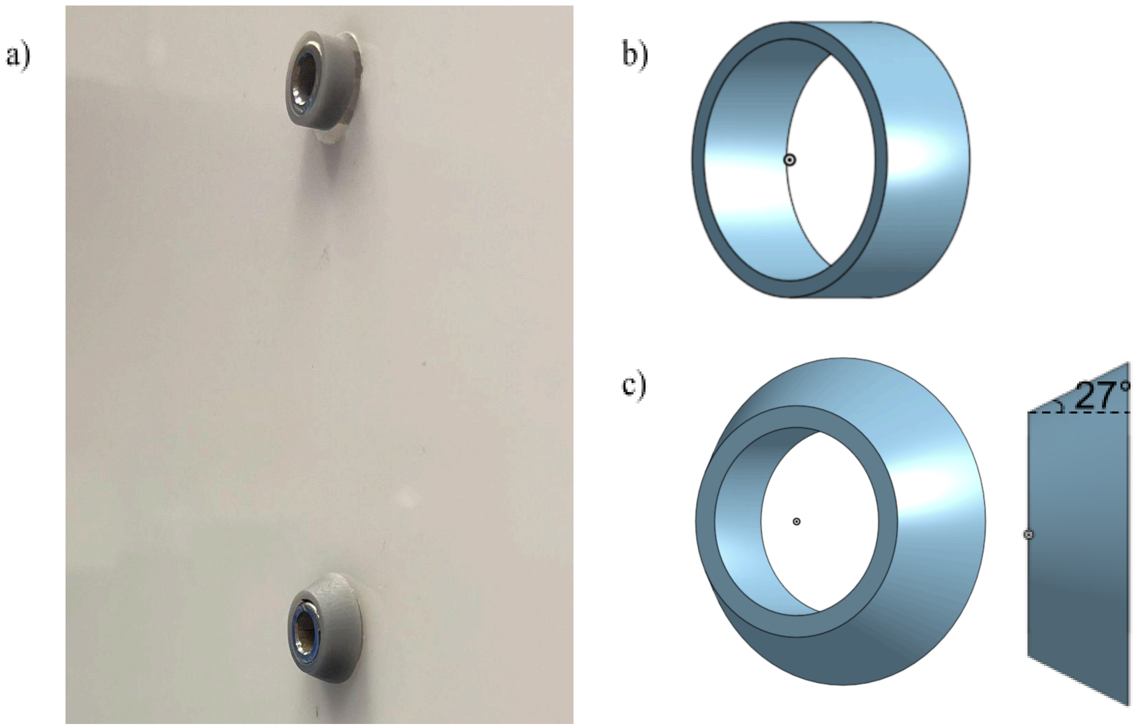

Figure 2.2a) Normal and tapered peg on the wall. Closeup of normal peg (b) and tapered peg (c).

The pegs on the wall are force sensitive, where each peg is connected to two mini load cells (see section 2.2.1 for more information about mini load cells), which are each connected to a signal amplifier, all connected to an Arduino Mega microcontroller, with two total Megas in the setup (Figure 2.3). The voltage signal from the pegs is converted to grams using code written in C++, adapted from “HX711-Adc.h” by Olav Kallvod [10]. This code takes 12 voltage measurements (V) per second, divides these measurements by a calibration constant (C), and outputs mass (m), in grams:

$$m = V * \frac{1}{C}. \tag{1}$$

The calibration constant is determined by the calibration function. First, the voltage (V_1) of an unloaded weight (m_1) is measured. Then, the voltage (V_2) of a known weight (m_2) is measured after the weight is placed on the load cell and entered into the command line. The calibration constant is then calculated:

$$C = (V_2 - V_1)/(m_2 - m_1). \tag{2}$$

Additionally, the climbing wall has a few variables that can be manipulated: vertical spacing between the pegs; the size, shape, and length of the pegs; and angle and texture of the wall. However, in this thesis, we only focus on varying the peg shape and how these variations affect the snake's ability to climb.

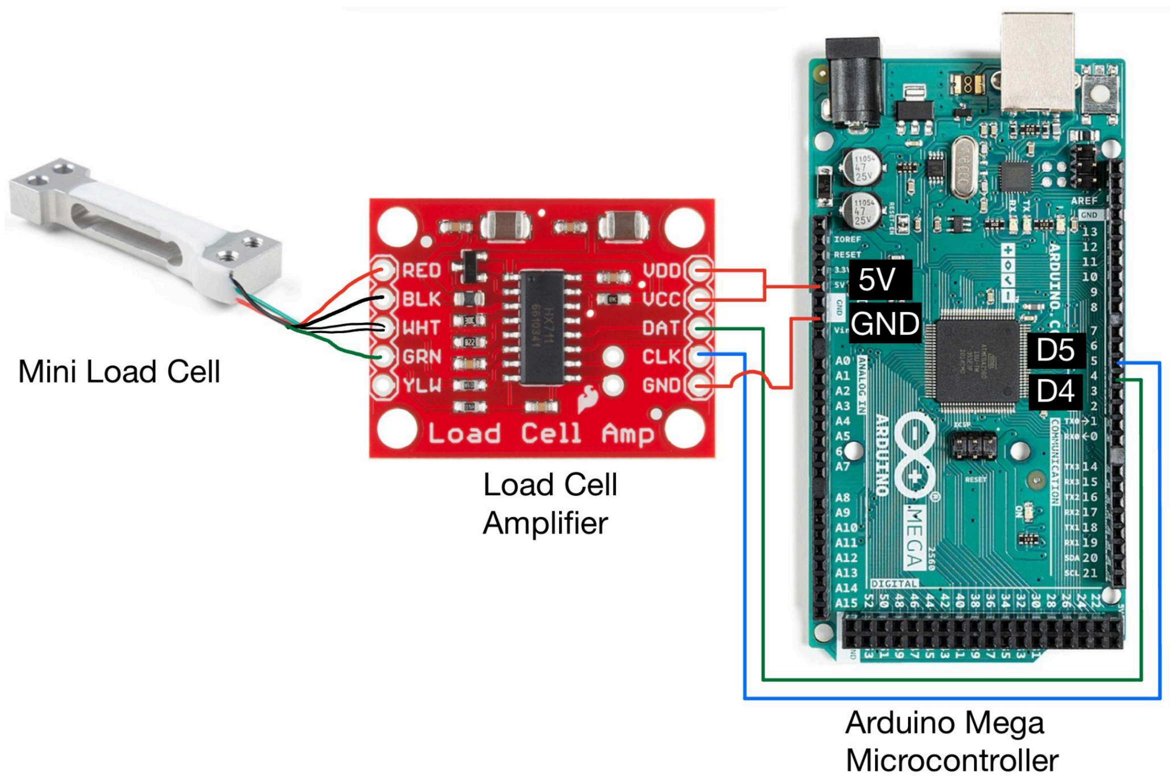

Figure 2.3: Example miniature load cell setup: A mini load cell [11] is connected to an amplifier [12], which is connected to an Arduino Mega microcontroller [13].

2.2 Pegs: Load Cells

2.2.1 Load Cell Functional Description

Each of the 22 pegs along the wall is force-sensitive, meaning they are able to record the amount of force the snake uses to push on the pegs while climbing. Each peg is attached to two miniature straight bar load cells, one for measuring force vertically and the other horizontally (Figure 2.4). Inside the mini-load cell is a bridge circuit, which is made up of four strain gauges, which measure electrical resistance (Figure 2.5). When pressure is applied downward at the tip of the load cell, the load cell deflects, and the amount of resistance changes. This change in resistance is proportional to the force applied and the resulting voltage difference is converted into grams for real-time force data, which is outputted on the Arduino serial monitor. Similarly, if pressure is applied on the bottom of the cell, upward, the load cell measures negative forces – one load cell measures forces in both directions of an axis (Figure 2.6a). In addition, getting another load cell and turning it 90 degrees gives left and right force measurements, resulting in a peg with two load cells that, combined, measure 2D force (Figure 2.6b).

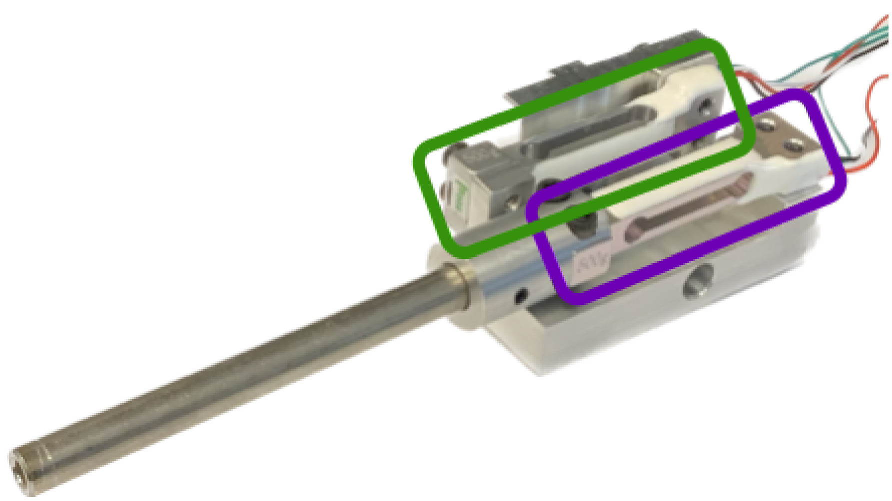

Figure 2.4: Peg setup with 2 load cells. The load cells are held together by custom metal housing. The green box indicates the load cell that measures vertical forces, while the purple box indicates the one that measures horizontal forces.

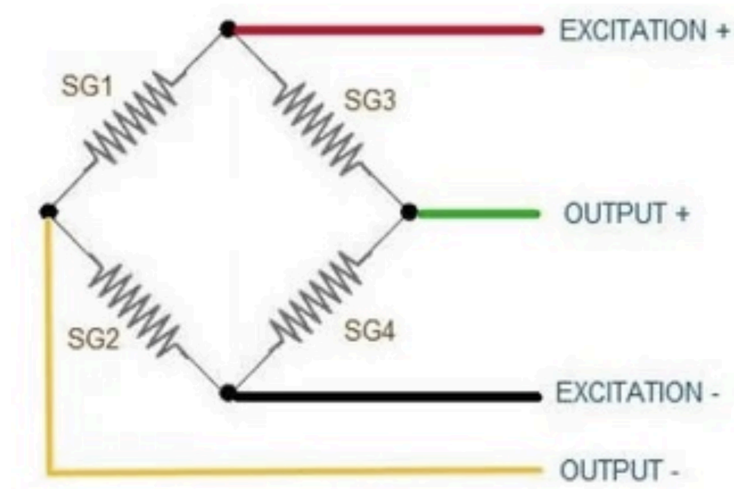

Figure 2.5: Bridge circuit of four resistors in each of the load cells [14].

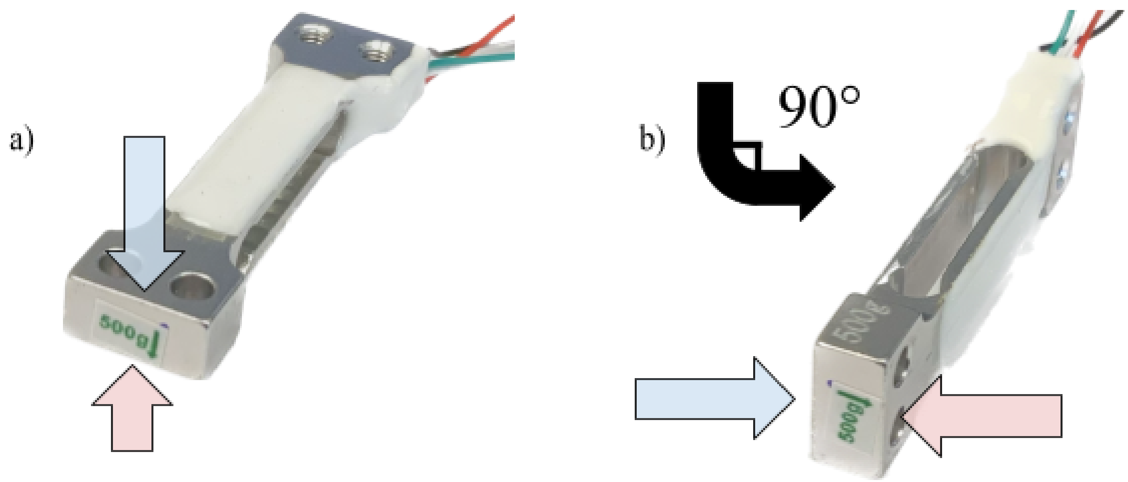

Figure 2.6: Pushing down (blue arrow) on the load cell on the left (a), gives us a downward force, while pushing upward (red arrow) gives an upward force. Another load cell load cell turned 90 degrees (b) measures right (blue arrow) and left (red arrow) force.

2.2.2 Precision and Accuracy of Load Cells

To gauge their reliability, the load cells' precision and accuracy were tested. They are built to withstand and measure loads from -500g to 500g and the average weight of each corn snake is around 100g. Since the average weight of the whole snake fits comfortably within the measuring range of the load cells, any inaccuracies toward the ends of the load cell measuring capacities will not be of concern.

Although the load cells demonstrated consistent and precise measurements, we wanted to ensure their reliability over time. To test this, we ran a load cell positioned vertically (like in Figure 2.6a) to measure an unloaded weight for 60 hours. It was calibrated with a mass of 250g, the middle of the load range. By doing this, we hoped to catch any drift or variation in the measurements that might have occurred over an extended period of time. The resulting graph, shown in Figure 2.7a, illustrates our findings.

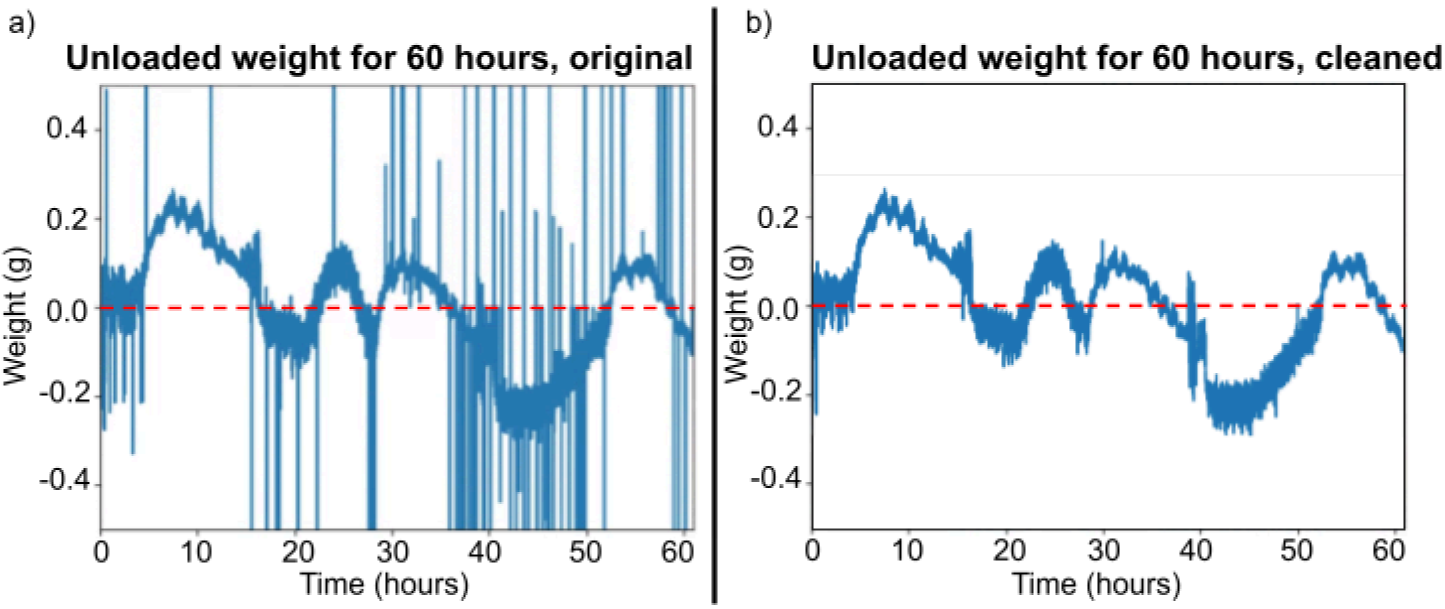

Figure 2.7: Noise measurements for an unloaded weight for 60 hours of noisy original data (a) and cleaned data (b). The red dotted line indicates where weight = 0g.

A few noticeable issues arise: significant spikes in the data and notable oscillations with an amplitude of up to ±0.2g. These spikes are a consequence of errors in data output and are easily corrected with a median filter. The filter computes the median of each data point with four adjacent points, effectively eliminating noise.

Now, we address the oscillations in the data which raise doubts about the integrity of the calibration constants, *C*. Calvin Riiska, a graduate student involved in this project, conducted calibration tests. He gathered about 100 raw data points from each load cell (*C=1*) and calculated the average value. This process was repeated for 10 masses within the load cell range. After, he fitted a line to these values and the resulting slope value gave the calibration constant. Using this approach, he found the calibration constant for each of the 44 load cells, with a 95% confidence interval. In addition, the load cells will not run for any longer than ten minutes as the snakes are given a maximum of ten minutes to climb and load cells are reset afterward. Zooming into the first hour of the previous graph (Figure 2.8) the noise amplitude is within ±0.05g, about .05% of the snakes' body weights, and is insignificant.

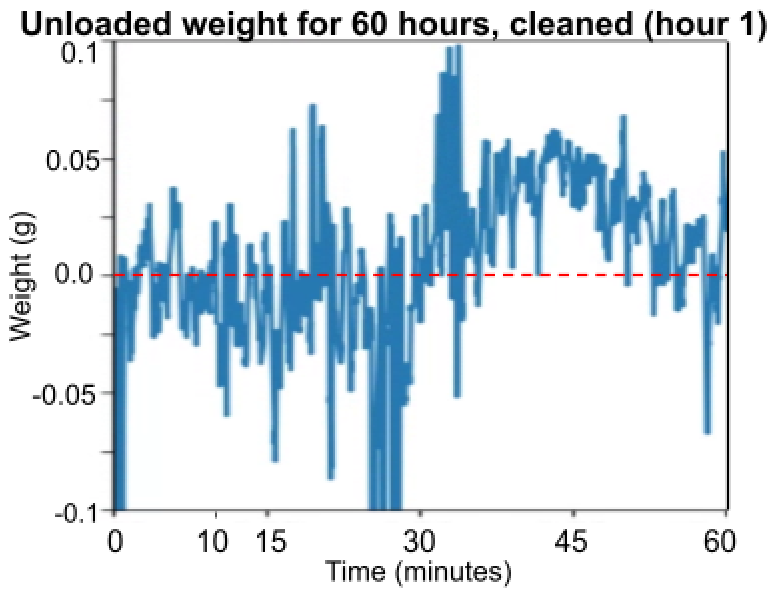

Figure 2.8: Figure 2.7 zoomed in at 0 to 1 hours.

Given that the load cells will be the primary tool for data collection and analysis, we want to be certain of their reliability and accuracy. As time passes, the load cells grow more inaccurate, but this decline is negligible within ten minutes– the maximum amount of time for each climb. By determining calibration constants for each load cell, we make sure our data is as accurate as possible. Overall, these load cells offer a novel, cost-effective solution for accurate data collection, priced at just $11 each.

2.1.3 Peg Shape Configuration on the Wall

While testing various peg configurations, our goal was to create a wall that posed a challenge for the snakes without being impossible to climb. We started with a wall with 22 normal pegs and the snakes were able to successfully grip onto these normal 3 mm pegs and navigate both upward and downward climbs. To introduce an additional challenge, we incorporated tapered pegs into the wall design. The angle of these tapered pegs significantly impacted the snakes' ability to grip the wall and push on them, therefore resulting in a more demanding climbing experience.

Upon experimentation, we found that including six tapered pegs rendered the climbs excessively difficult, resulting in failure in every run. However, with five tapered pegs, we achieved a climbing success rate of 40%, which we consider appropriate for our study. In this configuration, the first and last few pegs remained normal, providing a secure foundation for the snakes to begin their climbs. In between, every third peg was tapered, resulting in a total of five tapered pegs.

With a relatively balanced distribution of successful and failed climbs, we can analyze and compare these results to gain insights into how the geometry of tapered pegs impacts the climbing abilities of the snakes.

2.1.4 3D Kinematic Data:

The last part of the setup records 3D kinematic tracking data to go with the 2D force data. Through software called Optitrack, consisting of an infrared camera system with six cameras, we are able to record 3D data of the snake's movement to a sub-millimeter resolution. This is done by attaching 30-40 tracking markers along the back body of the snake, spaced about 1 cm apart. Each of the cameras captures the movements and triangulates the position of these markers along the snake and gives its 3D location in time.

Figure 2.9: Optitrack camera setup facing the climbing wall.

In Figure 2.10, we visualize the climbing wall setup in its entirety.

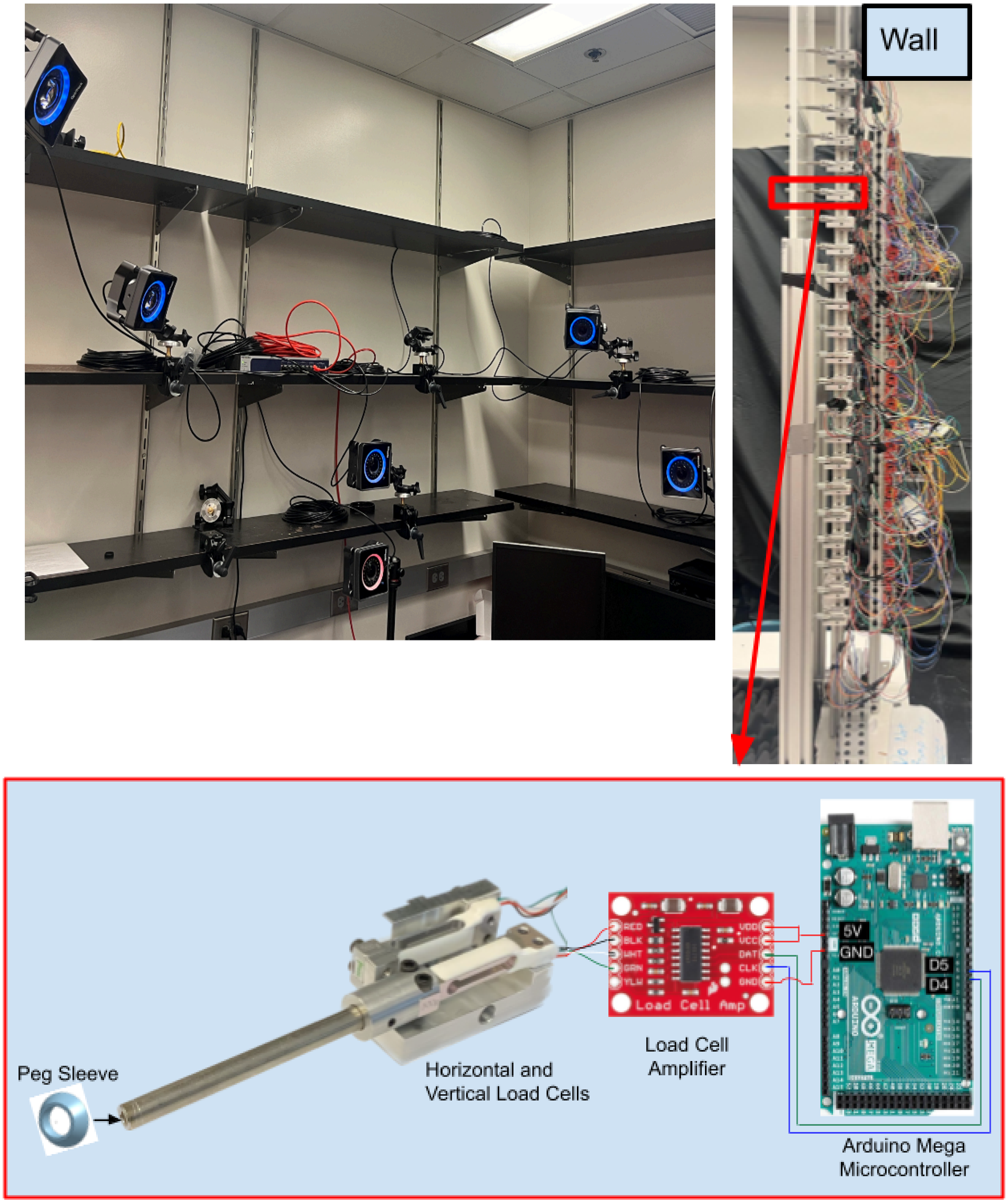

Figure 2.10: The entire experimental setup

CHAPTER 3

EXPERIMENTAL DATA COLLECTION

3.1 Running Climbing Trials

3.1.1 Modes of Snake Locomotion

Although there are five corn snakes in the lab: Elote, Taki, Candy Corn, and Corn Chowder, only four of the individuals were able to climb the setup and three of them climbed consistently. Climbing trials were not run with individuals within 72 hours of being fed.

To minimize bias, a random number generator is used to select two individuals and their direction of climbing, for ten trials. Each individual is given a ten minute window to complete their upward or downward climb. If they are able to complete the climb, the ten minutes are cut short and we move on to the next trial. If they are unable to complete the climb within ten minutes, we move on to the next trial. For upward climbs, the snakes are held up to the bottom of the wall and they climb off the hands holding them onto the wall. Similarly, the snakes are held to the top of the wall for downward climbs.

3.1.1 Successful vs. Unsuccessful Climbs:

If the snake is able to complete the climb from bottom to the top or almost to the top, or vice versa, the trial is counted as successful. If the snake makes a significant amount of progress (climbs at least five pegs) and decides to switch directions, or falls off the wall during the middle of the trial, we count this as an unsuccessful trial. However, if the snake does not make any progress, moves up/down one or two pegs, or promptly falls off the wall, we do not count this in our data as either a successful or unsuccessful trial.

3.1.2 Upward Climbs

On upward climbs, we see behavior similar to both concertina and lateral undulation (See section 1.1.1 for definitions). Looking at the snake's initial position, its body alternates on the left and right side of the pegs, in a sinusoidal wave-like position (See Figure 4.1a for a visual). To move upward, it curves its head around a post and hooks onto it, pulling the rest of its body up segment by segment. Its body follows the same curves, similar to lateral undulation. However, this movement is very slow and choppy and it appears to be quite arduous for the snake to move in this manner, reminiscent of concertina. As the snake inches up, there is frequent stopping, especially when its body slips over the tapered pegs. Multiple attempts are required to cling onto these tapered pegs, but the snake utilizes every peg its body touches.

3.1.3 Downward Climbs

Downward climbs are more fluid than upward climbs, emulating lateral undulation more closely than upward movement. It looks like the snake is sliding down the wall. There still is a bit of choppiness as the snake waves its head back and forth when it looks for the next peg. In addition, when the snake initially attempts to situate on a tapered peg, it often slips over the peg, but it is frequently able to skip past the tapered peg. The snake still utilizes every peg its body touches but does not rely as heavily on the peg the head touches to stay on the wall.

CHAPTER 4

RESULTS AND DISCUSSION

In total, we studied 14 upward climbs and 14 downward climbs, with success rates of 36% and 47%, respectively. This data allows us to conduct analysis and draw initial conclusions. We will first observe the forces behind snake climbing behavior.

4.1 Comparing Successful Upward with Downward Climbs

4.1.1 Climbing Forces and Kinematics on Upward VS. Downard Climbs

With 3D kinematic data, we visualize the snake's locomotion up and down the wall by taking the 30-40 tracking markers along the snake and fitting a spline onto the curves of its body. Graphing this data gives us the snake's body position in time. Additionally, the 2D force data can aid in visualizing the force exerted on the pegs. By taking the horizontal and vertical force components, we construct vectors with both the direction and magnitude of force applied to each peg. Combining the 3D kinematic data and the 2D force data enables us to visualize the snake's climbing behavior, at any time, *t*. Figure 4.1a illustrates an example of a successful ascent, while Figure 4.2a illustrates a successful descent, both at *t=60s*. The red dots and vectors represent tapered pegs and subsequent forces, respectively, while blue represents normal ones.

Additionally, with the 2D force data from the pegs, we can plot the vertical and horizontal forces of each peg over time, normalized by total body weight. Figure 4.1b depicts an ascent and 4.2b depicts a descent where pegs range from dark blue at the bottom of the wall, to yellow at the top. The magenta lines represent the total force exerted by all pegs in their respective orientations and the vertical red line indicates the climb, at *t=60s*.

a) b)

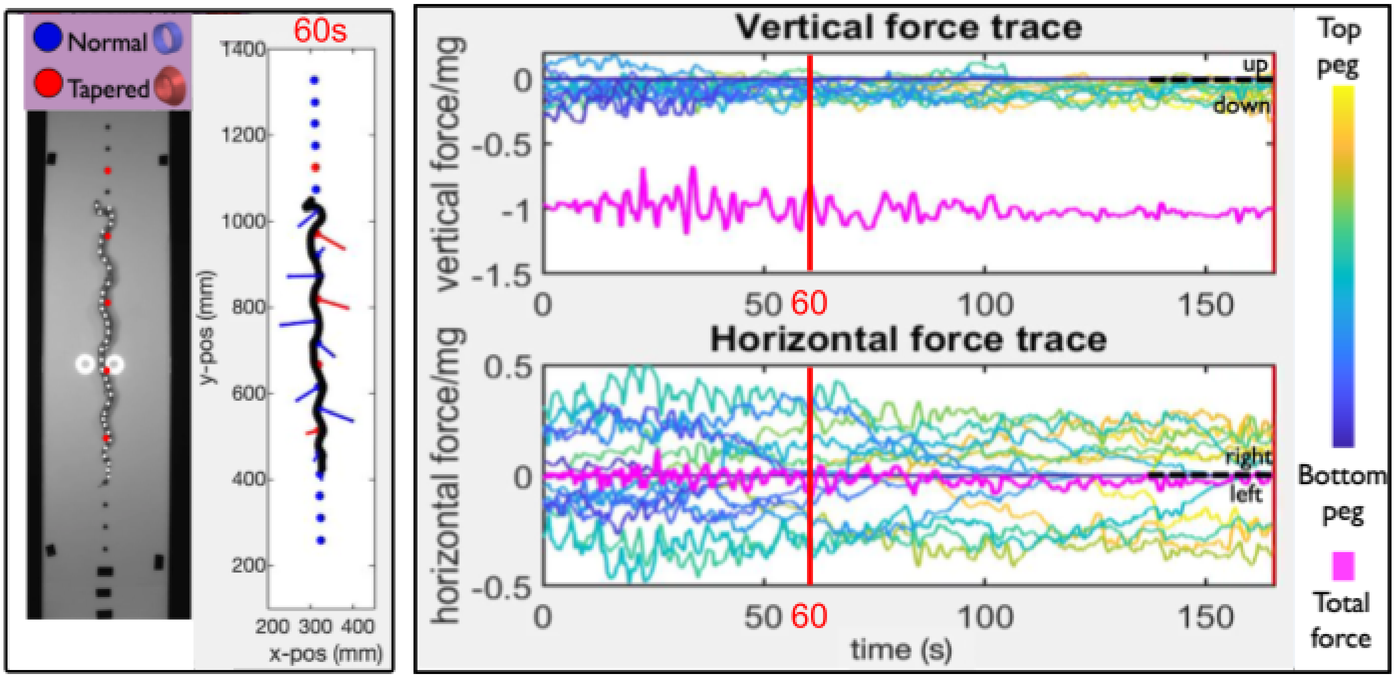

Figure 4.1 (a): Snapshot of **ascent** (left) with splined kinematic data with force vectors (right) at 60 seconds. (b): Vertical (top graph) and horizontal force (bottom graph) trace for each peg as a function of time. The red line indicates time at 60 seconds.

a) b)

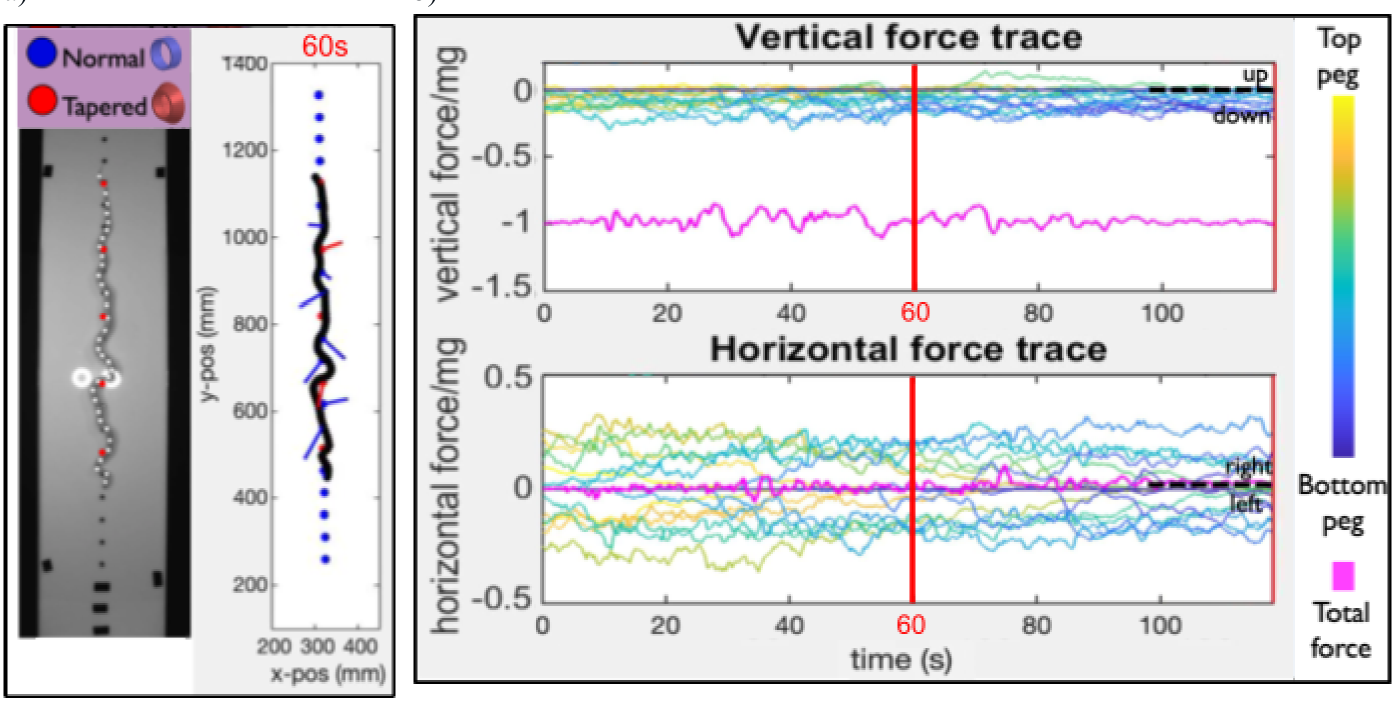

Figure 4.2 (a): Snapshot of **descent** (left) with splined kinematic data with force vectors (right) at 60 seconds. (b): Vertical (top graph) and horizontal force (bottom graph) trace for each peg as a function of time. The red line indicates time at 60 seconds.

First, we analyze the upward climb (Figure 4.1) and then compare it with the downward climb (Figure 4.2). On the upward climb, we observe a snapshot in time during the snake's upward climb, at 60 seconds. The snake's body alternates between each peg, applying strong lateral forces with mostly the midsection of its body, including some of the tapered pegs. Presumably, these horizontal forces help the snake stay secure on the wall, by pressing into the pegs and creating tension to support its body and work against gravity. This concept is analogous to a human holding themself aloft in a chimney by extending their limbs pushing outward from the body. The lack of vertical forces indicates that the snake depends mainly on lateral stability to remain upright on the wall. If the snake were to cease applying horizontal force and rely solely on gravity while balancing on the wall, it would likely peel away from the wall and fall off.

Now, let us direct our attention to the force trace graphs in Figure 4.1b, which provide insight into all the forces applied throughout the duration of the climb, rather than just a single snapshot. The top graph illustrates the vertical force trace, where negative values represent downward forces and positive values indicate upward forces. The total force line oscillates around -1, reflecting the snake's overall downward mass due to gravity. Upon closer examination, we observe seemingly counterintuitive upward forces. However, these upward forces are genuine, as the snake stabilizes itself by exerting upward pressure. In the bottom graph, horizontal forces are depicted, with negative values representing leftward forces and positive values indicating rightward forces. Once again, we observe significant lateral forces, surpassing the magnitude of the vertical forces. Moreover, the left and right forces remain evenly balanced, resulting in the total horizontal forces consistently summing up to zero.

Secondly, we observe a moment halfway through the snake's downward climb, also at 60 seconds, in Figure 4.2b. The snake still applies lateral forces, but they are not as strong as the upward climb's lateral forces. The forces on the tapered pegs during the downward climb are also less longitudinal. This suggests that the snake does not rely on the tapered pegs for stability as much during downward climbs compared to upward climbs. There is a more mixed distribution of horizontal and vertical forces, indicating that the snake relies less on the pegs, in general, to stay secure on the wall for downward climbs.

Looking at the forces for the entirety of the downward climb in Figure 4.2a., notice the sequence of peg colors now begins with yellow and progresses to blue, instead of the reverse order, as the snake starts the climb from the top of the wall. In this scenario, similar observations to the ascent can be made, where the majority of vertical forces are downward, summing up to approximately -1, and the horizontal forces summing to 0. However, there appears to be less variability and noise around both of these sums. This could be attributed to the snake exhibiting a smoother motion during downward climbs compared to upward climbs, where frequent stops and choppy motion are common.

4.1.2 Modes of Locomotion on Upward vs. Downward Climbs

Next, we will examine two types of graphs that reveal more about the forms of locomotion the snakes are employing: trajectory path graphs and velocity graphs.

The trajectory of the snake's body during both ascent (left graph) and descent (right graph), is shown in Figure 4.3, starting with dark blue for its initial position of the whole body and transitioning to a gradient of grayish-white for its final position. These graphs reveal the snake generally follows its body in smooth, sinusoidal waves, characteristic of lateral undulation.

On both climbs, we see bulbs around each of these individual waves, indicated by the pink arrows because the snake waves its head back and forth as it searches for the next peg. Thicker lines in the trajectory, marked by a blue arrow, indicate areas where the snake's body slips over tapered pegs. While this slipping occurs more frequently during downward climbs (right), the snake is more stable during descents, disregarding slipping.

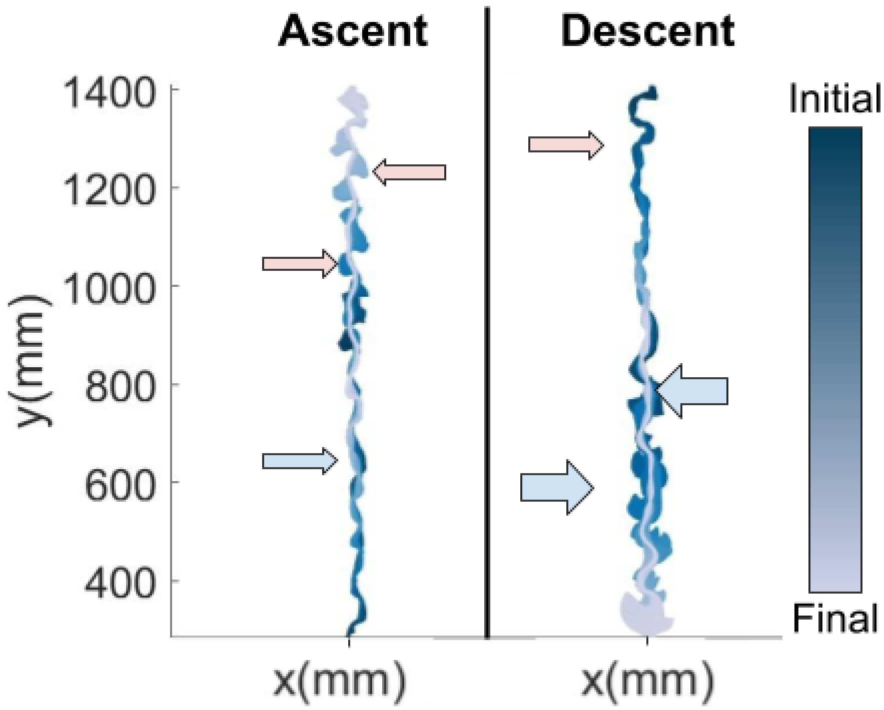

Figure 4.3: Climbing trajectory graphs of an upward climb (left) and downward climb (right).

The velocity as a function of time of the upward climb (left) and downward climb (right) is depicted in Figure 4.4. Velocity is calculated by deriving the position components of the 100-point spline from the earlier 3D kinematic data. This process yields the total velocity, depicted by the color bar, for each of the 100 body points over time. The white box represents the velocity of each point on the snake after 60 seconds. The top of the graph corresponds to the head position while moving downward indicates travel along the snake's body length, with the bottom of the graph representing the tip of the tail.

In the first 40 seconds of the upward climb, the graph displays numerous vertical stripes of dark and light blue, indicating choppy fluctuations in the snake's speed, characteristic of concertina. However, upon closer inspection, these vertical stripes are slightly tilted counterclockwise. This means the head moves first and the preceding body segments are pulled upward, one after the other. Once the rest of the body has inched upward, the head moves again and repeats this behavior. In contrast, the initial 40 seconds of the downward climb appear smoother, with more consistent velocity throughout the snake's body. Additionally, during the downward climb, the snake's head moves with greater velocity as it swings back and forth to locate the next peg. However, the snake cannot display the same blind reliance on upward climbs, as any sudden or wrong movements may cause it to fall.

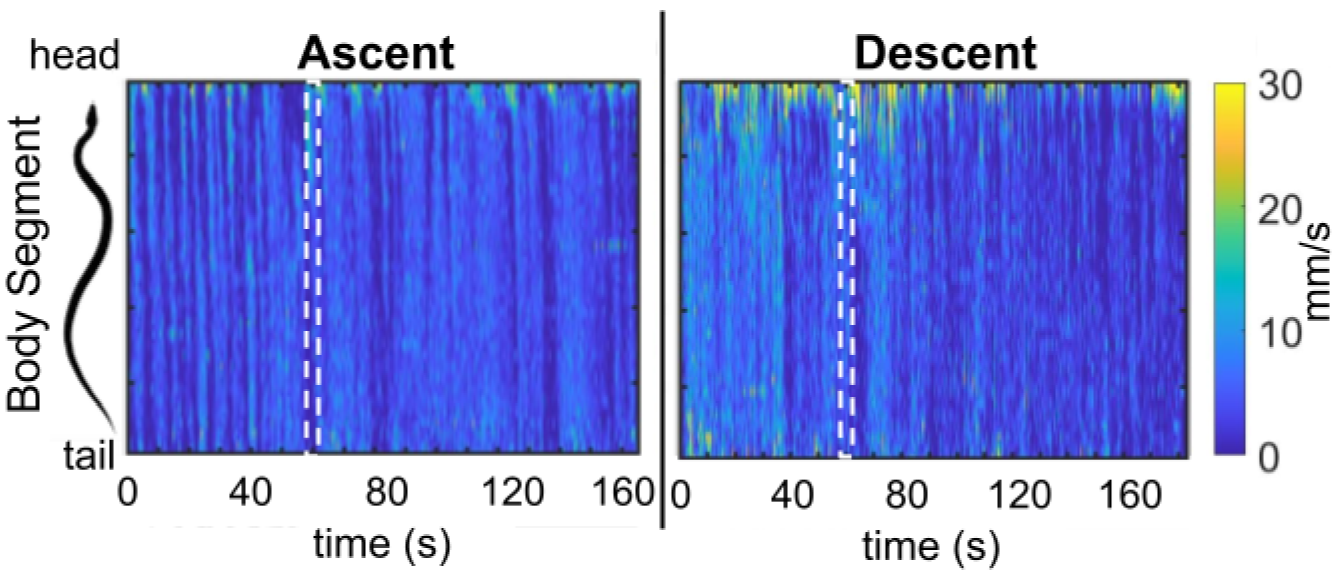

Figure 4.4: Velocity-time plots for each segment of the body for upward (left) and downward (right) climbs. The white box indicates velocities at 60 seconds. Snake photo [15].

In summary, our analysis begins with the visualization of the snake's locomotion and force output, using 3D kinematic data and 2D force data from the pegs. We observe the snake's reliance on lateral forces to cling to the wall for upward climbs, whereas the dependence is not as strong for downward climbs and the snake is able to skip tapered pegs. Furthermore, trajectory path and velocity graphs provide insights into the snake's climbing strategy, where we observe the similarities between upward climbs with concertina and downward climbs with lateral undulation. This analysis, allows us to refine our understanding of the snake's climbing abilities and the role of peg shapes in its performance. Overall, these analyses refine our understanding of the intricate mechanisms involved in snake climbing behavior and set the stage for how peg shape plays a role in both successful and unsuccessful trials.

4.2 Comparing Successful trials with Unsuccessful trials

Up until now, our focus has been on examining and analyzing successful upward and downward climbs, along with their differences. Now, we will shift our attention to comparing successful trials with unsuccessful ones. This comparison will help us fine-tune our understanding of the limits of the snake's climbing abilities and how the peg shape comes into play.

First, we examine something familiar: forces. We aim to discern the distinct roles played by different sections of the snake while climbing. Next, we shift our focus to the forces acting on the pegs. Analyzing the same individual upward and downward trials, as well as combined data from successful and unsuccessful runs, we aim to identify and analyze behaviors on tapered pegs that turn seemingly steady climbs into falls.

4.2.1 Forces on Segments of the Body for All Climbs

We begin by dividing the snake's body length into thirds: top, middle, and bottom sections. By graphing histograms depicting how often each body section applies horizontal forces relative to vertical forces across all trials, we generate the graphs depicted in Figures 4.5 and 4.6. The x-axis indicates the ratio of horizontal forces over vertical, while the y-axis represents the frequency of these forces. The dotted line indicates where these forces are equal. Points to the left of this line indicate stronger vertical forces than horizontal, and points to the right of the line indicate stronger horizontal forces than vertical. We first compare forces on successful upward climbs with unsuccessful ones, then we do a similar comparison for successful and failed descents.

Figure 4.5 depicts a histogram across all of the five successful ascent trials and all of the nine failed ascent trials. Here, we observe a majority of the forces being lateral, especially from the front two-thirds of the body. The midsection, in green, peaks higher in the successful ascents than failed. This further supports the claim that the midsection is crucial for stability, as it applies the most lateral forces, and almost no vertical forces. Additionally, the most glaring difference between these two graphs is of the back section, where the failed ascents shift further left, into the vertical forces. This is likely from the snakes applying upward force with the tip of their tails for stabilization. However, since this method of stabilization is found in the failed ascents, this insinuates that it is less effective than lateral methods of stabilization. This also implies that snakes must use as much of their body length as possible to stabilize effectively on the wall by pushing laterally.

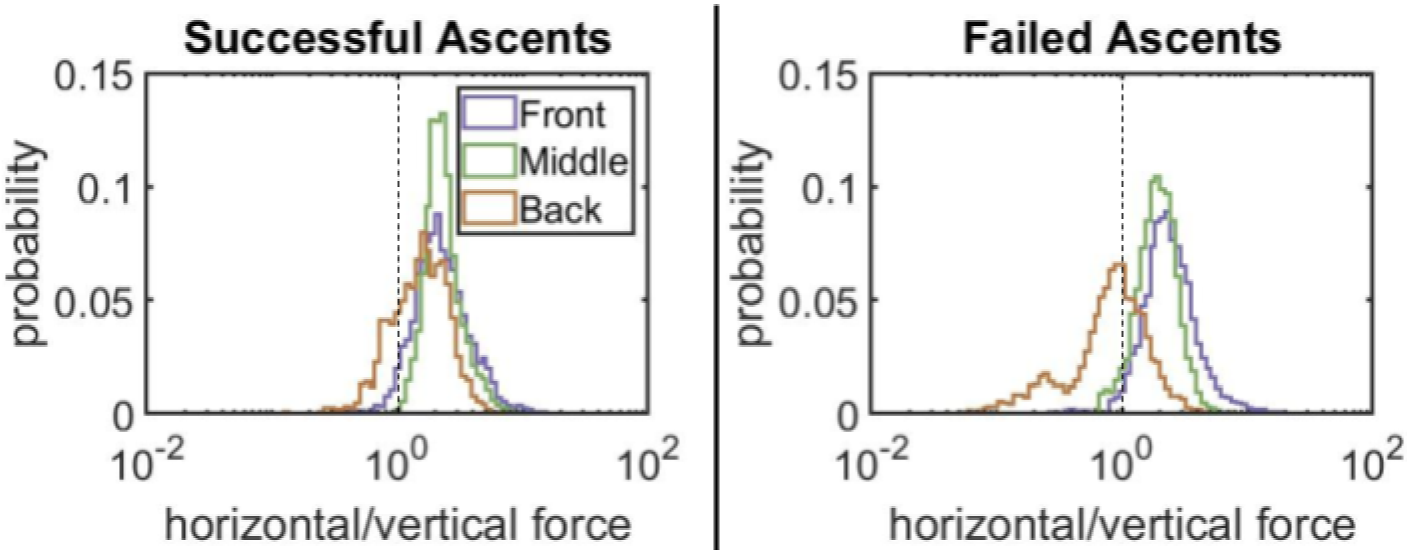

Figure 4.5: Histograms depicting the ratio of horizontal forces to vertical forces exerted by each third of the snake's body for successful (left) and failed (right) climbs on **upward climbs**.

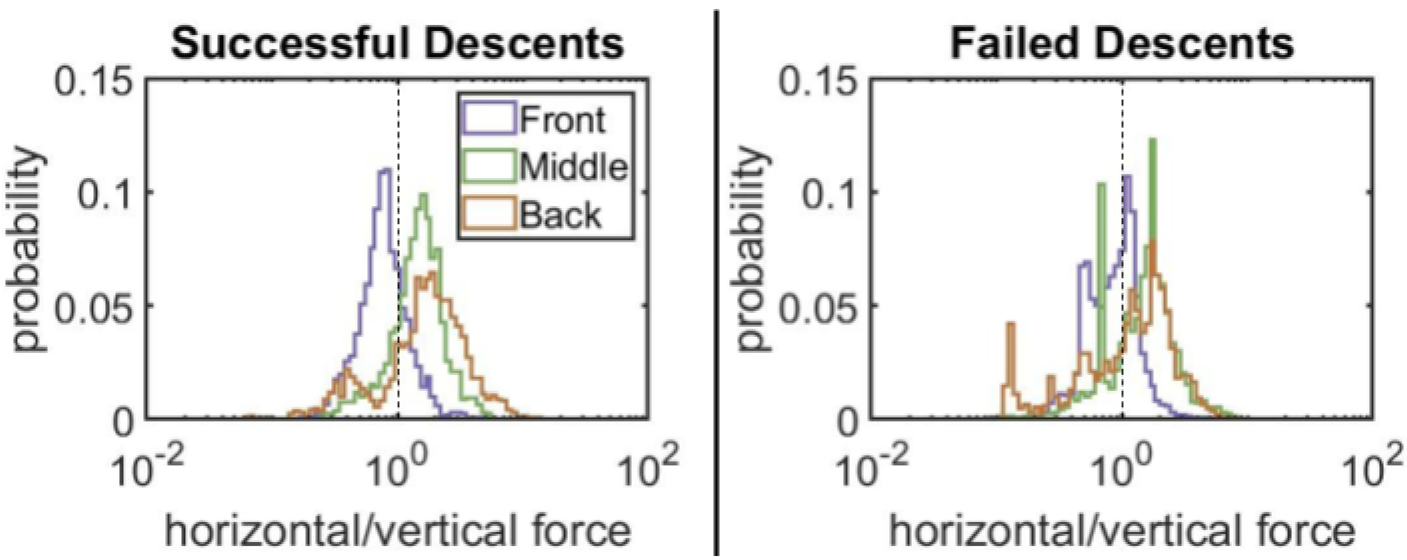

Figure 4.6: Histograms depicting the ratio of horizontal forces to vertical forces exerted by each third of the snake's body for successful (left) and failed (right) climbs on **downward climbs**.

Before comparing the successful descents (six climbs total) with the failed descents (eight total), shown in Figure 4.6, we first compare the successful ascents with successful descents. The most significant contrast lies in the forces exerted by the front third of the body. During successful descents, the front third snakes apply more vertical forces as they slide down the wall. While strong lateral forces are still evident from the middle third of the body, they are not as frequent or as strong as the successful ascents. Furthermore, the back third of the body appears to employ more vertical forces in the descents. This behavior can be explained by the anchoring technique sometimes employed by snakes, where they hook their tail around a peg as the front of their body slides down the wall.

We observe the distinct functions of each of the body segments during combined downward climbs while comparing successful descents, with failed ones. In particular, for successful descents, the front section primarily applies vertical forces, likely attributed to gravity, with some supporting lateral forces. Here, snakes methodically transfer the weight of the front third of their bodies onto the pegs while the back two-thirds provide stability against the wall. This deliberate weight distribution enables them to assess the reliability of the pegs in supporting their entire body weight. In contrast, the failed descents have fewer instances of vertical forces, indicating a lesser understanding of the shape and reliability of the next peg. Carelessly sliding onto a tapered can risk a fall. The forces from the back two-thirds of the body both have a peak on the vertical forces, showing where the snakes are not applying the stabilizing lateral forces, which may have contributed to the failed descents.

Here we summarize the roles of each section of the body. For upward climbs, the front third of the body primarily functions to locate the next peg, hooking onto the next peg to pull the rest of the body upward, while still applying strong lateral forces. For downward climbs, it also functions to locate the next peg while exerting significant downward forces, as it slides down the wall. Meanwhile, the midsection of the body applies the strongest lateral forces, which is key for stabilization on the wall, especially for upward climbs. Conversely, downward climbs rely slightly more on the back end of the snake for lateral stability, contributing to its overall locomotion.

4.2.2 Forces on Individual Pegs for Singular Climbs

In this next section, we now examine the forces on each of the 22 pegs on successful runs vs. failed runs with the same individual upward and downward trials we looked at previously (see Figures 4.1 and 4.2). Graphing the vertical and horizontal forces separately, as a function of time, we get two graphs for both Figure 4.7 and 4.8. The order of the pegs is indicated by the y-axis, where 0 is the bottom peg and 22 is the top peg. The dotted boxes indicate where each of the tapered pegs lies. The color bar represents the magnitude of forces relative to body weight applied, with red indicating forces directed upwards/right, and blue indicating forces directed downwards/left. We will first compare successful and failed upward climbs and then compare successful and failed downward climbs.

Figure 4.7 illustrates the forces measured during a successful climb. In the vertical graph (left), the predominant forces appear as blue, indicating a downward force. Although there are occasional instances of upward force, which we believe are for stabilization, they are relatively light. Additionally, most of them are directed onto the normal pegs, rather than the tapered ones.

Looking at the horizontal force graph (right), we see much stronger forces, including on the tapered pegs to our surprise. We see the strongest force applied on tapered peg 12 as well as the surrounding normal pegs, 11 and 13, for about half the duration of the climb. However, their unexpected usage prompts us to question whether upward climbs present greater overall challenges compared to downward climbs. This leads us to consider that the difficulty of an upward climb may surpass the difficulty of clinging to tapered pegs, forcing the snake to rely on all pegs to maintain security on the wall.

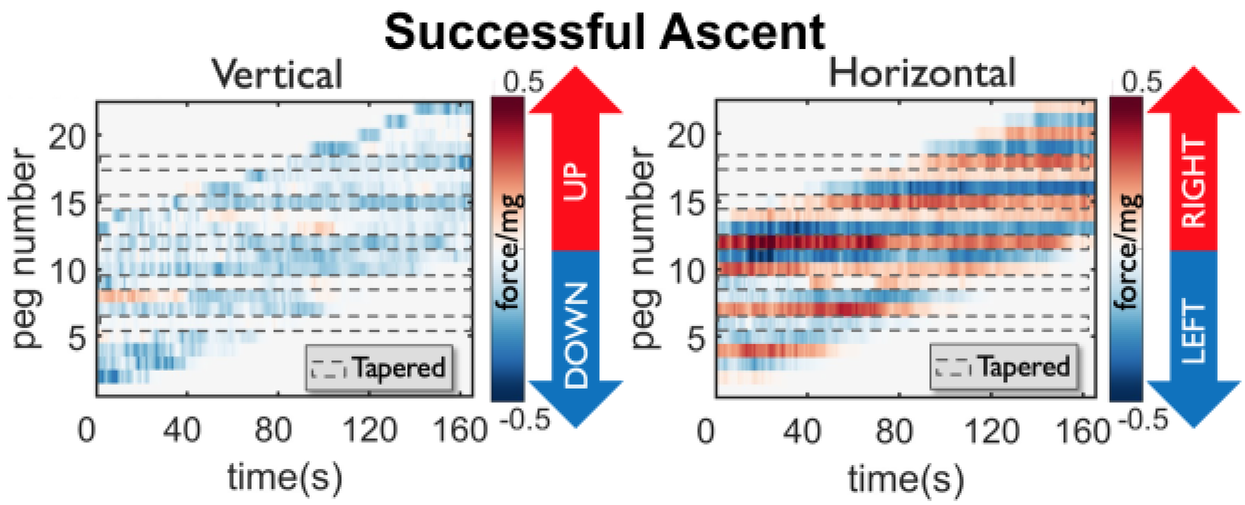

Figure 4.7: Vertical (left) and Horizontal (right) force graphs per peg as a function of time for **successful upward** climbs. Dotted boxes indicate where the tapered pegs are.

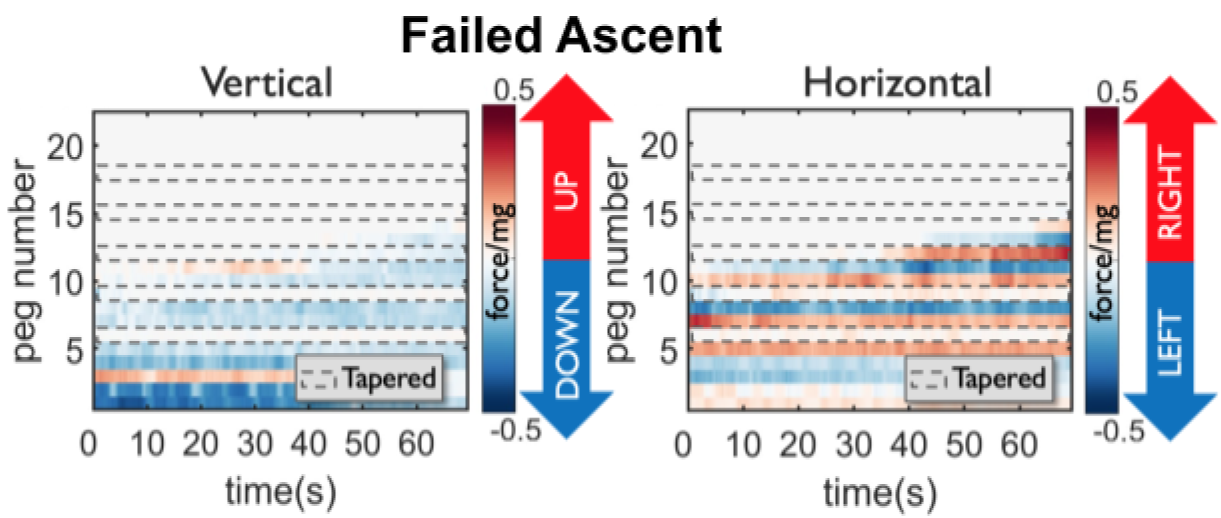

Figure 4.8: Vertical (left) and Horizontal (right) force graphs per peg as a function of time for **unsuccessful upward** climbs. Dotted boxes indicate where the tapered pegs are

To confirm these speculations, we compare this run with an unsuccessful upward run, depicted in Figure 4.8. We see where on the wall the snake falls – when the graph turns all white. On the vertical force graph (left), the forces look similar: predominantly downward forces exerted on normal pegs. On the horizontal graph (right), the lateral forces are smaller in magnitude than the successful climb. As it climbs upward, the snake skips the first two tapered pegs and we see forces on normal pegs 7 and 8, and tapered peg 12, right before its fall. This is where we gain valuable insight. On the successful climb (Figure 4.7), the forces on tapered peg 12 are matched and sandwiched by normal pegs 11 and 13. Although the snake utilizes a tapered peg, it uses an additional two normal pegs to support its reliance on the tapered peg. In other words, without reinforcement from adjacent normal pegs, the snake's reliance on a tapered peg alone significantly increases the risk of falling. This is evidenced by the unsuccessful attempt on peg 12, as the reinforced support on the normal pegs 11 and 13 are not nearly as strong as the forces we see in the successful run. Additionally, as hypothesized earlier in this section the difficulty of upward climbs forces the snake to rely on tapered pegs in addition to normal pegs. However, since the snake avoided the tapered pegs and exhibited weaker lateral forces overall, its stability on the wall was compromised, resulting in the fall.

Now, we examine downward climbs, which have a more straightforward analysis. The vertical force graph of the successful ascent (Figure 4.9, left) shows similar trends as the upward climb’s vertical forces. Although there are significantly fewer forces exerted on the tapered pegs compared to the normal ones, the frequency of forces applied on tapered pegs is more prominent in the downward climbs than upward. Additionally, the magnitude of vertical forces matches the horizontal forces (right) more closely. The snake applies less lateral force on the tapered pegs than the normal pegs but does not avoid them completely.

On the failed descent, in Figure 4.10, the two dark red spots on the horizontal force graph (right) draw immediate attention. These two surges of strong lateral forces on peg 12 highlight the most notable disparity between the successful and failed graphs: the magnitude of lateral force applied to the tapered pegs. We can deduce that the snake's heavy reliance on the tapered pegs, both laterally and longitudinally, almost certainly caused the fall.

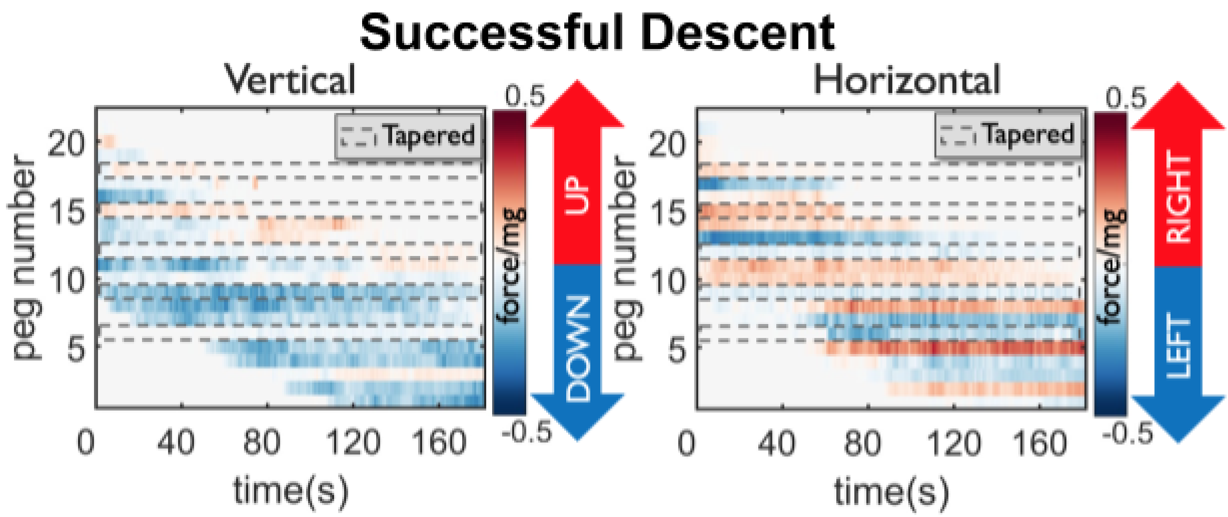

Figure 4.9: Vertical (left) and Horizontal (right) force graphs per peg as a function of time for **successful downward** climbs. Dotted boxes indicate where the tapered pegs are.

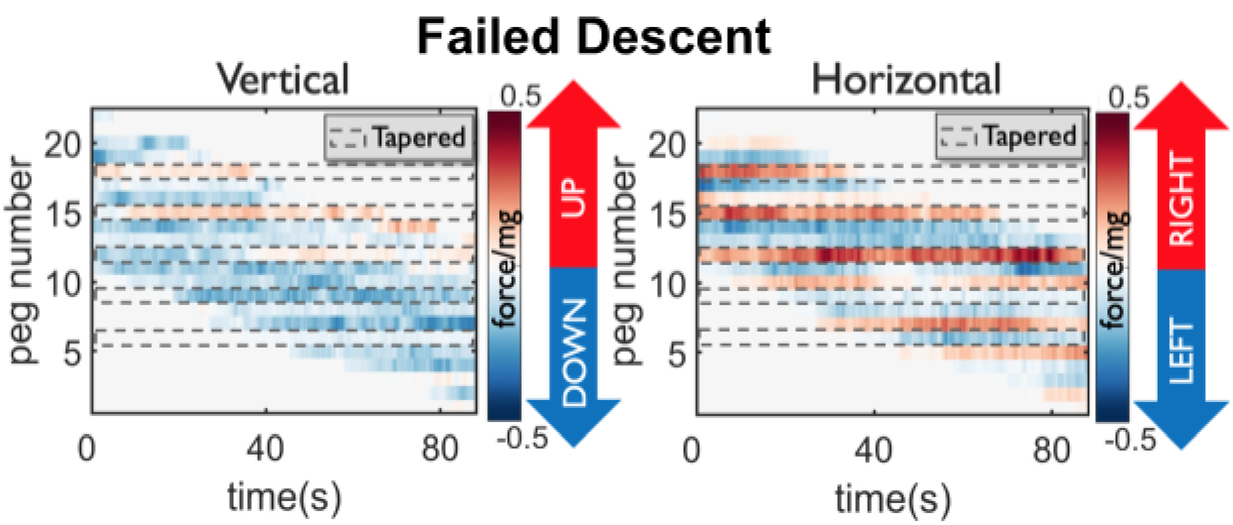

Figure 4.10: Vertical (left) and Horizontal (right) force graphs per peg as a function of time for **failed downward** climbs. Dotted boxes indicate where the tapered pegs are.

4.2.3 Force Histograms of Normal and Tapered Pegs for All Climbs

Lastly, we will compare directly compare data from the normal pegs and the tapered pegs. Combining the force data for all of the trials, we overlay histograms of the frequency of vertical forces on one graph and horizontal on the other, of the normal and tapered pegs. In these histograms, the purple plots represent the forces on the normal pegs, while the green plots represent the forces on the tapered pegs. Since there are more normal pegs than tapered pegs on the wall, the data has been normalized to account for the respective number of pegs. We present four sets of these histograms: successful ascents, failed ascents, successful descents, and failed descents, denoted by graphs 4.11-4.14, respectively.

First, we examine and compare successful ascents with failed ascents (Figures 4.11 and 4.12), looking at vertical forces first, then horizontal. The vertical forces for the successful upward climbs look very similar to the failed ones. Both of these graphs have a sharp peak from the tapered pegs, showing that there was a considerable number of times no force or close to no force was applied to them. Additionally, there is an even distribution of upward and downward forces applied to the tapered pegs. The normal peg histograms, for both the successful and failed climbs, are positioned to the left of 0, indicating that the majority of the vertical force applied was directed downward, due to gravity. The small tails extending into the positive side represent instances where the snake exerted upward force, likely for stability purposes. The vertical forces exerted on the tapered pegs during the successful ascents exhibited a slightly broader distribution around 0, compared to the failed ascents. This suggests that even applying a small amount of force to tapered pegs contributes to successful climbs more than not applying any force at all.

The horizontal graphs of the upward climbs reveal more significant differences. On the successful climbs, we see a very wide distribution of horizontal forces applied on both the normal and tapered pegs. However, the failed ascends have a narrower distribution and the tapered peg histogram has a small peak at 0. This further solidifies that applying strong lateral forces leads to a successful upward climb. Looking at the normal histograms for the successful and failed runs, notice two humps on either side of 0. These humps are a result of the snakes' sinusoidal climb, where it weaves to the left and right of the pegs. The tapered peg histograms have a perplexing shape, however. We believe this is due to some bias in the data, where once the snake climbs up the wall, its body usually ends up on the same side of all of the tapered pegs. We can see this when we refer back to Figure 4.7, where almost all of the horizontal force applied on the tapered pegs is pointed to the right. With more data, we believe this histogram will look more even on both sides of 0. All of this data aligns with our previous observation that, despite the difficulty in gripping tapered pegs, the snake must rely on them to complete upward climbs. Utilizing more pegs results in greater stability and a more even distribution of dependence across the pegs. If a snake is on ten pegs total and slips off of one, it still has nine others to support itself, resulting in only 10% of its original support gone. However, if the snake is only using five pegs and slips off one, 20% of its original support is lost.

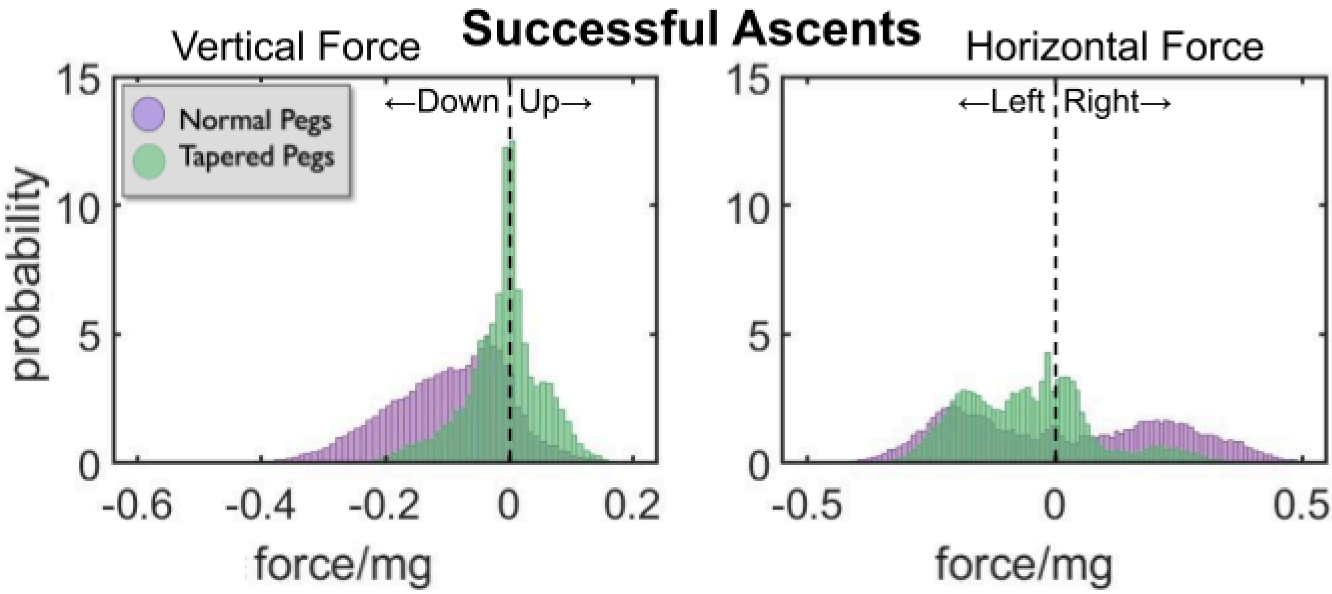

Figure 4.11: Probability distributions of tapered pegs vs. normal pegs split into vertical and horizontal components of **successful ascents.** The normal pegs are indicated in purple, while tapered in green.

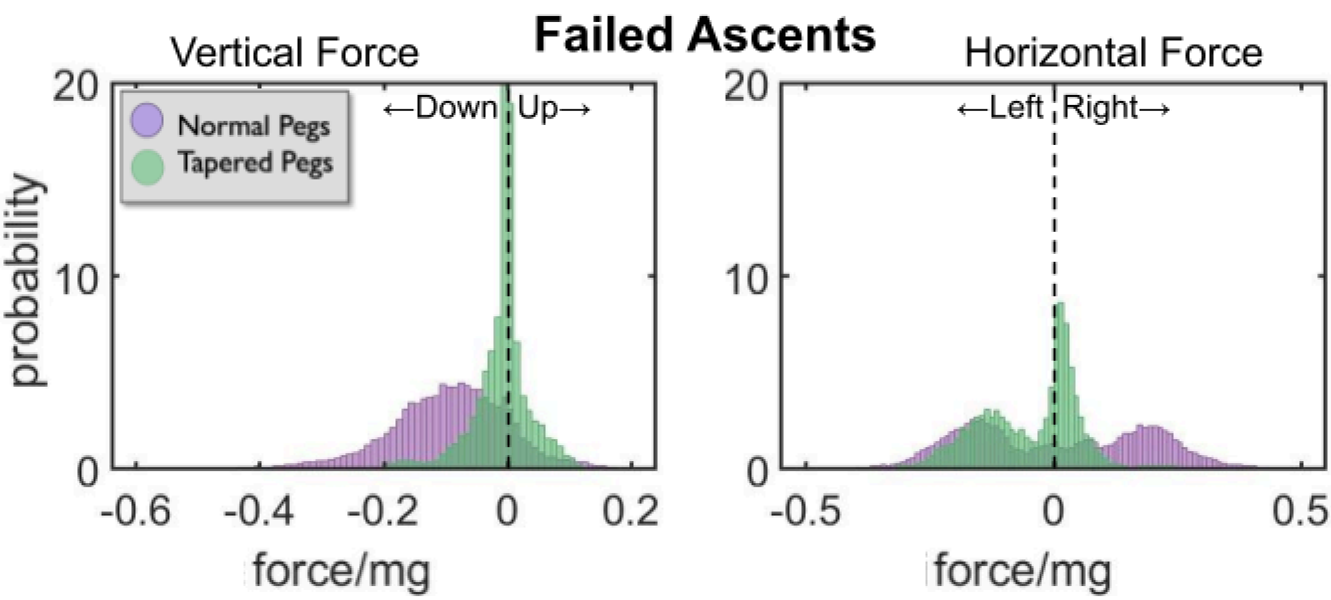

Figure 4.12: Probability distributions of tapered pegs vs. normal pegs split into vertical and horizontal components of **failed ascents.** The normal pegs are indicated in purple, while tapered in green.

Now we shall compare data between the successful descents and failed descents (Figures 4.13 and 4.14), starting with vertical forces again. The tapered pegs peak higher on the failed descent than the successful one, and again, have a narrower distribution. The normal peg distributions are very similar, however.

Looking at the horizontal forces, we see an even match of the left and right forces on both the normal and tapered pegs, at least for the successful descent. There are fewer lateral forces applied on the tapered pegs than the normal ones, as we've seen earlier. On the failed climbs, we see some bias once again, for the same reason: the snakes' bodies usually end up on the same side of all of the tapered pegs. Taking more data will smooth out this bias. The same two humps observed on the horizontal graphs of 4.11-4.13 are not as prominent on the failed downward climbs. This may be due to the fact that the snakes apply less horizontal forces in general while climbing downward, as they do not need the extra stability.

Moreover, previous studies have highlighted the considerable energy usage associated with climbing techniques involving wrapping, using up to three times the force required to support the snake's body weight. However, our analysis, as depicted in Figures 4.1b and 4.2b, reveals that the total force exerted by the snake throughout the entire wrap-less climb equates to its own body weight, a third of the energy usage observed in climbs involving wrapping. This suggests that climbing without wrapping is more energy-efficient and likely less demanding for the snake.

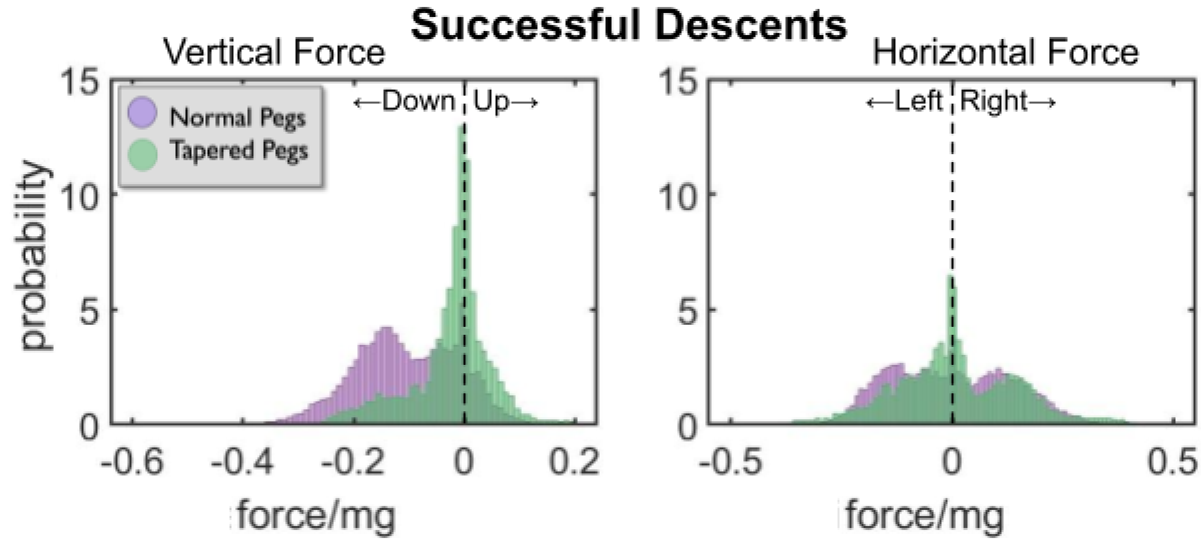

Figure 4.13: Probability distributions of tapered pegs vs. normal pegs split into vertical and horizontal components of **successful descents.** The normal pegs are indicated in purple, while tapered in green.

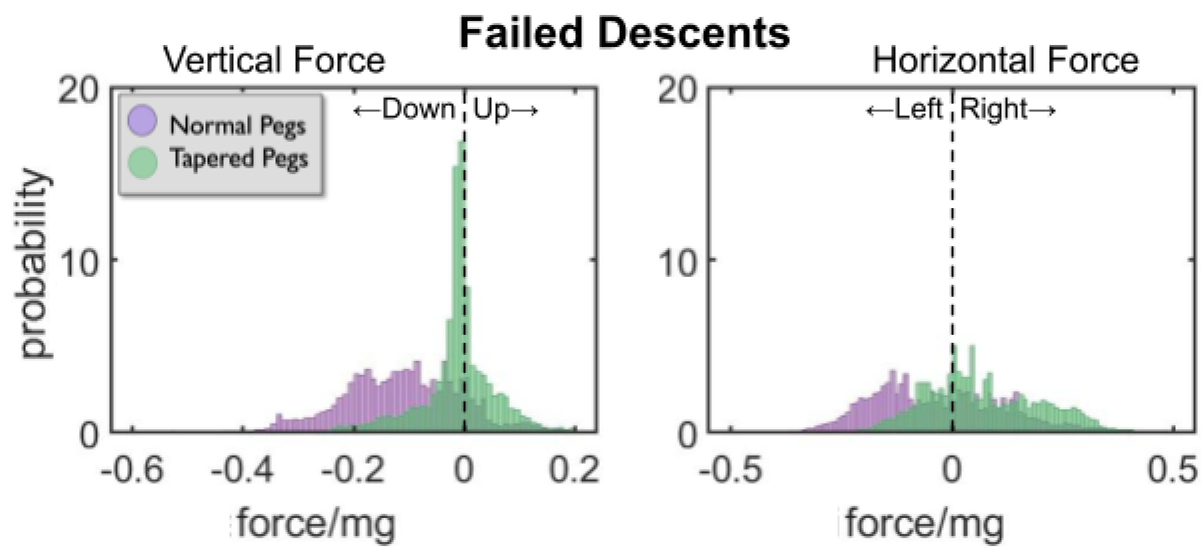

Figure 4.14: Probability distributions of tapered pegs vs. normal pegs split into vertical and horizontal components of **failed descents.** The normal pegs are indicated in purple, while tapered in green.

In summary, our analyses revealed insights into the different roles that each section of the snake's body plays and how climbing direction has a lot of subtle differences, especially with tapered pegs. Upward climbs closely follow concertina locomotion, utilizing the middle third of the body for strong, stabilizing lateral forces. This mode of locomotion is more difficult, evidenced by double the length of descent time on average and a lower success rate of 10%. Due to this difficulty, the snake has an unexpected reliance on tapered pegs, despite being more difficult to grip, as it is forced to utilize all the pegs it has access to. However, a similar dependence on tapered pegs on downward climbs results in failure. They require less stabilizing lateral forces, which come from the back of the body rather than the middle. Descents are also similar to lateral undulation, a faster and easier form of locomotion. As a result, the snakes can get away with – and are better off – skipping tapered pegs. In conclusion, our analysis reveals the nuanced dynamics of propulsive snake locomotion in response to peg shape.

CHAPTER 5

CONCLUSION

In summary, our study sheds light on the distinct nuances between upward and downward climbing, a topic that has received very limited attention in previous research. Furthermore, we propose that climbing without wrapping may offer a more energy-efficient and less strenuous technique for snakes. By exploring the complexities of these climbing behaviors, we enhance our understanding of snake locomotion dynamics and open up possibilities for future research aimed at refining climbing strategies.

5.1 Applications

A potential application of this research lies in robotics. By developing limbless robots capable of replicating the propulsive locomotion of tree-climbing snakes, we can envision their use in search-and-rescue operations following natural disasters. These robots could navigate various terrains, including hazardous and inaccessible areas filled with rubble and debris, that are too dangerous for a human to set foot in. Designing such snake-like robots could become a focus of future research, and I believe that the insights from my findings will advance the field of biomechanics and potentially have life-saving implications.

5.2 Future Work

In the future, we hope to run more trials with the current setup to solidify our findings. Furthermore, our current wall setup allows for extensive modifications, offering ample room for various experimental manipulations. We plan to investigate how factors such as peg spacing, wall angle, the texture of both the wall and pegs, and peg shape influence snake climbing abilities and how different combinations of these factors influence their capabilities. Additionally, while we currently only do a 2D analysis with our 3D kinematic data, we are eager to explore the role of distance off the wall in climbing success. Similarly, we plan to introduce a third dimension of force measurements. By examining forces exerted by the snakes on the z-axis as they press onto the wall, we hope to gain a deeper understanding of their climbing mechanics.

Expanding our trials to involve different species of snakes in collaboration with Zoo Atlanta also presents an exciting opportunity. We anticipate potential differences between arboreal and semi-arboreal species, which could provide valuable insights into climbing behaviors across snake types.

Finally, we are interested in exploring the microscopic structures of snake scales, particularly focusing on keel formation and how the flaring of scales aids in climbing. We have observed instances where removing snakes from the wall feels like they have adhered to the surface, where they may have inserted their scales into the peg holes. Investigating how these microscopic features interact with different textures along with 3D force data could shed light on the mechanisms underlying snake climbing locomotion.

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