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Amphisbaenian Head Movement and Burrowing Forces in Damp Granular Media

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Honors Research Project

Abstract

Damp granular media is a difficult environment to study because it is both practically complex and it lacks equations which fully describe its behavior. In this study, an oscillatory lateral head movement and its effects while penetrating damp granular media were tested using a robophysical model. This experimental research was inspired by the burrowing behavior of the clade *Amphisbaenia*, a group of usually limbless squamates that employ a variety of different burrowing behaviors, but it can apply to a wide range of burrowers. This research could help with both human burrowing technologies and the further investigation of animal behaviors.

Keywords: *Amphisbaenia*, burrowing, wet granular media, fossorial locomotion

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Introduction

Amphisbaenians are a group of small burrowing reptiles in the clade *Amphisbaenia*, part of the Squamata order of reptiles. These reptiles, usually limbless, burrow in a variety of regions across several continents, mostly in tropical and subtropical areas. Amphisbaenians have developed several strategies for burrowing in their environments. These strategies range from complex, multi-axial twisting motions to much more simple oscillatory motions (Gans, 1968). Amphisbaenians tend to live in high-humidity substratum for several reasons (Gans, 1968). The plasticity of these systems allows for semi-permanent tunnels, and the water keeps them hydrated. They construct their own galleries of tunnels in these environments, and they use the different strategies of burrowing to create their semi-permanent tunnels.

In limbless species, the characteristics of their substrata are related closely to their locomotion (Astley et al. 2020). Granular media such as sand can undergo several changes in the way that it behaves depending on the forces being applied, and this can be particularly relevant to limbless organisms. Limbless locomotion, especially in burrowing through granular media, is dominated by drag (Hosoi and Goldman, 2015). Due to this, an experimental approach can be the best, especially in wet granular media. Because these species are difficult to keep alive in captivity, a robotic approach was taken to study these movements and the success or lack thereof of decreasing the amount of force required to penetrate the burrowing media.

Granular media is a complex substrate to model for burrowing, and especially wet granular media. No studies to date have determined the way that forces interact

with wet granular media, and few have been done to investigate the relationships between the unusual mechanics of these environments and the forces involved in burrowing through it. What is known, however, is that the fossorial locomotion found in burrowing species is very costly energetically. Compared to terrestrial locomotion strategies, fossorial motion can take 350 times the energy expenditure (Wu et al. 2015). Furthermore, animals burrowing in wet granular media specifically may have to overcome around 4 times the resistance of dry granular media (Sharpe et al. 2015). Due to the high forces involved, amphisbaenians have high cross-sectional area muscles such as their *Longissimus dorsi* (Navas et al. 2004). This is a large, pennate dorsal muscle which runs along the length of the body and can produce considerable force.

Here, we conduct an experiment to see the role that head movement plays in the burrowing strategies of amphisbaenians. Due to several factors, a robotic approach was used. First, the species in question are difficult to keep alive in captivity. A robotic analog allows this testing without any live specimens. Second, it allows for a simple method of measuring the forces involved, which has rarely been done in wet granular media. Simple, easily constructed load cells can be placed in the interfaces of force transfer to measure the forces that pass through them. Finally, the robot is modular and easy to replace components to fix or change the function.

The robot in this experiment uses a pattern of motion most consistent with the “keel-snouted” species of amphisbaenia. These species penetrate forward and use horizontal motions to compact the sand on the edges of the tunnel by unilateral contraction of the muscles which control the head (Gans, 1968). This motion is thought

to decrease the amount of force required to advance and this specific hypothesis will be tested in this study. Previous research has shown that at high amplitudes, head movement can decrease penetration force (Edwards et al., 2023). This study will use a different amplitude of head movement to provide more context for those results and to advance understanding of these and similar systems.

Methods

To gather this data, a simplified robot analog of the amphisbaenian was created to mimic one form of amphisbaenian burrowing. Due to constraints in space and complexity within the penetrator and due to consideration of the high forces involved, only simple oscillatory motion was replicated with this robot. The robot is controlled by two Arduino boards which are programmed with the movements desired for the trial to be performed. These Arduino boards send commands to two high-power stepper motor drivers (Pololu item 3730) which then drive two high-torque stepper motors (MPN: SY57STH76-2804A) (Fig. 1). High-torque stepper motors were chosen both for the high forces involved, but also for the precision and repeatability they can bring compared to other types of non-stepper motors. When turning, the stepper motors rotate a lead screw that pushes or pulls on a carrier block attached to a piston (Fig. 1).

The pistons driven by the motors are part of a pair of hydraulic systems, which operate on two separate circuits. One piston rotates the head to the left and right to imitate the lateral yawing motion of certain amphisbaenians' burrowing mechanics, while the other serves to push the penetrator forward into the media. Hydraulics were chosen due to their ability to transmit high forces and transmit motion mostly losslessly.

Due to this, more force can be generated by the robot than could be easily accomplished if the force had to be generated in the relatively small envelope of the shell of the penetrator shaft, which is only about 15 cm long and 5 cm in diameter.

The construction of the hydraulic system is made to be both robust and easily serviced. From the drive pistons, vinyl tubing is used for its characteristics of both flexibility and strength. These sections of tubing are filled with AW ISO 32 hydraulic oil and are linked together using acetal compression fittings. These fittings were chosen because they are both inexpensive and seal well with no further sealing methods such as teflon tape or a thread locker.

The burrowing component of the robot consists of the two driven pistons, a 3D printed shaft piece, and a 3D printed mobile head piece (Fig. 2). This is the part of the robot actually penetrating into the media and whose reaction forces are measured. A 3D printed construction was chosen to keep costs low and to make it easier to replace or prototype new parts. The penetrator portion also has several layers of plastic and rubberized insulation to protect from the grit of the environment. The exterior most portion of the insulation, which serves to keep the texture consistent and to protect the inner hinge mechanism, is made of two-part silicone (Dragon Skin 20), and the inner portion of the insulation is a plastic skin.

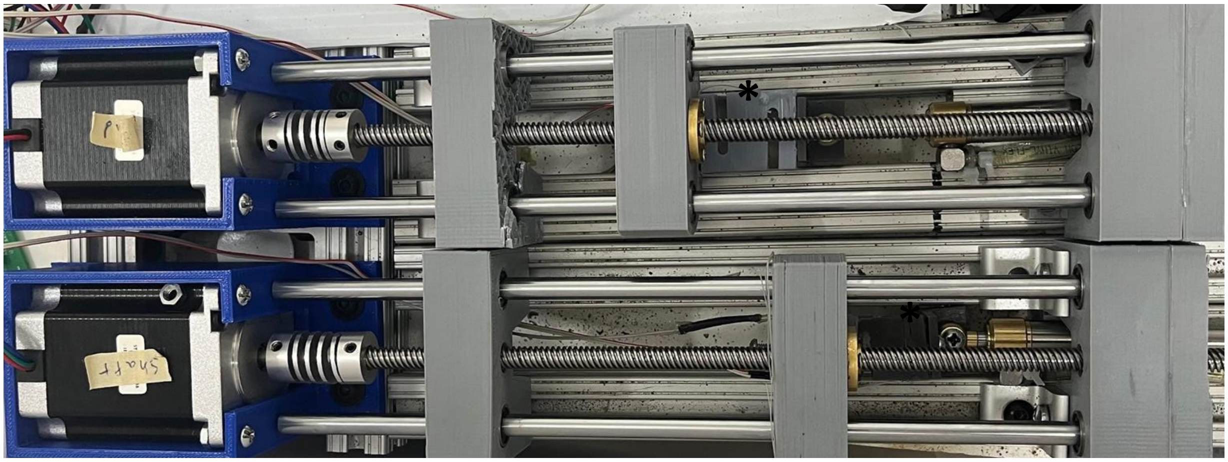

Figure 1: The driving portion of the robot, which consists of the stepper motors, the load cells, and the pistons. The load cells are the S-shaped pieces connected to the carrier blocks and are marked with an asterisk.

Figure 2: The penetrator portion of the robot outside of the sand. The conical portion on the left is the rotating head, and the shaft piston pushes the robot to the left. A meter stick is included for scale.

Between the lead screw and the pistons, there is a load cell which uses two strain gauges in a Wheatstone bridge configuration to measure the linear force being transmitted (Fig. 1). This load cell is a S-shaped 3D printed part which is easily replaced and serviced, and which can be modified for higher or lower force applications. The

changes in voltage across the Wheatstone bridge are amplified using a custom circuit and received by a NIDAQ USB 6002(MPN:782606-01). This NIDAQ transmits the data to a computer which both records and filters the data using a low pass filter with a cutoff frequency of 11 Hz. in MATLAB using a custom script. MATLAB then plots the data from the zeroed and filtered data, and both the MATLAB workspace and a comma-separated value file are saved.

The load cells were calibrated using the same code as the trials, measuring the voltage output for 30 seconds while various known forces were applied using weights hanging on the load cells, either compressing or extending them. The mean of the voltages measured over time for each load was then used to determine the relationship between voltage and force using a simple linear regression (Fig. 3 & 4). These regressions were used to transform the data from voltages into force, and the means and peaks of those forces were taken via MATLAB from the beginning of the trial to just before the end of the trial. While 30 seconds of voltages were recorded, the active penetration phase was only 7.5 seconds and was the portion all statistics were taken from.

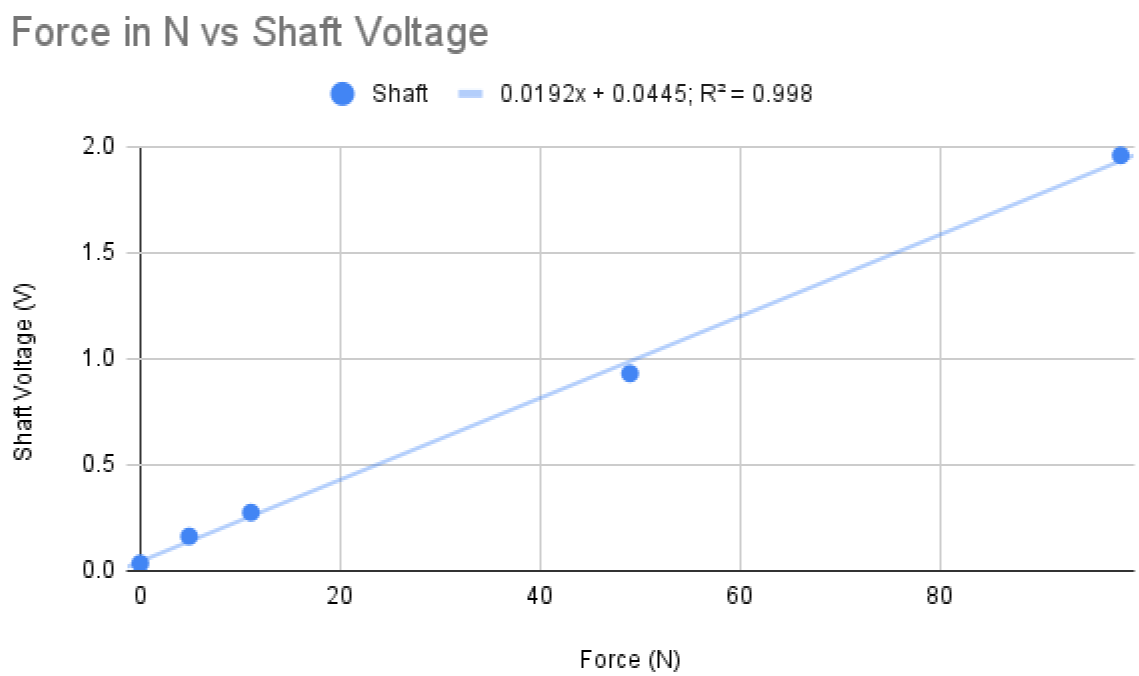

Figure 3: Scatter plot of data points gathered for calibration of the shaft and the linear regression line (line formula + R2 value). These regressions were used to transform the data from voltages to forces. This calibration was done with the load cell for the shaft.

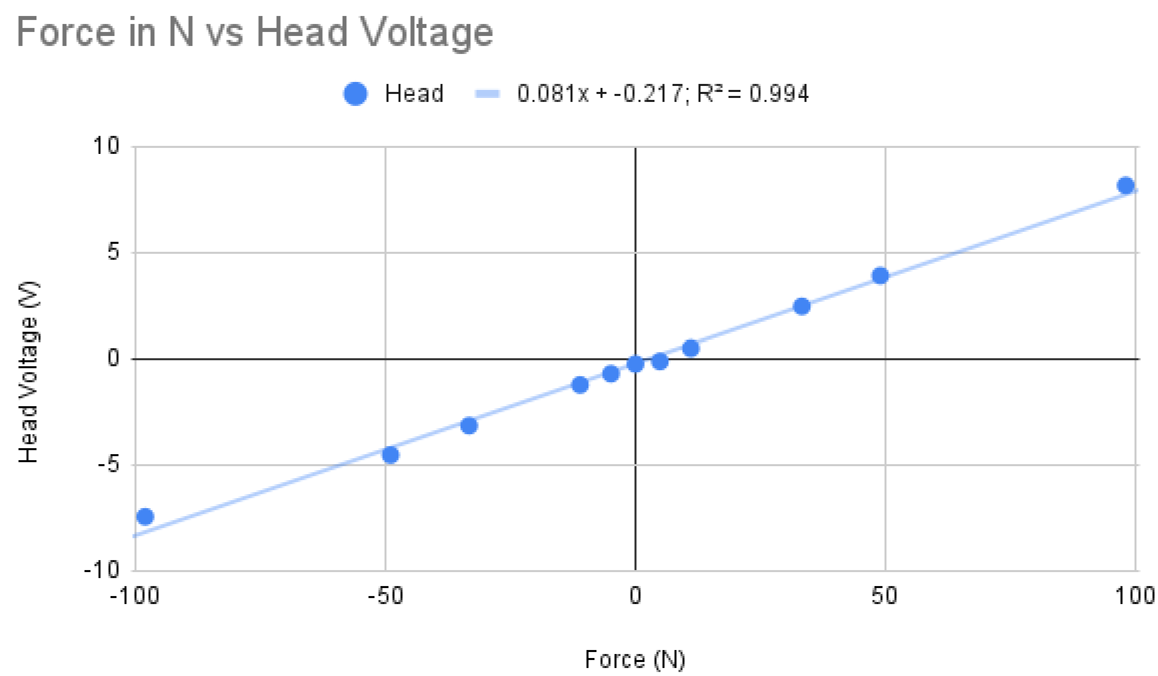

Figure 4: Scatter plot of data points gathered for calibration of the head and the linear regression line (formula +R2). These regressions were used to transform the data from voltages to forces. This calibration was done with the load cell for the head, and so had to be calibrated for both tensile and compressive forces. Positive forces indicate tension while negative forces indicate tension.

Each trial was completed from a starting standard position of the head being positioned horizontally forward and the shaft fully retracted. Before securing the robot in place, the container must be partially filled with damp granular media. The substrate used is natural rock sand, approximately 100 lbs or 1 cubic foot. In this research, the wet granular media was pre-wet in another container to the point where it could hold its own shape when deformed and its density is 2.1g/mL ∓ 0.1 g/mL, but as many trials as possible are completed in the same day to minimize changes in soil composition due

the evaporation. Furthermore, the hydration was monitored through density daily. To avoid clumping or uneven packing, the sand is passed through a screen and falls into the container (Sharpe et al. 2015). The container is filled up about halfway to where the robot can be comfortably positioned on top of the sand with little force. This is done to ensure that the robot has as few preloaded forces on it as possible and to ensure that the media encompasses it on all sides, as it would for a creature trying to burrow. From here, the burrowing portion of the robot is lowered into a container that has a bracket to receive the base of this portion of the robot, and then the rest of the sand is deposited on top via the same screen-based method.

Once the robot is in position and covered, the Arduino is sent a signal to begin a trial. From here, the data is collected and the burrowing portion of the robot retracted after being excavated from the sand, and another trial can begin (Fig. 5&6). We performed several trials with head movement in open air, several trials with a no head movement control in sand, and several trials with a small amplitude (~17.4 degrees) movement of the head in the sand. The data were converted from voltages into Newtons force using the linear regression formulas from the calibration.

In order to interpret the data, the means and maxima of each trial were taken and adjusted by subtracting the forces from the baseline out of sand trials (Tables 1-3). These corrected data were used for all statistical analysis. The statistical analysis included comparison of means and variances for the in sand head movement trial and the in sand no head movement trial. To compare the results, a one tailed t-test with unequal variance was used as well as an F-test for variance using XLMiner Analysis Toolpak. All statistics were done with shaft forces only, because only one head

movement pattern was used, and so there was no way to compare different head movement patterns.

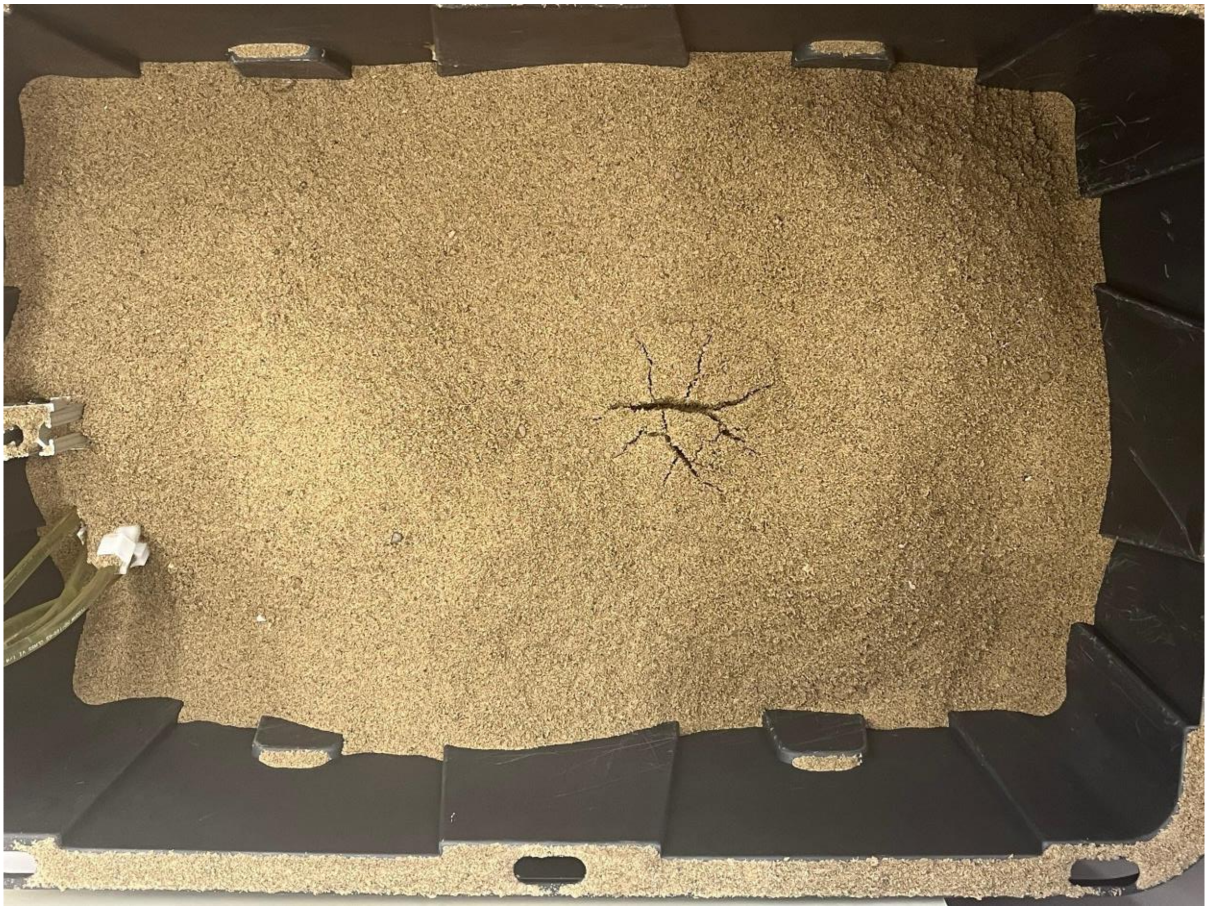

Figure 5: After finishing a trial, the robot is ready to be retrieved and has left visible cracks on the surface of the sand.

Figure 6: The penetrator portion of the robot is being excavated after a successful trial.

Results and Data

Figures 7-9 are representative samples of the filtered results of the trials. In Figures 8&9, the corrections for baseline forces were not used to show the total forces exerted.

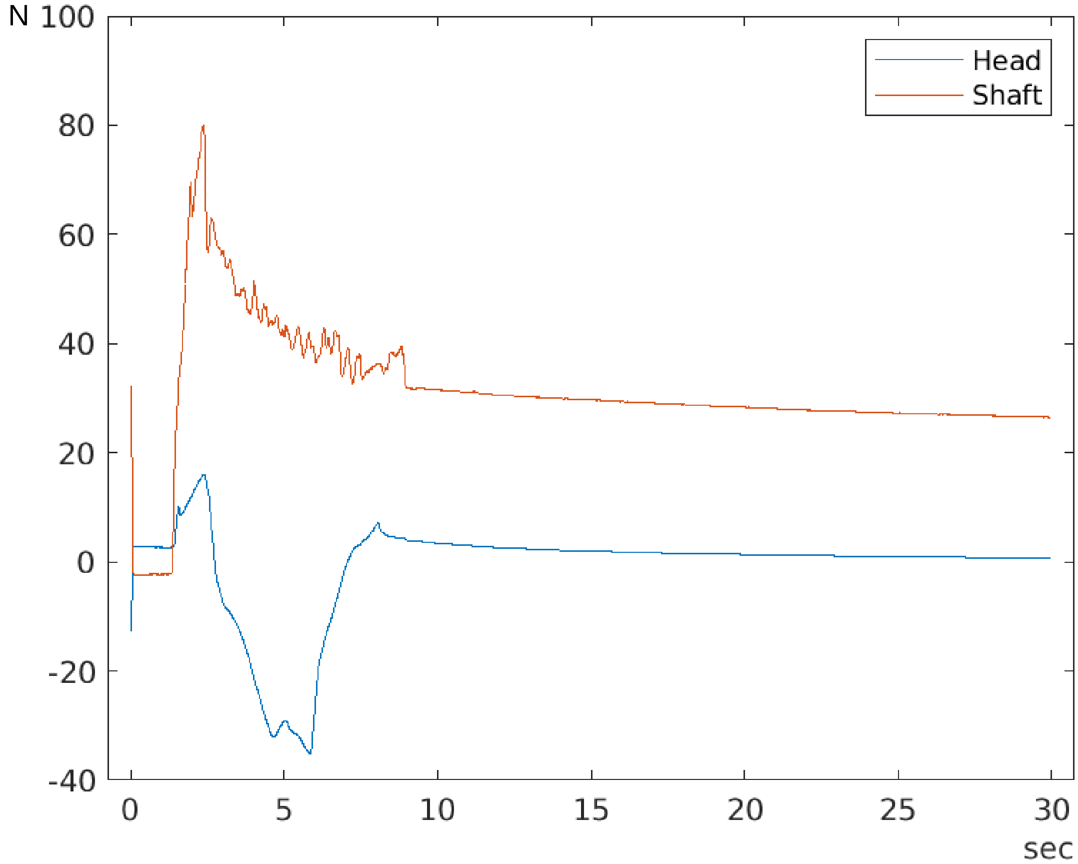

Figure 7: Data collected from a baseline run of the Arduino code outside of the sand. The peak shaft force was 80 N. This baseline data was used to adjust the mean forces of experimental trials into mean force over baseline.

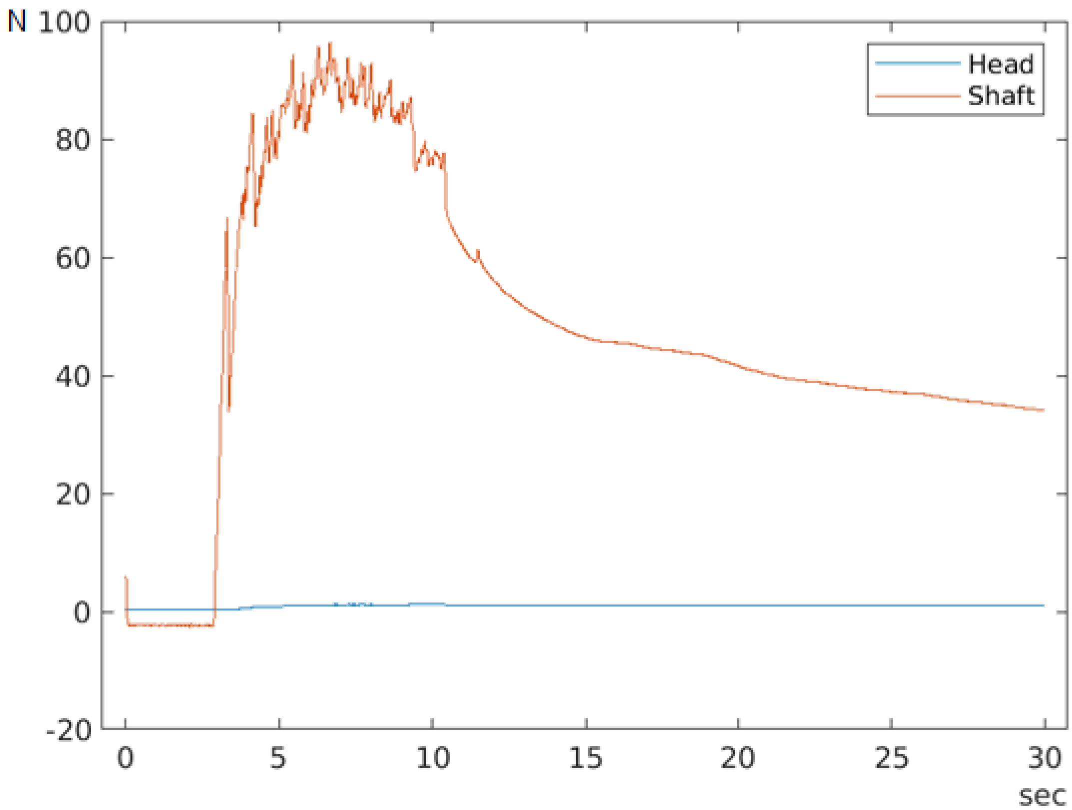

Figure 8: Uncorrected data collected from a control run of the Arduino code in the sand with no head movement. The peak value for uncorrected shaft force was 96 N, and the mean uncorrected shaft force during the pushing phase was 79 N.

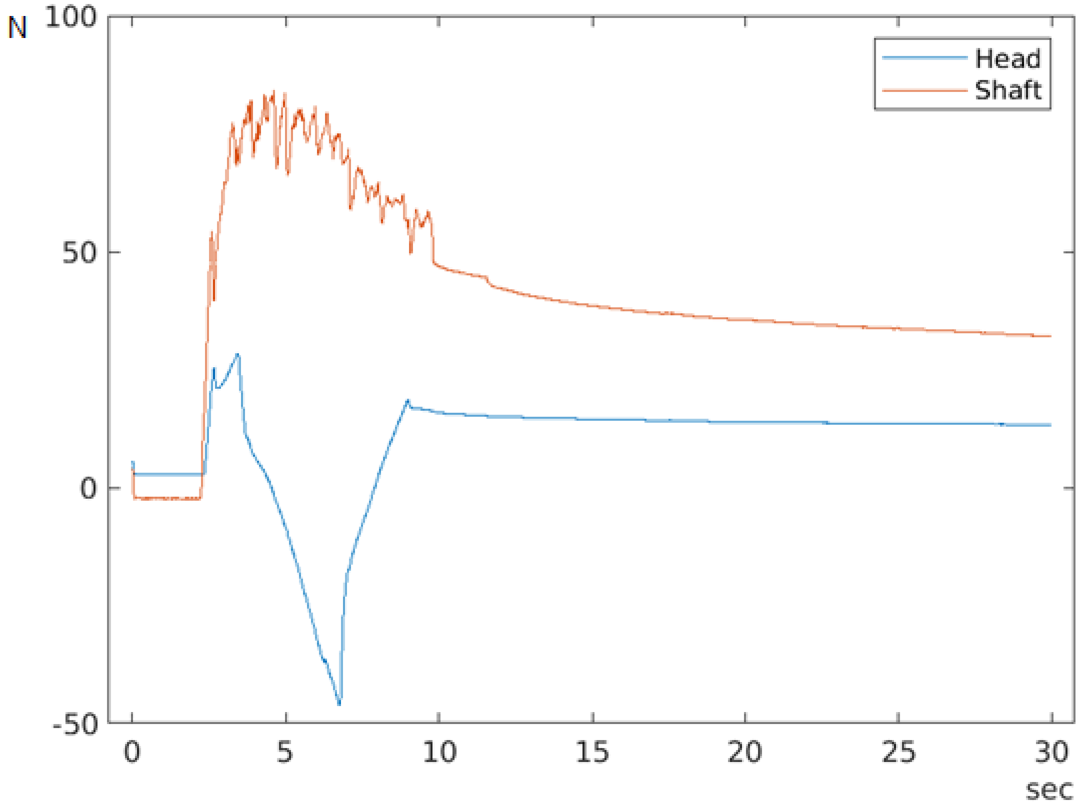

Figure 9: Uncorrected data collected from a trial with head movement in the sand. The peak uncorrected value for shaft force was 84 N, and the average uncorrected shaft force experienced during the pushing phase was 66 N.

Forces on the shaft were observed to be much higher than the forces on the head, which would be expected as the head is only moving from side to side and the shaft is experiencing the force from advancing in the media.

Baseline Trial Number	Mean Shaft Force(N)	Maximum Shaft Force (N)
1	20.87	80.00
2	44.45	67.28
mean	32.67	73.64

Table 1: Data from baseline trials run outside the sand used to correct data from experimental trials.

Control Trial Number	Mean Shaft Force (N)	Maximum Shaft Force (N)
1	67.708	95.203
2	45.942	63.673
3	39.669	54.467
4	18.953	43.820
5	23.242	37.639
mean	39.10	58.96
stdev	19.5	22.6

Table 2: Corrected data from control trials in sand with no head movement during the penetration sequence.

Experimental Trial Number	Mean Adjusted Shaft Force (N)	Maximum Adjusted Shaft Force (N)
1	33.690	64.366
2	32.252	54.424
3	27.226	41.804
4	33.605	51.565
5	35.124	54.204
mean	32.38	53.27
stdev	3.1	8.1

Table 3: Corrected data from the experimental trials with a low amplitude (~17.5 degrees) head movement and through sand.

t-Test: Two-Sample Assuming Unequal Variances		
Mean Adjusted Shaft Force	*Head Movement*	*No Head Movement*
Mean	32.4	39.1
Variance	9.3	380.7
Observations	5	5
df	4	
t Stat	-0.76	
P(T<=t) one-tail	0.24	
t Critical one-tail	2.13	

Table 4: The results of a one-tailed t-test between the adjusted mean forces in the head movement and no head movement trials. The differences in means are not statistically significant (p>0.05), indicating a lack of significant difference in means between average forces used in the head movement trials when compared to the no head movement trials.

t-Test: Two-Sample Assuming Unequal Variances		
Maximum Adjusted Shaft Force	*Head Movement*	*No Head Movement*
Mean	53.3	59.0
Variance	64.9	509.9
Observations	5	5
df	4	
t Stat	-0.53	
P(T<=t) one-tail	0.31	
t Critical one-tail	2.02	

Table 5: The results of a one-tailed t-test between the adjusted maximum forces in the head movement and no head movement trials. The differences in means are not statistically significant (p>0.05), indicating a lack of significant difference in means between peak forces used in the head movement trials when compared to the no head movement trials.

T-test results indicate that while both the mean and maximum shaft forces were on average lower in the head movement trials, the results were not statistically significant. Descriptive statistics of the baseline out of sand trials were found as well, and the average force in the baseline out of sand trials which was subtracted from the

other trials was 32.67 N. There were, however, only two viable out of sand baseline trials.

Finally, the F-test was performed to see if the variance between the head movement and no head movement data sets is different on shaft forces. It was found that the variance between the mean forces experienced is statistically significant ($p<0.005$). Furthermore, it was found that the variance in the maximum forces experienced is statistically significant ($p<0.05$).

Discussion

A statistical difference was not found between the means of maximum force or of average force between shaft forces of the control and experimental groups. It should be noted, however, that the number of trials is low and the variance is high. To investigate further, it would make sense to first establish a better baseline in-sand force profile. The standard deviation on the in-sand baseline trials were much higher, and likely contributed to the lack of statistical significance, because the standard deviation on the experimental trials was remarkably low in comparison. If the no head movement trials were more in line with the experimental trials in terms of variation, it is possible that the results would be statistically significant. It is possible that the head movement contributed to making the forces experienced more consistent, but this was not a focus of the investigation and more trials would be needed to make any definitive conclusions. A larger sample size would likely help greatly with the lack of consistency in some of the trial sets.

Limitations

One test that was not done due to time constraints and the scope of this investigation was the testing of different head behaviors. The work required for each trial makes multivariate testing incredibly work intensive, but the amount of control available means that it is trivial to actually change the behavior of the model.

This robotic mechanism is a successful way to measure the forces experienced in underground burrowing, and it holds up well to the forces experienced by such a force-intensive process. Because fossorial movement is so much more difficult energetically, the mechanism had to be able to withstand great forces to stay together on each trial (Wu et al. 2015). Some benefits of this system include the ease with which any one component can be replaced, an essential part due to the high forces involved, and the simple way in which high force is created in the first place, with a high-torque motor rotating a lead screw. Furthermore, the setup is mostly inexpensive pieces, and many of the components are either 3D printed or made of 80-20 aluminum extrusion. This allows a great degree of flexibility in the strength or purpose of the robot without fundamentally changing the mechanics.

Most of the challenges with conducting this investigation have been directly related to the high forces involved, which reached 100 N at times. On occasion, leaks occur or parts break not due to an error, but for the simple fact that the forces are great. This is however where the ease of replacement makes the process much easier. On the earlier models of this system, a broken piece could be much more difficult to replace, but an increase in hydraulic tubing diameter and an increased amount of caution have mitigated that issue in all but the most extreme cases.

One further challenge is the labor involved with performing each trial. Due to the nature of the wet granular media, moving the substrate between containers between trials can take a considerable amount of time, and this setup takes most of the time of conducting each trial.

Future Directions

Future methodologies have several promising avenues of investigation. First, differing hydration of the substrate is something that can influence results and is also biologically relevant. This is something difficult to control for, and as a result there was only time to test one hydration. Controlled hydration can be achieved, and using variable hydration could enlighten why different strategies could be chosen in different environments (Sharpe et al. 2015). Both amphisbaenians and other fossorial organisms burrow through a variety of substrata and changing this up could do a lot for making sure that the motions do something in a variety of environments.

Adjustment of both the substrate in particle size and in hydration level could help understanding of wet granular media in general. Because fossorial locomotion is dominated by drag and the characteristics of the substrate affect limbless locomotion greatly, these would be good parameters to modify to better understand the substrate and its characteristics (Astley et al., 2020; Hosoi and Goldman, 2015). It follows, too, that if drag is the dominant force that changing of the skin of the robophysical model could give different results, and something more similar to scales could experience forces more similar to those in the *Amphisbaenia* clade and other organisms that use similar locomotion techniques.

Because previous research has shown that an increased head rotation amplitude can cause a decrease in required force, the question remains what amplitude and frequency combination is optimal for decreasing force (Edwards et al., 2023). Future investigations in this movement with different parameters will help increase understanding of both burrowing and wet granular media as a burrowing substrate.

Another topic of interest is the different burrowing strategies practiced by amphisbaenians. Different species of amphisbaenians practice different strategies such as the multi-axial twisting motion practiced by other species of amphisbaenian could be a good future direction (Gans, 1968). The head shapes represented by these strategies, too, is something that could be fairly easily tested, given the correct motion is attainable, by using 3D printing technology and the modularity of the system to its advantage. Furthermore, the locomotion strategy practiced by the model is not exactly analogous to the amphisbaenian's strategy, in which the driving forward and the sweeping of the head tend to be different "phases" of a movement cycle (Gans, 1968).

Statistical analysis of the head forces, too, could be helpful in understanding the biology of the model *Amphisbaenia* species as well. The piston which actuates head movement is analogous to the *Longissimus dorsi* muscle, and while it is known to be highly pennate, the relative forces that have to be exerted could be important in understanding the mechanics at work in burrowing with this strategy (Navas et al., 2004)

One more way that this research could be advanced is simply finding a new way to do trials in wet granular media without as much work involved in each trial. Finally, different scales could easily be tested with this strategy. While the technology isn't able

to be scaled down very far as is without either finding or machining smaller pistons, it could easily be scaled up especially due to the fact that the power is provided apart from the penetrator.

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