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# The Kinematics of Salamander Underwater Walking on Smooth and Rough Substrate

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# The Kinematics of Salamander Underwater Walking on Smooth and Rough Substrate

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## Abstract

The transition from aquatic to terrestrial locomotion was a landmark event in the evolutionary history of vertebrates. In order to better understand how early tetrapods were able to transition to land, salamanders have proven to be a useful animal model. With current research focusing heavily on the anatomy, physiology, and kinematics defining salamander terrestrial walking capabilities, this experiment was designed to extract information about the kinematics of salamander walking underwater. Underwater walking of salamanders was analyzed on smooth and rough substrates to provide more insight into the early vertebrate water-to-land transition. Average salamander stride duration, time in stance phase, time in swing phase, duty factor, stride length, stride velocity, minimum foot velocity phase location, maximum foot velocity phase location, and foot slip distance were compared between salamander underwater walking on smooth and rough substrate conditions. It was found that stride duration, stance duration, and swing duration were significantly greater when salamanders walked underwater on rough substrate. Thus, the kinematics of underwater salamander walking differ to some degree when the salamander walks on smooth or rough substrate.

## Introduction

Understanding the locomotion of animals has been essential to discovering more about their limb evolution. Past research on limb use has primarily targeted purely terrestrial or purely aquatic fauna and consequently, science has great knowledge of locomotive schemes such as axial propulsion swimming or spring-loaded inverted pendulum running. However, determining the limb properties that allow certain species to move both underwater and on land is vital to providing evolutionary insight for the water-to-land transition of animals and to creating biomimetic robots able to move in multiple environments.

Current fossil records reveal that the evolution of tetrapod limbs occurred before the evolution of terrestrial animal life. Therefore, tetrapod limbs evolved first for use in underwater movement and later adapted for use on land (Clack, 2002). Adult salamanders inhabit a mix of terrestrial and aquatic environments and thus exhibit a range of locomotive gaits including axial swimming and terrestrial lateral sequence walking (Ashley-Ross and Bechtel, 2004). Morphologically, salamander body plans have not changed significantly in the past 150 million years: salamanders have four limbs extending from their torso with the feet lateral to the body. Their sprawling body plan does not allow for salamander bodyweight to balance across the four limbs (Ashley-Ross et al., 2009). Based on their habitat and morphological properties, salamanders have proven to be the best extant proxy for early tetrapod posture and locomotion in limb studies focused on illuminating vertebrate invasion of land.

As aforementioned, salamanders are capable of swimming, walking on land, and transitioning between these two gaits. However, salamanders also exhibit a third and understudied locomotive gait: underwater walking. The mechanical requirements for walking underwater vary from those of terrestrial walking due to water viscosity resisting limb motion and salamander buoyancy reducing the functional need for limbs to stabilize the body while simultaneously providing forward thrust. Salamander buoyancy also reduces the effects of gravity on limb movement (Azizi and Horton, 2004).

In the present study, we quantify the kinematics of salamander underwater walking on smooth and rough substrates. In nature, salamanders have not only adapted to terrestrial and aquatic environments but have also adapted to varying substrate conditions in both habitats. Therefore, discovering more about substrate effects on their underwater walking can provide us with more information regarding their biology and limb evolution. It is believed that a rough substrate will provide the salamander with a better grip to thrust forward for walking underwater such that the kinematics will differ greatly from underwater walking on a smooth surface. The average salamander stride duration, time in stance phase, time in swing phase, duty factor, stride length, stride velocity, minimum foot velocity phase location, maximum foot velocity phase location, and foot slip distance were used as kinetic markers to compare the effects of substrate condition on underwater walking.

## Materials and Methods

### Animals

Four adult Barred Tiger Salamanders (*Ambystoma tigrinum*) were purchased from Exotic Pets LV and were brought into the lab. Salamanders were maintained under identical conditions in two separate terrarium containers (two per container) and fed earthworms once a week. The mean snout-to-hip lengths (StH) of the salamanders was 9.12 cm with a standard deviation (SD) of 1.93 cm. The mean terrestrial mass was 23.14 g with a SD of 1.93 g at the time of the experiments. The mean underwater mass of Salamander 1 and Salamander 4 was 0.82 g with a SD of 0.35 g. Salamander 2 and 3 passed away after experiments before their underwater masses could be calculated.


**Figure 1.** The salamanders used in trials.

### Video Recording

One Nikon AF-S Nikkor 18-55mm high speed digital camera was placed in front of an aquarium tank with additional LED video lighting to capture a lateral view of salamander motion at a rate of 60 frames/second. The camera was level and perpendicular to the substrate surface. The tank bottom was covered with small sized gravel for rough substrate trials or a plexiglass sheet for smooth substrate trials. The tank was filled roughly halfway with dechlorinated water.

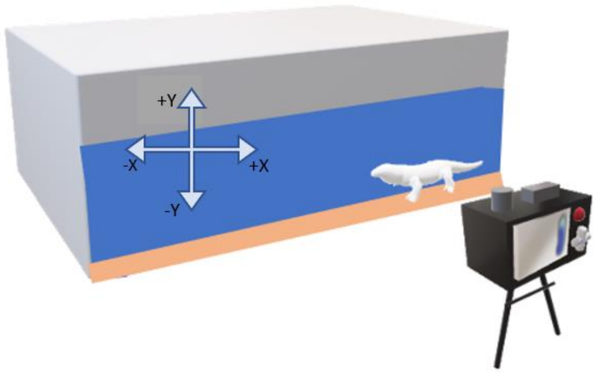


**Figure 2.** The setup for recording salamander underwater walking. The orange represents the gravel for rough substrate trials or plexiglass for smooth substrate trials. Negative and positive directions of motion were captured based on which way the salamander was walking. Going from the right-hand side of the tank to the left-hand side was quantified as negative motion while positive motion occurred as the salamander walked from the left to the right.

**Video Processing**

Video .MOV files were first converted to .avi files for use in MATLAB. Video files were then trimmed to a frame range capturing salamander motion, filtered, and compressed with the Xvid codec using VirtualDub 1.10.4 software.

**Digitizing Salamander Locomotion**

In biomechanics, 2D digitizing refers to the process of tracking specific points on an image throughout the frames in a video to obtain the frame-by-frame x- and y- coordinates of that point. This allows for the quantification of that point's motion. In this experiment, a MATLAB graphical interface module called DLTdv5 was used to digitize the salamander underwater walking videos and thus create a kinematic model of their motion. Frame by frame, the x-y- coordinates for landmark anatomical features were tracked. From the lateral view, the following points were digitized: the tip of the snout, the vertebral column midway down the trunk as a proxy for the center of mass, the sacrum midway between the hip joints, and the front foot carpus of the arm facing the camera.

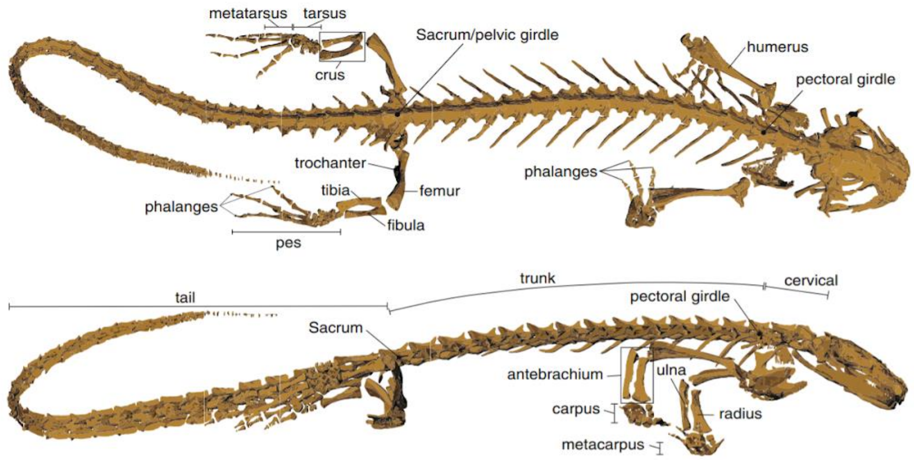


**Figure 3.** The dorsal and lateral skeletal anatomy of a salamander used for defining digitizing points (Karakasiliotis et al., 2013).

Only sequences in which the salamander showed continuous, steady-speed, nonangled from the camera lens motion for two or more full strides were selected for analysis. Trials where the animal paused or stopped between successive strides were not used. At least six trial videos were obtained and digitized from each animal model for each substrate condition: rough gravel and smooth plexiglass.

All kinematic measurement values derived from the digitized points for each salamander were converted from frames to seconds after multiplying by video frame rate and pixels to meters after multiplying by the ratio of:

$$\frac{\text{StH of the salamander (pixel)}}{\text{StH of the salamander (meter)}}$$

The StH of the salamanders was found in meters using ImageJ software. Identification pictures were taken of each salamander resting near a ruler and the ImageJ line tool was used to find StH in pixels. The line tool was also used on the ruler to determine the number of pixels in 10 cm, or 0.1 m. Thus, the StH in pixels could be converted to meters and used in the ratio above to standardize all measurements to the metric system.

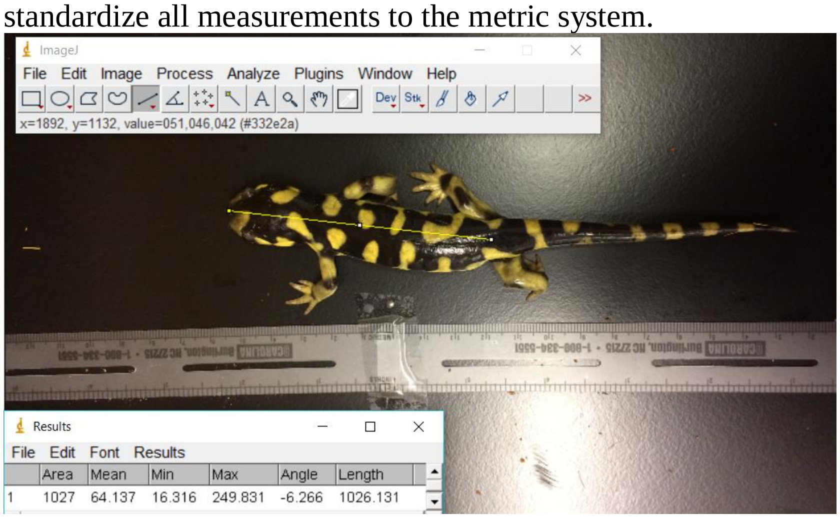


**Figure 4.** The line tool of ImageJ providing pixel length of the StH for salamander 4.

**Variable Definitions**

- A ‘stride length’ is defined as the displacement (in m.) of the salamander’s foot between the time when the front foot is at a minimum distance from the hip to the next point at which the foot is at a minimum distance.
- The ‘stride velocity’ is stride length divided by stride duration. It is an average velocity (in m./s.).
- The ‘swing phase’ is the time period (in s.) during the stride over which the front foot is raised and being moved into position to begin the next stride (Ashley-Ross and Bechtel, 2004). In this experiment, the swing phase starts when the front foot is at a minimum distance from the hip and ends when the front foot is at a maximum distance from the hip.

**Figure 5.** The swing phase of a step.

- The ‘stance phase’ is the time period (in s.) during the stride over which the front foot is in contact with the substrate (Ashley-Ross and Bechtel, 2004). In this experiment, the stance phase starts when the front foot is at a maximum distance from the hip and ends when the front foot reaches a minimum distance from the hip.

**Figure 6.** The stance phase of a step

- The ‘duty factor’ is the percentage of the stride that the front foot is in the stance phase. It can be calculated as follows: $\frac{Stance\ Phase\ Duration\ (s)}{Stride\ Duration\ (s)}$.
- The ‘foot slip’ is the distance (in m.) the foot skids on the substrate during a stride. For videos where the salamander is traveling in the positive direction, i.e. from the left to the right side of the tank, foot slip is found by integrating the foot velocity curve from the

frame that foot velocity goes from a positive to a negative value within the stride to the frame when foot velocity switches back to the positive direction within the stride. For videos where the salamander is traveling in the negative direction, i.e. from the right to the left side of the tank, foot slip is found by integrating the foot velocity curve from the frame that foot velocity goes from a negative to positive value within the stride to the frame when foot velocity switches back to the negative direction within the stride.

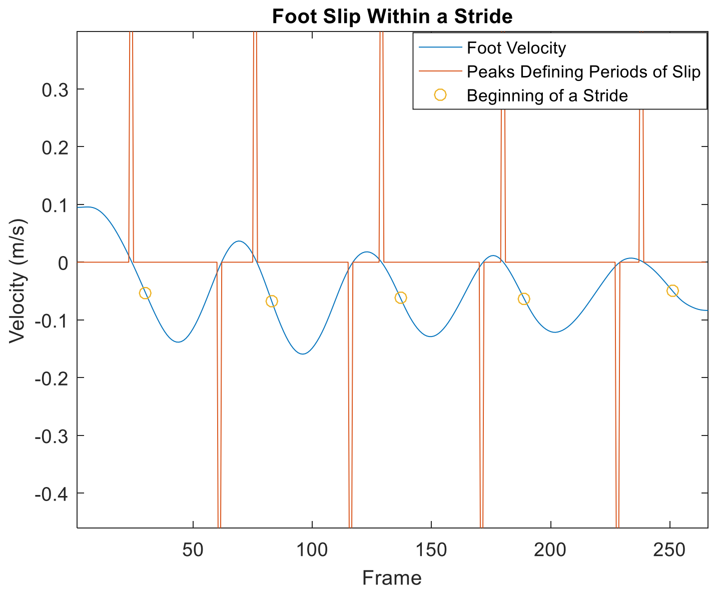


**Figure 7.** Representation of the foot slip on the foot velocity plot for salamander 3 walking in the negative direction on glass trial 4. Spikes within strides indicate the switch from negative foot velocity to positive foot velocity and the switch back to negative velocity. The area under the curve between the spikes is the slip distance in that stride.

**MATLAB Analysis**

From each trial video, the date filmed, substrate conditions, salamander identity, and trial number were extracted. The Excel file of that trial's digitized foot, center of mass, snout, and hip points was imported to manipulate the x- and y- coordinates of motion. Only coordinates from video frames where center of mass and foot motion were both tracked were analyzed. In other words, sometimes the foot came into the view of the camera before the center of mass and was therefore tracked for longer than the center of mass. The frames where the foot was tracked before the back came into view could be ignored. All digitized coordinates were separated into their x- and y- components before analysis. The StH distance (in pixels) was determined based off the imported coordinates and used to calculate the meter conversion ratio described earlier. A smoothing spline was used to depict the x- and y- motion of the center of mass and foot. An example of this can be seen in **Figure 8** below.

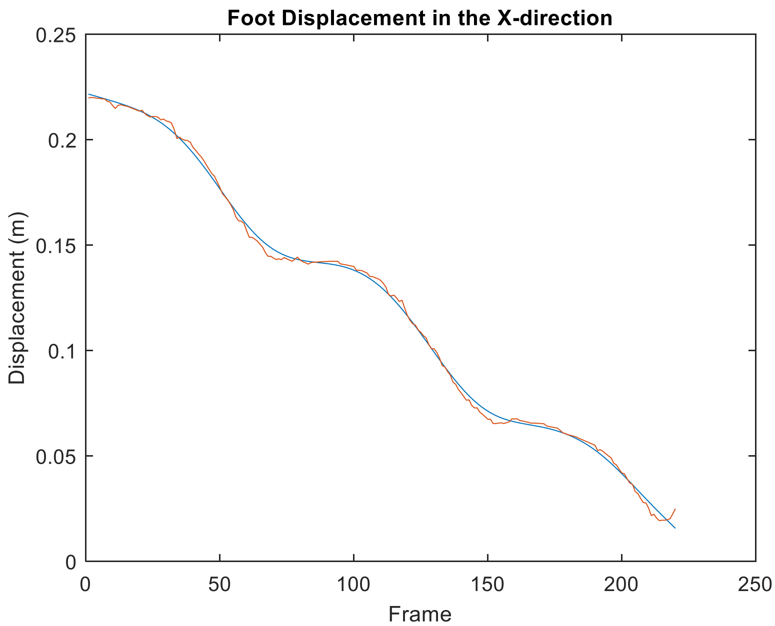


**Figure 8.** An example of a smoothing spline applied to salamander 1's front foot displacement in the first smooth substrate trial.

Using the smoothed data, the foot's velocity could still be accurately calculated. The indices of the starting and ending points for each stride of the trial were hand selected based on the graph displaying the changes in foot-to-hip distances, such as **Figure 9** below, because some strides were cut short by the range of usable coordinates and thus the computer would erroneously calculate extra strides.

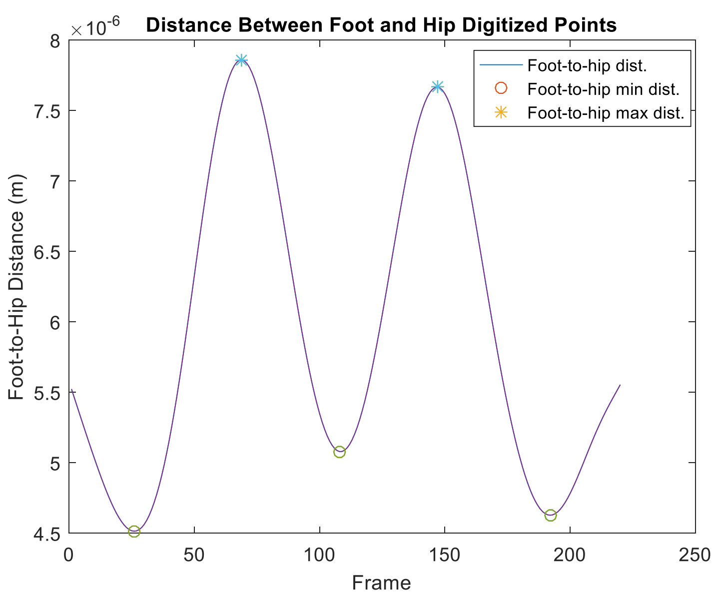


**Figure 9.** An example of the foot-to-hip distances calculated for salamander 1's front foot in the first smooth substrate trial. Minimum distances were at frames 26, 108, and 192. Maximum distances occurred at frames 69 and 147.

Stride lengths were subsequently calculated from minimum to minimum. In **Figure 9**, for example, there were two strides to analyze. From the strides, the duty factor could be derived based on time spent by the front foot in the swing walking phase. In addition, the front foot's minimum velocity, maximum velocity, and average velocity per stride were determined. These values were highlighted on foot velocity graphs such as in **Figure 10** below.

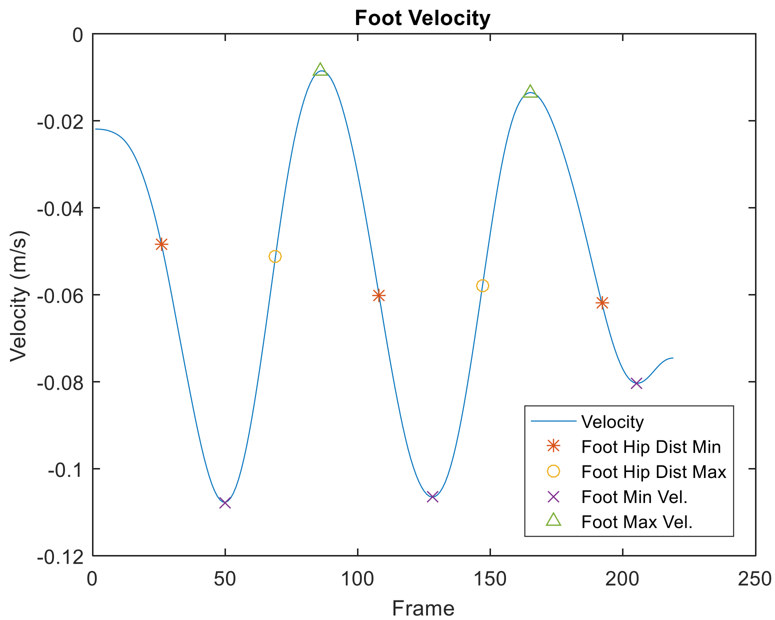


**Figure 10.** An example of the foot velocity calculated for salamander 1's front foot in the first smooth substrate trial. Stride starting points and swing phase ending points are plotted. Maximum foot velocity and minimum foot velocity are also labeled however, only those occurring within strides were recorded for analysis.

Of importance for smooth and rough substrate trials, foot slip distance was determined based on periods of front foot velocity in the opposite direction of motion.

All MATLAB code used to obtain this kinematic data can be seen in **Appendix 1.**

**Statistical Analysis**

All the values for each kinetic variable for each salamander walking on each substrate type were subject to SAS Institute's JMP Pro 13 statistical software ANOVA analysis model to determine if there were any significant differences in value between the levels of substrate type, the fixed factor. An ANOVA test analyzes the variance between three or more independent groups to determine if there are statistically significant differences between their means. It tests the null hypothesis that all group means are equal. Salamander identity and the factorial of salamander identity*substrate type were treated as random factors in this experiment's ANOVA's. The figure below depicts the specifications used for data analysis.

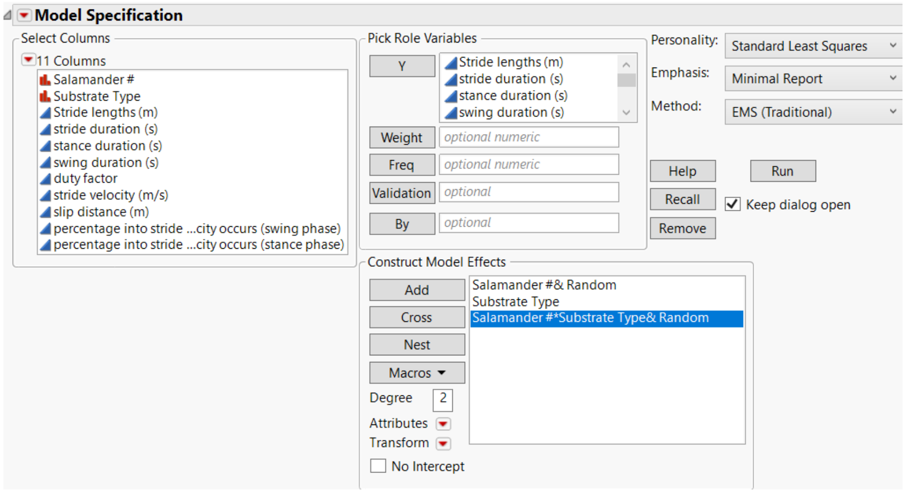


**Figure 11.** The fixed factors and random factors for determining significant effects of substrate type on kinematic measurements of salamander underwater walking.

The F-tests run by the JMP software for each dependent variable tested the null hypothesis that all means were the same across substrate types at a significance level of $\alpha=0.05$.

## Results

The data, extracted from video trials by the MATLAB code of **Appendix 1**, used to calculate the average stride length, stride duration, stance duration, swing duration, duty factor, stride velocity, slip distance, percentage into the stride maximum foot velocity occurred, and percentage into the stride minimum foot velocity occurred for each salamander on gravel and on glass substrate can be viewed in **Table 1-8** in **Appendix 2.** A summary of the average values found for these variables based on substrate and salamander can be seen below in **Tables 1-2.**

| Salamander | Stride lengths (m) | stride duration (s) | stance duration (s) | swing duration (s) | duty factor | stride foot velocity (m/s) | slip distance (m) | percentage into stride max foot velocity occurs (swing phase) | percentage into stride min foot velocity occurs (stance phase) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.067 | 1.21 | 0.652 | 0.554 | 0.537 | 0.059 | 6.22E-05 | 0.224 | 0.685 |
| 2 | 0.050 | 0.815 | 0.420 | 0.395 | 0.538 | 0.066 | 0.167 | 0.240 | 0.669 |
| 3 | 0.054 | 0.851 | 0.418 | 0.433 | 0.491 | 0.066 | 0.130 | 0.248 | 0.734 |
| 4 | 0.059 | 0.687 | 0.357 | 0.330 | 0.516 | 0.089 | 0.012 | 0.242 | 0.704 |

**Table 1.** Average kinematic data of each experimental salamander walking on glass substrate.

| Salamander | Stride lengths (m) | stride duration (s) | stance duration (s) | swing duration (s) | duty factor | stride foot velocity (m/s) | slip distance (m) | percentage into stride max foot velocity occurs (swing phase) | percentage into stride min foot velocity occurs (stance phase) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.068 | 1.50 | 0.873 | 0.626 | 0.583 | 0.047 | 0.041 | 0.210 | 0.620 |
| 2 | 0.0821 | 1.16 | 0.628 | 0.535 | 0.539 | 0.071 | 0.018 | 0.226 | 0.686 |
| 3 | 0.114 | 1.04 | 0.515 | 0.530 | 0.490 | 0.142 | 0.00 | 0.223 | 0.723 |
| 4 | 0.077 | 0.828 | 0.441 | 0.387 | 0.530 | 0.103 | 0.012 | 0.239 | 0.717 |

**Table 2.** Average kinematic data of each experimental salamander walking on gravel substrate.

The collection of values for each salamander's dependent kinematic variables were subject to JMP Pro 13 ANOVA statistical analysis to determine any significant differences in value between the fixed factor substrate types. Recall that the null hypothesis assumed that all means were equal. Therefore, the F-ratio outputted by JMP reflects the assumption that the independent variable, substrate type, has zero effect on the dependent kinematic variables. Prob>F is the p-value of the individual ANOVA tests completed by the software for each dependent variable. The p-value reveals the probability of obtaining the F-ratio outputted. Since the significance level was set to 0.05 for analysis, any p-value less than 0.05 requires rejection of the null hypothesis. Thus, it can be concluded that for Prob>F less than 0.05, there are significant differences between the kinematic variable means for glass substrate walking and gravel substrate walking. Nparm refers to the number of parameters associated with the variable source. Both salamander identity and substrate type are nominal parameters so Nparm is one less than the number of levels for each parameter.  Salamander identity has four levels while substrate type has two levels. DF refers to the degrees of freedom while DFden refers to the degrees of freedom in the denominator of the test. Instances where significant differences occurred have the p-value highlighted in red and marked with a '*' in the figures below.

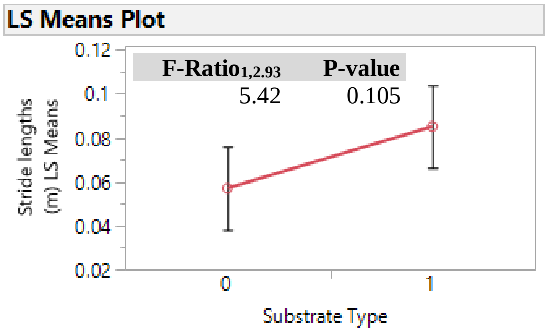


**Figure 12.** The F-ratio$_{DF,DFden}$, p-value, and least squares means plot for stride length. 0 is glass substrate 1 is gravel substrate.

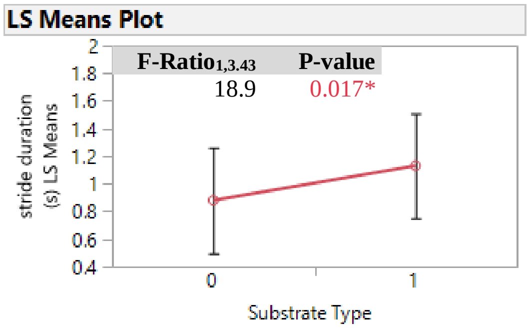


**Figure 13.** The F-ratio$_{DF,DFden}$, p-value, and least squares means plot for stride duration. 0 is glass substrate 1 is gravel substrate.

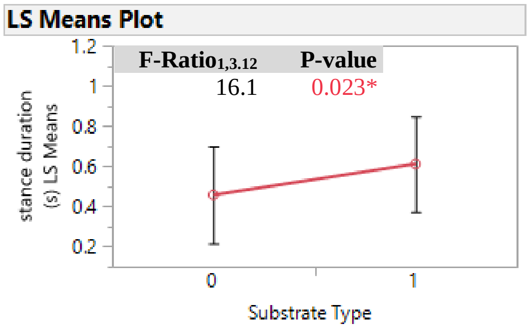


**Figure 14.** The F-ratio$_{DF,DFden}$, p-value, and least squares means plot for stance duration. 0 is glass substrate 1 is gravel substrate.

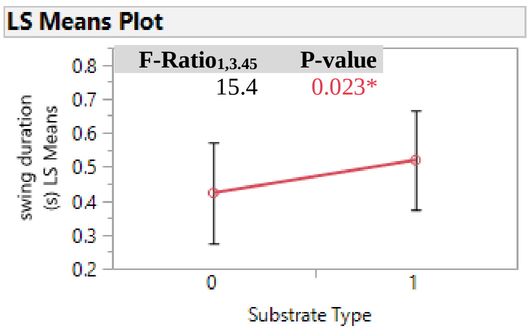


**Figure 15.** The F-ratio$_{DF,DFden}$, p-value, and least squares means plot for swing duration. 0 is glass substrate 1 is gravel substrate.

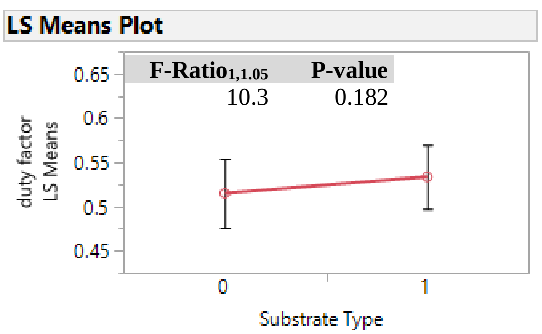


**Figure 16.** The F-ratio$_{DF,DFden}$, p-value, and least squares means plot for duty factor. 0 is glass substrate 1 is gravel substrate.

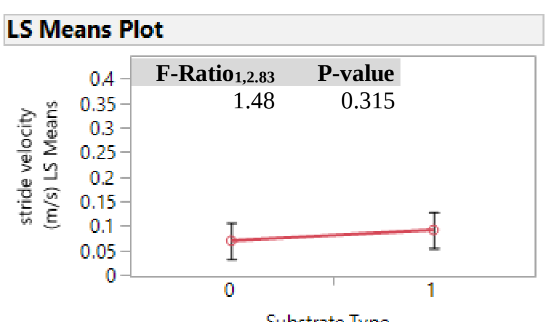


**Figure 17.** The F-ratio$_{DF,DFden}$, p-value, and least squares means plot for stride velocity. 0 is glass substrate 1 is gravel substrate.

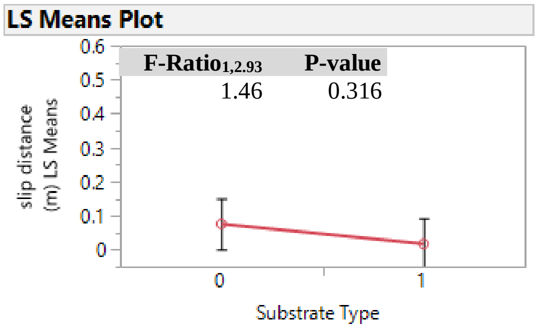


**Figure 18.** The F-ratio$_{DF,DFden}$, p-value, and least squares means plot for slip distance. 0 is glass substrate 1 is gravel substrate.

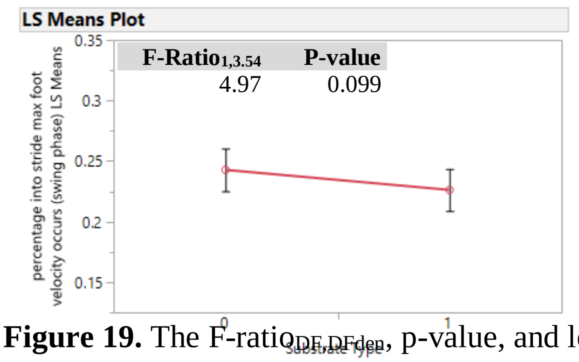


**Figure 19.** The F-ratio$_{DF,DFden}$, p-value, and least squares means plot for fraction into stride that foot maximum velocity occurs. 0 is glass substrate 1 is gravel substrate.

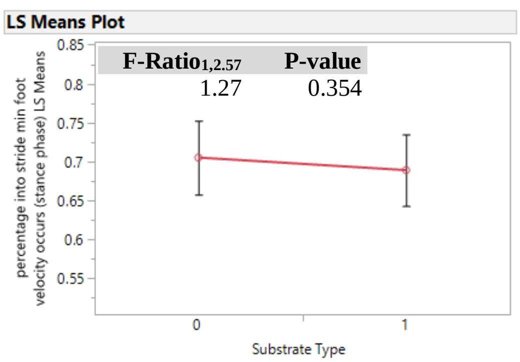


**Figure 20.** The F-ratio$_{DF,DFden}$, p-value, and least squares means plot for fraction into stride that foot minimum velocity occurs. 0 is glass substrate 1 is gravel substrate.

## Discussion

The underwater walking of salamanders observed in this experiment matched the observations of previous studies. Salamanders of this study used an underwater diagonal step sequence with periods of foot suspension, whereby diagonally related limbs were in suspension at the same time. In addition, their underwater walking had a reduced duty factor thereby classifying their gait as a trot. The gait type is defined by duty factor and phase of limbs which was not studied in this experiment. In a previous study conducted by Ashely-Ross et al., newt terrestrial walking was categorized by a duty factor of 77% while the terrestrial "trotting" gait was previously defined by a reduced duty factor and two-leg supported movement (Ashley-Ross et al., 2009; Ashley-Ross, 1994). In their study, submerged newt walking revealed step sequences similar to the terrestrial trotting gait, with added periods of body suspension, due to a reduced duty factor of 41% (Ashley-Ross et al., 2009).

Despite having obtained videos where the salamander underwater walking sequences appeared, to the human eye, to be continuous and nonangled with steady-speed motion for two or more full strides, MATLAB analysis of the digitized videos showed otherwise in many cases. Most of the digitized videos did not end up having the preferred number of strides after cropping coordinates to the usable range and applying the MATLAB code of **Appendix 1**. For this reason, the average stride length, stride duration, stance duration, swing duration, duty factor, stride velocity, slip distance, percentage into the stride maximum foot velocity occurred, and percentage into the stride minimum foot velocity occurred were calculated from a variable number of analyzed strides for each salamander on each substrate type.

If the salamander walked at a 5º angle away or towards the view of the camera, the kinematic values obtained by MATLAB would be cos(5º), or 99.6%, of the actual value. For this study, it was considered acceptable to use data from videos where walking angle did not exceed 10º, as values would be at least cos(10º), or 98.5%, of the true value. Due to suspected angled walking of the salamanders , the y- coordinates of motion were ignored and all displacement and velocity measurements were based on the x- coordinates of the digitized salamander motion. Although angled walking affected values obtained from x- directed motion as well, measurements derived from this motion were still acceptable to use in analysis as long as the angle of walking was kept under the 10º cap.

Foot slip, especially on the smooth glass substrate, could have also affected measurements calculated for salamander motion. In addition, environmental conditions and salamander health may have also played a role in kinematic discrepancies. Various external stimuli in the lab room where trials were completed could have caused abnormal underwater walking if the stimuli had stressed the salamanders. Trials were not completed immediately after weekly feeding however two of the original salamanders used in the study passed away shortly after trials were completed, one having undergone weight loss during the study, which may have affected the integrity of the data collected.

JMP analysis of averaged stride duration, stance duration, and swing duration values for each salamander on each substrate condition revealed that all durations are significantly greater for walking on gravel versus glass substrate. The least squares means plots in **Figures 13-15** depict these significant differences. No other significant differences for kinematic variable values were observed based on the substrate type walked on. Most surprising was the fact that no significant difference in stride velocity or slip was found between smooth and rough substrate walking as foot grip was greatly reduced on a glass bottom. *Thus, the kinematics of underwater salamander walking differ to some degree when the salamander walks on smooth or rough substrate.*

## Conclusion

In the present study, the kinematics of salamander underwater walking on smooth and rough substrates were quantified. After statistical analysis, it was found that average stride duration, stance duration within strides, and swing duration within strides were significantly greater when salamanders walked underwater on rough substrate. This may be a result of the heightened foot grip on gravel allowing for greater step propulsion and thus greater time in stride. In conclusion, the kinematics of underwater salamander walking differ to some degree when the salamander walks on smooth or rough substrate.

With data affected by angled walking, small sample size, foot slip, and environmental conditions, current research is working to limit the effects of these factors on kinematic data being extracted. To prevent the effects of slipping on the plexiglass substrate in current research, this smooth substrate condition has been replaced by a sheet of homemade sandpaper. The gravel substrate has gone unchanged. Sample size has also been increased to six salamanders in current trials. Environmental conditions and salamander health are still variable. Previously, salamanders either walked voluntarily along the bottom of the tank or were stimulated to locomote by touching the tip of the tail. Current research is looking for new methods to convince the salamanders to walk more naturally. Greater care is also being taken to make sure that aquatic walking sequences do in fact contain steady bouts of locomotion with a minimum of three complete stride cycles.

Current research also eliminates the effects of angled walking on kinematic data extracted by MATLAB by employing two GoPro recording devices which simultaneously obtain dorsal and lateral views of underwater walking. The lateral and dorsal views of each trial will both be digitized, with greater care, for MATLAB analysis. In doing so, the y- coordinate of motion can be used for calculations. Foot velocity will be based on both x- and y- motion and the salamanders' center of mass movements will be analyzed vertically and horizontally. Measurements of the center of mass will further allow for the calculation of kinetic and potential energy fluctuations during underwater walking after taking into account the effects of buoyancy.

Ultimately, these new kinematic markers, and updated versions of the kinematic variables analyzed in this report, will be compared across substrate conditions. In the more distant future, the force exerted by the salamanders' feet during underwater walking will be recorded and analyzed. The kinematic data of this report and the data currently being extracted will not only help science understand more about the effects of substrate on underwater salamander walking and more about the transition from aquatic to terrestrial motion, but will also help with the design of salamander robotic mimics that are better equipped for handling aquatic and terrestrial environments with different substrates.

## Acknowledgments

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# Appendix

**Appendix 1.** Script File of Code

```
clear all

%read in the salamander file xypts
% example FileName = '040717_Sal1_NoSub_vid1xypts.csv';
[FileName,PathName] = uigetfile('*xypts.csv','Select the MATLAB file');
cd(PathName);%changes the working directory so it's not pulling from matlab scripts

%extract date, salamander#, substrate conditions, and video# from FileName
date=str2double(FileName(1:6));

a=strfind(FileName,'Sal');
salnumber=str2double(FileName(a+3));

b=strfind(FileName,'NoSub');
if isempty(b)==1
  substrate='gravel';
else
  substrate='glass';
end

%for vid number find vid and x and take the number before it
v=strfind(FileName,'vid');
d=strfind(FileName,'xy');
vidnum=str2double(FileName(v+3:d-1));

%bring in excel file but exclude first row
%***everything is Row:column in matlab
%then split up into arm, body, length coordinates
%foot is columns 1 and 2
```

```
%back is column 3 and 4
%snout is column 5 and 6
%hip is column 7 and 8
salamander=csvread(FileName,1,0);

%THE FOOT
foot=salamander(:,1:2);%uses all rows of columns one and two

%separates foot points x and y and determine where data exists (1 if NaN, 0 if has value)
footxval= isnan(foot(:,1));

e=find(abs(diff(footxval)),2);
%looking for when switches from a zero to a one or a one to a zero
%gives the first two indices where this occurs
%get back the index of the 0 if finds a 0->1 swith or the index of the 1 if 1->0


%check to see if data spans the entire excel file
if isempty(e)
   footstartcell=2;
   footendcell=size(salamander,1);%gives back first dimension (#rows) of array

%check to see if data starts at a point and goes to the end of the file
%or if data starts at the beginning of the file and ends at a certain point
elseif size(e,1)==1
   if footxval(1)==1 %first value is NaN so the data starts at certain point and goes to the end
      footstartcell=e(1)+1;
      footendcell=size(salamander,1);
   else %the data starts at the beginning and ends at certain point
      footstartcell=2;
      footendcell=e(1);
   end
%if data starts AND ends at certain points in the file
else
    footstartcell=e(1)+1;%recall got back index of 0 so add to get index of 1
    footendcell=e(2);
end

%check to see if there are any missing foot x,y data points in the excel file that
%would cause error in the footstartcell to footendcell range
figure(1)
plot(isnan(salamander(footstartcell:footendcell, 1))), title('isNaN  x foot')
figure(2)
plot(isnan(salamander(footstartcell:footendcell, 2))), title('isNaN y foot')

%THE BACK
```

```
back=salamander(:,3:4);
backxval= isnan(back(:,1));%separate back points x and y
f=find(abs(diff(backxval)),2);
%find which cells contain the data just like above
if isempty(f)
   backstartcell=2;
   backendcell=size(salamander,1);
elseif size(f,1)==1
   if backxval(1)==1
      backstartcell=f(1)+1;
      backendcell=size(salamander,1);
   else
      backstartcell=2;
      backendcell=f(1);
   end
else
    backstartcell=f(1)+1;
    backendcell=f(2);
end

%check to see if there are any back foot x,y data points in the excel file that
%would cause error in the backstartcell to backendcell range
figure(3)
plot(isnan(salamander(backstartcell:backendcell, 3))), title('isNaN x back')
figure(4)
plot(isnan(salamander(backstartcell:backendcell, 4))), title('isNaN y back')

%find where foot and back data both exist in the file
if footstartcell<backstartcell
   filestartcell=backstartcell;
else
   filestartcell=footstartcell;
end
if footendcell<backendcell
   fileendcell=footendcell;
else
   fileendcell=backendcell;
end

%Thus define the foot and back usable x and y values based on overlap
FootX=foot(filestartcell:fileendcell,1);
FootY=foot(filestartcell:fileendcell,2);
BackX=back(filestartcell:fileendcell,1);
BackY=back(filestartcell:fileendcell,2);

%THE HIP
```

```
hip=salamander(:,7:8);
hipxval=isnan(hip(:,1));%separate hip points x and y
g=find(abs(diff(hipxval)),1);%g(1) will be index of 0 for the 0->1 switch
hipstartcell=g(1)+1;
HipX=hip(hipstartcell,1);
HipY=hip(hipstartcell,2);

%THE NOSE
nose=salamander(:, 5:6);
nosexval=isnan(nose(:,1));%separate nose points x and y
h=find(abs(diff(nosexval)),1);%h(1) will be index of 0 for the 0->1 switch
nosestartcell=h(1)+1;
NoseX=nose(nosestartcell,1);
NoseY=nose(nosestartcell,2);

%Find nose to hip distance in pixels
bodylength=sqrt((HipX-NoseX).^2+(HipY-NoseY).^2);
%find conversion from pixels to meters
%use the nose to hip distance in pixels and the one in cm measured from sal pic using imageJ
if salnumber==1
     mlength=.0876;
    elseif salnumber==2
     mlength=.09209;
    elseif salnumber==3
     mlength=.09372;
    else
     mlength=.09148;
 end
pixeltometer=mlength/bodylength; %m/pixel
bodylength=bodylength.*pixeltometer;


%For a smoothing spline like we discussed, use [sp,values] = spaps(x,y,tol);
%where tol is the tolerance (smoothing coefficient),
%and values will be the output smoothed data (sp are the spline coefficients)
%spline back point x
tolx=50000;%change in factors of 10
i=linspace(1,size(BackX,1),length(BackX))';
%generates n=length(BackX) points between 1 and #rows in BackX.
%The spacing between the points is (x2-x1)/(n-1)
%linspace is based on time so goes by index/row# not by value @ that index
% the ' swaps rows and columns

%Spline back point x, y, foot point x and y then convert to cm
[bxsp,BackXSp]= spaps(i,BackX,tolx);
BackXSp=BackXSp.*pixeltometer;
```

```
toly=7000;
j=linspace(1,size(BackY,1),length(BackY))';
[bysp,BackYSp]= spaps(j,BackY,toly);
BackYSp=BackYSp.*pixeltometer;

k=linspace(1,size(FootX,1),length(FootX))';
[fxsp,FootXSp]= spaps(k,FootX,tolx);
FootXSp=FootXSp.*pixeltometer;

l=linspace(1,size(FootY,1),length(FootY))';
[fysp,FootYSp]= spaps(l,FootY,tolx);
FootYSp=FootYSp.*pixeltometer;


%Finding Stride Length

%Stride starts and ends with min distance diff b/w foot and hip point
FootHipDist=sqrt((FootXSp-BackXSp).^2+(FootYSp-BackYSp).^2);
FootHipDist=FootHipDist.*pixeltometer;
figure(5)
plot(FootHipDist), title('Distance Between Foot and Hip Digitized Points')
xlabel('Frame')
ylabel('Foot-to-Hip Distance (m)')
hold on
%CODE FOR THE COMPUTER TO FIND MINS AND MAX INDECES
o=0;
p=0;
FHminprelim=zeros(1,10);
FHmaxprelim=zeros(1,10);
for m=3:size(FootHipDist,2)%the min can't be the first value in foothipdist
    if FootHipDist(m-1)<FootHipDist(m-2) && FootHipDist(m)>FootHipDist(m-1)
        o=o+1;
        FHminprelim(1,o)=m-1;%index of a minimum

    elseif FootHipDist(m-1)>FootHipDist(m-2) && FootHipDist(m)<FootHipDist(m-1)
        p=p+1;
        FHmaxprelim(1,p)=m-1;%index of maximum

    end
end
FHminprelim=FHminprelim(1,1:o);
FHmaxprelim=FHmaxprelim(1,1:p);
FHminprelim
FHmaxprelim
plot(FHminprelim, FootHipDist(FHminprelim), 'o')
```

```
hold on
plot(FHmaxprelim, FootHipDist(FHmaxprelim), '*')
legend('Foot-to-hip dist.','Foot-to-hip min dist.', 'Foot-to-hip max dist.')

%pause %give time to find values for next part
%MANUALLY CREATE VECTORS OF MIN AND MAX FOOT TO HIP DISTANCE
INDECES
%compare computer found max and min to the graph to choose correct strides
FHmin=input('enter values of indeces where the foot hip distance is at a minimum within
brackets\n');
FHmax=input('enter values of indeces where the foot hip distance is at a maximum within
brackets\n');

%Import Video
 %filename needs to be .avi not excel .csv
 [VideoName,TrialName] = uigetfile('*.avi','Select the MATLAB file');
 cd(TrialName);%changes the working directory so it's not pulling from matlab scripts
 vidObj = VideoReader(VideoName);

 %duration=frames/frame rate which is 60fps (frames per sec)
 %VidDuration=vidObj.NumberOfFrames/vidObj.FrameRate;
 VidDuration=vidObj.Duration;

%measures foot displacement from start to end of stride (FHmin to FHmin)
%already in cm since FootXsp in cm
%play with start and end of stride and let user know if start at min
%how many strides you get vs how mant strides you get if max distance
%simultaneously determine time elapsed during stride
%Simultaneously determine average velocity over the stride (displacement/time)
stridelengthsminstart=zeros(10,1);
strideduration=zeros(10,1);
%stridelengthsmaxstart=zeros(1,10);
stridefootvelocity=zeros(10,1);
for q=2:length(FHmin)
    stridelengthsminstart(q-1,1)=abs(FootXSp(FHmin(q))-FootXSp(FHmin(q-1)));
    strideduration(q-1,1)=abs(FHmin(q)-FHmin(q-1))./vidObj.FrameRate;
    stridefootvelocity(q-1,1)=stridelengthsminstart(q-1,1)/strideduration(q-1,1);
end
stridelengthsminstart=stridelengthsminstart(1:q-1,1);
strideduration=strideduration(1:q-1,1);
stridefootvelocity=stridefootvelocity(1:q-1,1);

%Time in swing phase (FHmin to FHmax)
for q=1:length(strideduration)
    if q<=length(FHmax)
        swingduration(q,1)=abs(FHmin(q)-FHmax(q))./vidObj.FrameRate;
```

```
    end
end

%Time in stance phase (FHmax to FHmin)
for q=1:length(strideduration)
    if q+1<=length(FHmin)
        stanceduration(q,1)=abs(FHmax(q)-FHmin(q+1))./vidObj.FrameRate;
    end
end

%Duty Factor
for q=1:length(strideduration)
    dutyfactor(q,1)=stanceduration(q,1)./strideduration(q,1);
end

%{
this is the code for if we switched strides to being between FHmax
distances
for zz=2:length(FHmax)
    stridelengthsmaxstart(1,zz-1)=abs(FootXSp(FHmax(zz))-FootXSp(FHmax(zz-1)));
    strideduration(1,zz-1)=abs(FootXSp(FHmax(zz))-FootXSp(FHmax(zz-
1)))/vidObj.FrameRate;
    stridefootvelocity(1,zz-1)=stridelengthsmaxstart(1,zz-1)/strideduration(1,zz-1);
end
stridelengthsmaxstart=stridelengthsmaxstart(1,1:zz-1);
%}

%Plot x direction foot displacement
figure (6)
plot(FootXSp), title('Foot Displacement in the X-direction')
xlabel('Frame')
ylabel('Displacement (m)')
%total foot displacement in the x direction
 FootXDisp=zeros(1,length(FootXSp)-1);
 %subtract 1 since don't include first point of FootX in displacement calc
 for r=2:length(FootXSp)
    FootXDisp(1,r-1)=FootXSp(r)-FootXSp(1);
 end

 %Plot Y direction foot displacement might be faulty due to angled walking
figure (7)
plot(FootYSp), title('Foot Displacement in the Y-direction')
xlabel('Frame')
ylabel('Displacement (m)')

%displacement of the foot in the Y direction
```

```
 FootYDisp=zeros(1,length(FootYSp)-1);
 %subtract 1 since don't include first point of FootY in displacement calc
 for r=2:length(FootYSp)
   FootYDisp(1,r-1)=FootYSp(r)-FootYSp(1);
 end

%foot x and y direction velocity in m/s
footXvel=diff(FootXSp).*vidObj.FrameRate;
footYvel=diff(FootYSp).*vidObj.FrameRate;
%takes velocity between frame pairs so multiply by frame rate

%TotalFootVel=hypot(footXvel,footYvel);%hypotenuse of the x and y

%only use velocity in X direction cuz foot Y is faulty if angled walking
%find the indeces of min and max footX velocities
   u=0;
   v=0;
   FootXVelMin=zeros(1,20);
   FootXVelMax=zeros(1,20);
   for m=3:size(footXvel,2)
      if footXvel(m-1)<footXvel(m-2) && footXvel(m)>footXvel(m-1)
         u=u+1;
         FootXVelMin(1,u)=m-1;%index of a minimum

      elseif footXvel(m-1)>footXvel(m-2) && footXvel(m)<footXvel(m-1)
         v=v+1;
         FootXVelMax(1,v)=m-1;%index of maximum

      end
   end
   FootXVelMin=FootXVelMin(1:u);
   FootXVelMax=FootXVelMax(1:v);

%Percent into stride that max foot vel occurs
k=1;
for q=1:length(strideduration)

   if FootXVelMax(k)>FHmin(q)
   MaxFootVelFraction(q,1)=((FootXVelMax(k)-
FHmin(q))./vidObj.FrameRate)./strideduration(q,1);
   else
   k=k+1;
   MaxFootVelFraction(q,1)=((FootXVelMax(k)-
FHmin(q))./vidObj.FrameRate)./strideduration(q,1);
   end
end
```

```
%Percent into stride that min foot vel occurs
k=1;
for q=1:length(strideduration)
   if FootXVelMin(k)>FHmin(q)
   MinFootVelFraction(q,1)=((FootXVelMin(k)-
FHmin(q))./vidObj.FrameRate)./strideduration(q,1);
   else
   k=k+1;
   MinFootVelFraction(q,1)=((FootXVelMin(k)-
FHmin(q))./vidObj.FrameRate)./strideduration(q,1);
   end
end


 figure(8)
 plot(footXvel), title('Foot Velocity')
 hold on
 %plot strides
 plot(FHmin, footXvel(FHmin), '*')
 hold on
 plot(FHmax, footXvel(FHmax), 'o')
 hold on
 %plot min and max foot vel
 plot(FootXVelMin, footXvel(FootXVelMin), 'X')
 hold on
 plot(FootXVelMax, footXvel(FootXVelMax), '^')
 xlabel('Frame')
 ylabel('Velocity (m/s)')

 legend('Velocity', 'Foot Hip Dist Min', 'Foot Hip Dist Max', 'Foot Min Vel.', 'Foot Max Vel.')


%{
 %find the indeces of min and max footY velocities
   u=0;
   v=0;
   FootYVelMin=zeros(1,20);
   FootYVelMax=zeros(1,20);
   for m=3:size(footYvel,2)
       if footYvel(m-1)<footYvel(m-2) && footYvel(m)>footYvel(m-1)
           u=u+1;
           FootYVelMin(1,u)=m-1;%index of a minimum

       elseif footYvel(m-1)>footYvel(m-2) && footYvel(m)<footYvel(m-1)
           v=v+1;
           FootYVelMax(1,v)=m-1;%index of maximum
```

```
        end
    end
    FootYVelMin=FootYVelMin(1:u);
    FootYVelMax=FootYVelMax(1:v);
 %}

%{
%USING TOTAL VELOCITY TAKING INTO ACCOUNT FOOT X AND Y
%find the indeces of min and max overall foot velocities
    u=0;
    v=0;
    FootVelMin=zeros(1,20);
    FootVelMax=zeros(1,20);
    for m=3:size(TotalFootVel,2)
        if TotalFootVel(m-1)<TotalFootVel(m-2) && TotalFootVel(m)>TotalFootVel(m-1)
            u=u+1;
            FootVelMin(1,u)=m-1;%index of a minimum

        elseif TotalFootVel(m-1)>TotalFootVel(m-2) && TotalFootVel(m)<TotalFootVel(m-1)
            v=v+1;
            FootVelMax(1,v)=m-1;%index of maximum

        end
    end
    FootVelMin=FootVelMin(1:u);
    FootVelMax=FootVelMax(1:v);

%Percent into stride that max foot vel occurs
k=1;
for q=1:length(strideduration)

    if FootVelMax(k)>FHmin(q)
    MaxFootVelFraction(q,1)=((FootVelMax(k)-
FHmin(q))./vidObj.FrameRate)./strideduration(q,1);
    else
    k=k+1;
    MaxFootVelFraction(q,1)=((FootVelMax(k)-
FHmin(q))./vidObj.FrameRate)./strideduration(q,1);
    end
end
%Percent into stride that min foot vel occurs
k=1;
for q=1:length(strideduration)
    if FootVelMin(k)>FHmin(q)
```

```
   MinFootVelFraction(q,1)=((FootVelMin(k)-
FHmin(q))./vidObj.FrameRate)./strideduration(q,1);
   else
   k=k+1;
   MinFootVelFraction(q,1)=((FootVelMin(k)-
FHmin(q))./vidObj.FrameRate)./strideduration(q,1);
   end
end


 figure(8)
 plot(TotalFootVel), title('Foot Velocity')
 hold on
 %plot strides
 plot(FHmin, TotalFootVel(FHmin), '*')
 hold on
 plot(FHmax, TotalFootVel(FHmax), 'o')
 hold on
 %plot min and max foot vel
 plot(FootVelMin, TotalFootVel(FootVelMin), 'X')
 hold on
 plot(FootVelMax, TotalFootVel(FootVelMax), '^')

 legend('Velocity', 'Foot Hip Dist Min', 'Foot Hip Dist Max', 'Foot Min Vel.', 'Foot Max Vel.')
%}

 %Foot slip
  direction=diff(BackXSp);
 %if salamander is moving from the left to the right side of the tank in the postive direction
 %find zeros at shift from positive to negative vel and the shift back from
 %negative to positive then integrate that negative velocity area for footslip distance

 if direction(1)>0%positive direction

 for ee=1:length(footXvel)
    if footXvel(ee)>=0
        PosFootVel(1,ee)=1;
    else
         PosFootVel(1,ee)=0;
    end
 end
 %the spikes where positive negative velocity switches occur
 StartEndNegFootVel=diff(PosFootVel);
 startslipcounter=1;
 endslipcounter=1;
 slipdistcounter=1;
```

```
 for ff=1:length(StartEndNegFootVel)
    if StartEndNegFootVel(ff)==-1 %go from pos to neg velocity difference will be -1
       startslipcounter=ff;
    elseif StartEndNegFootVel(ff)==1%go from neg to pos velocity difference will be 1
       endslipcounter=ff;
       slipdist(slipdistcounter,1)=abs(trapz(footXvel(1,startslipcounter:endslipcounter)));
       %integrate the negative velocity zone
       slipdistcounter=slipdistcounter+1;
    end
 end

 end

 %if salamander is moving from the right to the left side of the tank in the negative direction
 %find zeros at shift from negative to positive vel and the shift back from
 %positive to negative then integrate that positive velocity area for footslip distance

if direction(1)<0 %negative direction

 for ee=1:length(footXvel)
    if footXvel(ee)<=0
       NegFootVel(1,ee)=1;
    else
        NegFootVel(1,ee)=0;
    end
 end
%the spikes where negative to positive velotcity switches occur
 StartEndPosFootVel=diff(NegFootVel);
 startslipcounter=1;
 endslipcounter=1;
 slipdistcounter=1;
 for ff=1:length(StartEndPosFootVel)
    if StartEndPosFootVel(ff)==-1 %go from  neg to pos velocity difference will be -1
       startslipcounter=ff;
    elseif StartEndPosFootVel(ff)==1%go from pos to neg velocity difference will be 1
       endslipcounter=ff;
       slipdist(slipdistcounter,1)=abs(trapz(footXvel(1,startslipcounter:endslipcounter)));
       %integrate the positive velocity zone
       slipdistcounter=slipdistcounter+1;
    end
 end

end

 %{
 %graph of displacement hoz and vertical over time (center of mass)
```

```
%hoz
figure('Name','Back Horizontal Displacement','NumberTitle','off');
plot(BackXDisp);
hold on
plot(FHmin, BackXDisp(FHmin), '*')
hold on
plot(FHmax, BackXDisp(FHmax), 'o')
legend('Horizontal Disp', 'Foot Hip Dist Min', 'Foot Hip Dist Max')
saveas(figure('Name','Horizontal Displacement','NumberTitle','off'),'Center of mass horizontal displacement.emf');
%}
```

**Appendix 2.** Compiled data for each salamander on each substrate as extracted by the code

| video # | Stride lengths (m) | stride duration (s) | stance duration (s) | swing duration (s) | duty factor | stride foot velocity (m/s) | slip distance (m) | percentage into stride max foot velocity occurs (swing phase) | percentage into stride min foot velocity occurs (stance phase) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.077493772 | 1.368033333 | 0.65065 | 0.717383333 | 0.475609756 | 0.056646114 | 0 | 0.292682927 | 0.743902439 |
| | 0.081378382 | 1.4014 | 0.75075 | 0.65065 | 0.535714286 | 0.058069347 | 0 | 0.238095238 | 0.678571429 |
| 2 | 0.059315426 | 0.684016667 | 0.333666667 | 0.35035 | 0.487804878 | 0.086716345 | 0 | 0.268292683 | 0.731707317 |
| | 0.055760555 | 0.717383333 | 0.367033333 | 0.35035 | 0.511627907 | 0.077727698 | 0 | 0.255813953 | 0.697674419 |
| | 0.049329357 | 0.834166667 | 0.5005 | 0.333666667 | 0.6 | 0.059136092 | 0 | 0.18 | 0.64 |
| 5 | 0.078232137 | 1.384716667 | 0.717383333 | 0.667333333 | 0.518072289 | 0.056496855 | 0 | 0.228915663 | 0.698795181 |
| | 0.054260168 | 1.584916667 | 0.9009 | 0.684016667 | 0.568421053 | 0.034235345 | 0.00093344 | 0.189473684 | 0.621052632 |
| 7 | 0.079622616 | 0.867533333 | 0.45045 | 0.417083333 | 0.519230769 | 0.091780469 | 0 | 0.25 | 0.711538462 |
| | 0.070225093 | 1.001 | 0.55055 | 0.45045 | 0.55 | 0.070154938 | 0 | 0.216666667 | 0.683333333 |
| 8 | 0.065253638 | 1.1011 | 0.55055 | 0.55055 | 0.5 | 0.059262226 | 0 | 0.242424242 | 0.727272727 |
| | 0.065691414 | 1.234566667 | 0.7007 | 0.533866667 | 0.567567568 | 0.053210098 | 0 | 0.202702703 | 0.662162162 |
| 9 | 0.072405144 | 1.468133333 | 0.75075 | 0.717383333 | 0.511363636 | 0.049317826 | 0 | 0.170454545 | 0.806818182 |
| | 0.0657491 | 1.668333333 | 1.034366667 | 0.633966667 | 0.62 | 0.03941005 | 0 | 0.13 | 0.6 |
| 11 | 0.076611249 | 1.518183333 | 0.834166667 | 0.684016667 | 0.549450549 | 0.050462449 | 0 | 0.241758242 | 0.626373626 |
| | 0.055632397 | 1.25125 | 0.684016667 | 0.567233333 | 0.546666667 | 0.044461456 | 0 | 0.253333333 | 0.64 |
| **avg** | **0.067130696** | **1.205648889** | **0.651762222** | **0.553886667** | **0.537435291** | **0.059139154** | **6.2229E-05** | **0.224040925** | **0.684613461** |

**Table 1**. Salamander 1 strides on glass.

| video # | Stride lengths (m) | stride duration (s) | stance duration (s) | swing duration (s) | duty factor | stride foot velocity (m/s) | slip distance (m) | percentage into stride max foot velocity occurs (swing phase) | percentage into stride min foot velocity occurs (stance phase) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.051932711 | 1.918583333 | 1.184516667 | 0.734066667 | 0.617391304 | 0.027068259 | 0 | 0.147826087 | 0.539130435 |
| 2 | 0.072273718 | 1.35135 | 0.867533333 | 0.483816667 | 0.641975309 | 0.053482605 | 0.06130303 | 0.160493827 | 0.49382716 |
| | 0.058834866 | 1.368033333 | 0.85085 | 0.517183333 | 0.62195122 | 0.043006895 | 0.18243793 | 0.170731707 | 0.768292683 |
| | 0.073362 | 1.267933333 | 0.7007 | 0.567233333 | 0.552631579 | 0.057859509 | 0.00011208 | 0.210526316 | 0.592105263 |
| 5 | 0.079097503 | 1.468133333 | 0.834166667 | 0.633966667 | 0.568181818 | 0.05387624 | 0 | 0.238636364 | 0.625 |
| | 0.075420536 | 1.618283333 | 0.8008 | 0.817483333 | 0.494845361 | 0.046605272 | 0.00262605 | 0.329896907 | 0.701030928 |
| **avg** | **0.068486889** | **1.498719444** | **0.873094444** | **0.625625** | **0.417170568** | **0.04698313** | **0.04107985** | **0.209685201** | **0.619897745** |

**Table 2.** Salamander 1 strides on gravel.

| video # | Stride lengths (m) | stride duration (s) | stance duration (s) | swing duration (s) | duty factor | stride foot velocity (m/s) | slip distance (m) | percentage into stride max foot velocity occurs (swing phase) | percentage into stride min foot velocity occurs (stance phase) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.055466076 | 0.75075 | 0.367033333 | 0.383716667 | 0.488888889 | 0.073880887 | 0 | 0.266666667 | 0.688888889 |
| | 0.068095448 | 0.834166667 | 0.4004 | 0.433766667 | 0.48 | 0.081632905 | 0 | 0.3 | 0.72 |
| 2 | 0.054378791 | 0.684016667 | 0.35035 | 0.333666667 | 0.512195122 | 0.079499219 | 0.00415651 | 0.243902439 | 0.731707317 |
| | 0.079102407 | 0.884216667 | 0.467133333 | 0.417083333 | 0.528301887 | 0.089460435 | 0.18081415 | 0.245283019 | 0.679245283 |
| 3 | 0.046858081 | 0.784116667 | 0.417083333 | 0.367033333 | 0.531914894 | 0.059759068 | 0.19223 | 0.234042553 | 0.680851064 |
| | 0.064788502 | 0.917583333 | 0.483816667 | 0.433766667 | 0.527272727 | 0.070607758 | 0.12591346 | 0.236363636 | 0.672727273 |
| 6 | 0.056715287 | 0.567233333 | 0.25025 | 0.316983333 | 0.441176471 | 0.099985814 | 0.08096759 | 0.294117647 | 0.764705882 |
| | 0.04680621 | 0.533866667 | 0.283616667 | 0.25025 | 0.53125 | 0.08767397 | 0.09063858 | 0.21875 | 0.6875 |
| | 0.050550107 | 0.583916667 | 0.3003 | 0.283616667 | 0.514285714 | 0.086570756 | 0.10075525 | 0.228571429 | 0.714285714 |
| | 0.039130467 | 0.55055 | 0.3003 | 0.25025 | 0.545454545 | 0.071075229 | 0.0126277 | 0.212121212 | 0.696969697 |
| | 0.063316186 | 0.684016667 | 0.35035 | 0.333666667 | 0.512195122 | 0.092565267 | 0 | 0.268292683 | 0.682926829 |
| 7 | 0.037169417 | 0.684016667 | 0.35035 | 0.333666667 | 0.512195122 | 0.05433993 | 0.20794089 | 0.268292683 | 0.658536585 |
| | 0.042302154 | 0.7007 | 0.367033333 | 0.333666667 | 0.523809524 | 0.060371277 | 0.3481322 | 0.261904762 | 0.69047619 |
| | 0.045050033 | 0.734066667 | 0.4004 | 0.333666667 | 0.545454545 | 0.061370492 | 0.30174034 | 0.227272727 | 0.681818182 |
| 8 | 0.040596358 | 0.934266667 | 0.45045 | 0.483816667 | 0.482142857 | 0.043452645 | 0.48640409 | 0.303571429 | 0.714285714 |
| | 0.04442975 | 0.834166667 | 0.433766667 | 0.4004 | 0.52 | 0.053262438 | 1.96E-05 | 0.24 | 0.72 |
| | 0.046764715 | 0.884216667 | 0.467133333 | 0.417083333 | 0.528301887 | 0.052888298 | 0.20444199 | 0.245283019 | 0.716981132 |
| 9 | 0.042093018 | 0.884216667 | 0.483816667 | 0.4004 | 0.547169811 | 0.047604868 | 0.55353673 | 0.245283019 | 0.698113208 |
| | 0.054961509 | 0.917583333 | 0.467133333 | 0.45045 | 0.509090909 | 0.059898111 | 0.31400845 | 0.254545455 | 0.709090909 |
| 10 | 0.032935158 | 0.8008 | 0.433766667 | 0.367033333 | 0.541666667 | 0.041127819 | 0.20840495 | 0.25 | 0.666666667 |
| | 0.042042796 | 0.85085 | 0.45045 | 0.4004 | 0.529411765 | 0.0494127 | 0.24906668 | 0.254901961 | 0.68627451 |
| 11 | 0.025955892 | 0.934266667 | 0.45045 | 0.483816667 | 0.482142857 | 0.027782102 | 0.0969493 | 0.303571429 | 0.732142857 |
| | 0.036293211 | 0.967633333 | 0.483816667 | 0.483816667 | 0.5 | 0.037507193 | 0.07794807 | 0.25862069 | 0.706896552 |
| | 0.037701302 | 0.85085 | 0.45045 | 0.4004 | 0.529411765 | 0.044310163 | 0 | 0.235294118 | 0.68627451 |
| **avg** | **0.050152299** | **0.815307246** | **0.419984783** | **0.395322464** | **0.537553612** | **0.066349537** | **0.16681289** | **0.24043417** | **0.668629395** |

**Table 3.** Salamander 2 strides on glass.

| video # | Stride lengths (m) | stride duration (s) | stance duration (s) | swing duration (s) | duty factor | stride foot velocity (m/s) | slip distance (m) | percentage into stride max foot velocity occurs (swing phase) | percentage into stride min foot velocity occurs (stance phase) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.049422569 | 1.1011 | 0.684016667 | 0.417083333 | 0.621212121 | 0.044884723 | 0.00627156 | 0.166666667 | 0.666666667 |
| | 0.082304765 | 1.217883333 | 0.767433333 | 0.45045 | 0.630136986 | 0.067580172 | 0.00736442 | 0.164383562 | 0.561643836 |
| | 0.061480282 | 1.05105 | 0.567233333 | 0.483816667 | 0.53968254 | 0.058494156 | 0.21524799 | 0.238095238 | 0.682539683 |
| 2 | 0.094596849 | 0.984316667 | 0.483816667 | 0.5005 | 0.491525424 | 0.096104082 | 0 | 0.271186441 | 0.728813559 |
| | 0.089281993 | 1.134466667 | 0.617283333 | 0.517183333 | 0.544117647 | 0.07869953 | 0 | 0.161764706 | 0.735294118 |
| 3 | 0.108703078 | 1.067733333 | 0.517183333 | 0.55055 | 0.484375 | 0.101807328 | 0 | 0.3125 | 0.6875 |
| | 0.081296509 | 1.234566667 | 0.734066667 | 0.5005 | 0.594594595 | 0.065850238 | 0 | 0.202702703 | 0.648648649 |
| 4 | 0.091043477 | 1.167833333 | 0.567233333 | 0.6006 | 0.485714286 | 0.077959307 | 0 | 0.314285714 | 0.742857143 |
| | 0.097455832 | 1.518183333 | 0.784116667 | 0.734066667 | 0.516483516 | 0.0641924 | 0 | 0.208791209 | 0.714285714 |
| 5 | 0.07514291 | 1.4014 | 0.767433333 | 0.633966667 | 0.547619048 | 0.053619887 | 0 | 0.214285714 | 0.642857143 |
| | 0.074595079 | 1.167833333 | 0.55055 | 0.617283333 | 0.471428571 | 0.063874765 | 0 | 0.285714286 | 0.714285714 |
| 6 | 0.072506921 | 1.034366667 | 0.583916667 | 0.45045 | 0.564516129 | 0.070097891 | 0 | 0.209677419 | 0.661290323 |
| | 0.088983559 | 1.034366667 | 0.533866667 | 0.5005 | 0.516129032 | 0.086027095 | 0 | 0.193548387 | 0.725806452 |
| **avg** | **0.082062602** | **1.1627** | **0.62755** | **0.53515** | **0.539041146** | **0.071476275** | **0.01760646** | **0.226430927** | **0.685576077** |

**Table 4.** Salamander 2 strides on gravel.

| video # | Stride lengths (m) | stride duration (s) | stance duration (s) | swing duration (s) | duty factor | stride foot velocity (m/s) | slip distance (m) | percentage into stride max foot velocity occurs (swing phase) | percentage into stride min foot velocity occurs (stance phase) |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 0.028931151 | 0.967633333 | 0.517183333 | 0.45045 | 0.534482759 | 0.029898878 | 0.54545063 | 0.224137931 | 0.706896552 |
| | 0.052462766 | 1.017683333 | 0.467133333 | 0.55055 | 0.459016393 | 0.05155117 | 0.12107989 | 0.262295082 | 0.737704918 |
| | 0.03076532 | 1.017683333 | 0.533866667 | 0.483816667 | 0.524590164 | 0.030230739 | 0.17685992 | 0.229508197 | 0.704918033 |
| 3 | 0.093503843 | 0.75075 | 0.35035 | 0.4004 | 0.466666667 | 0.124547243 | 0 | 0.266666667 | 0.755555556 |
| | 0.07570084 | 0.767433333 | 0.383716667 | 0.383716667 | 0.5 | 0.098641584 | 0 | 0.217391304 | 0.739130435 |
| 4 | 0.047237728 | 0.884216667 | 0.417083333 | 0.467133333 | 0.471698113 | 0.05342325 | 0.34841685 | 0.264150943 | 0.735849057 |
| | 0.060986631 | 0.9009 | 0.433766667 | 0.467133333 | 0.481481481 | 0.067695228 | 0.13982034 | 0.240740741 | 0.740740741 |
| | 0.052939802 | 0.867533333 | 0.417083333 | 0.45045 | 0.480769231 | 0.061023363 | 0.06303768 | 0.25 | 0.75 |
| | 0.056764655 | 1.034366667 | 0.533866667 | 0.5005 | 0.516129032 | 0.054878658 | 0.04372685 | 0.209677419 | 0.725806452 |
| 5 | 0.03817241 | 0.583916667 | 0.283616667 | 0.3003 | 0.485714286 | 0.065373044 | 0.13554199 | 0.257142857 | 0.742857143 |
| | 0.047558836 | 0.633966667 | 0.316983333 | 0.316983333 | 0.5 | 0.075017881 | 0.06146301 | 0.236842105 | 0.736842105 |
| | 0.048610282 | 0.633966667 | 0.316983333 | 0.316983333 | 0.5 | 0.076676401 | 0.02759009 | 0.236842105 | 0.736842105 |
| 6 | 0.034920301 | 0.984316667 | 0.517183333 | 0.467133333 | 0.525423729 | 0.035476694 | 0.13983571 | 0.237288136 | 0.745762712 |
| | 0.052747712 | 0.917583333 | 0.417083333 | 0.5005 | 0.454545455 | 0.057485474 | 0.09386677 | 0.290909091 | 0.745454545 |
| | 0.053569043 | 0.8008 | 0.383716667 | 0.417083333 | 0.479166667 | 0.066894409 | 0.09600849 | 0.25 | 0.729166667 |
| 8 | 0.07260435 | 0.85085 | 0.4004 | 0.45045 | 0.470588235 | 0.085331551 | 0.21093779 | 0.294117647 | 0.745098039 |
| | 0.068563002 | 0.85085 | 0.417083333 | 0.433766667 | 0.490196078 | 0.080581773 | 0.0003736 | 0.254901961 | 0.705882353 |
| **avg** | **0.053884628** | **0.85085** | **0.418064706** | **0.432785294** | **0.490615782** | **0.065572197** | **0.12964762** | **0.248388952** | **0.734382789** |

**Table 5.** Salamander 3 strides on glass.

| video # | Stride lengths (m) | stride duration (s) | stance duration (s) | swing duration (s) | duty factor | stride foot velocity (m/s) | slip distance (m) | percentage into stride max foot velocity occurs (swing phase) | percentage into stride min foot velocity occurs (stance phase) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.132463766 | 0.85085 | 0.4004 | 0.45045 | 0.470588235 | 0.4004 | 0 | 0.274509804 | 0.745098039 |
| 2 | 0.117831033 | 0.95095 | 0.45045 | 0.5005 | 0.473684211 | 0.123908758 | 0 | 0.263157895 | 0.736842105 |
| 3 | 0.132512473 | 0.95095 | 0.433766667 | 0.517183333 | 0.456140351 | 0.139347466 | 0 | 0.228070175 | 0.736842105 |
| 4 | 0.079330626 | 1.317983333 | 0.767433333 | 0.55055 | 0.582278481 | 0.060190918 | 0 | 0.139240506 | 0.569620253 |
| 5 | 0.124657602 | 1.134466667 | 0.517183333 | 0.617283333 | 0.455882353 | 0.10988212 | 0 | 0.294117647 | 0.735294118 |
| 6 | 0.067177458 | 0.984316667 | 0.5005 | 0.483816667 | 0.508474576 | 0.068247811 | 0 | 0.169491525 | 0.813559322 |
| 7 | 0.128324152 | 1.001 | 0.5005 | 0.5005 | 0.5 | 0.128195956 | 0 | 0.233333333 | 0.7 |
| 8 | 0.127536233 | 1.167833333 | 0.55055 | 0.617283333 | 0.471428571 | 0.109207563 | 0 | 0.185714286 | 0.742857143 |
| **avg** | **0.113729168** | **1.04479375** | **0.515097917** | **0.529695833** | **0.489809597** | **0.142422574** | **0** | **0.223454396** | **0.722514136** |

**Table 6.** Salamander 3 strides on gravel.

| video # | Stride lengths (m) | stride duration (s) | stance duration (s) | swing duration (s) | duty factor | stride foot velocity (m/s) | slip distance (m) | percentage into stride max foot velocity occurs (swing phase) | percentage into stride min foot velocity occurs (stance phase) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.0682154 | 0.45045 | 0.2002 | 0.25025 | 0.444444444 | 0.151438339 | 0 | 0.259259259 | 0.740740741 |
| | 0.062473964 | 0.5005 | 0.283616667 | 0.216883333 | 0.566666667 | 0.124823104 | 0 | 0.233333333 | 0.666666667 |
| 2 | 0.059545996 | 0.667333333 | 0.333666667 | 0.333666667 | 0.5 | 0.089229764 | 0 | 0.275 | 0.7 |
| | 0.055961235 | 0.734066667 | 0.367033333 | 0.367033333 | 0.5 | 0.076234541 | 0.04846549 | 0.25 | 0.727272727 |
| | 0.05429593 | 0.767433333 | 0.433766667 | 0.333666667 | 0.565217391 | 0.070750029 | 0 | 0.195652174 | 0.652173913 |
| 3 | 0.067338115 | 0.834166667 | 0.45045 | 0.383716667 | 0.54 | 0.080725013 | 0.01606752 | 0.24 | 0.68 |
| | 0.075730535 | 0.8008 | 0.367033333 | 0.433766667 | 0.458333333 | 0.0945686 | 0 | 0.291666667 | 0.770833333 |
| | 0.043601706 | 0.75075 | 0.417083333 | 0.333666667 | 0.555555556 | 0.058077531 | 0.02979386 | 0.2 | 0.711111111 |
| | 0.057715712 | 0.9009 | 0.533866667 | 0.367033333 | 0.592592593 | 0.064064505 | 0 | 0.203703704 | 0.611111111 |
| 4 | 0.062917006 | 0.583916667 | 0.3003 | 0.283616667 | 0.514285714 | 0.107749975 | 0 | 0.257142857 | 0.714285714 |
| | 0.053307157 | 0.467133333 | 0.216883333 | 0.25025 | 0.464285714 | 0.114115507 | 0 | 0.25 | 0.75 |
| | 0.059449575 | 0.517183333 | 0.233566667 | 0.283616667 | 0.451612903 | 0.114948745 | 0 | 0.290322581 | 0.741935484 |
| 5 | 0.050617347 | 0.633966667 | 0.316983333 | 0.316983333 | 0.5 | 0.079842284 | 0.00126415 | 0.236842105 | 0.710526316 |
| | 0.052520436 | 0.7007 | 0.367033333 | 0.333666667 | 0.523809524 | 0.074954241 | 0.01908144 | 0.261904762 | 0.69047619 |
| 6 | 0.089866185 | 0.834166667 | 0.4004 | 0.433766667 | 0.48 | 0.10773169 | 0.00554912 | 0.26 | 0.72 |
| | 0.06641027 | 0.784116667 | 0.4004 | 0.383716667 | 0.510638298 | 0.084694374 | 0 | 0.255319149 | 0.70212766 |
| | 0.052249535 | 0.7007 | 0.367033333 | 0.333666667 | 0.523809524 | 0.074567626 | 0 | 0.238095238 | 0.714285714 |
| | 0.058367843 | 0.85085 | 0.483816667 | 0.367033333 | 0.568627451 | 0.068599452 | 0 | 0.215686275 | 0.62745098 |
| 7 | 0.071450422 | 0.717383333 | 0.35035 | 0.367033333 | 0.488372093 | 0.099598665 | 0 | 0.279069767 | 0.720930233 |
| | 0.062137219 | 0.75075 | 0.4004 | 0.35035 | 0.533333333 | 0.082766859 | 0.03711347 | 0.222222222 | 0.711111111 |
| | 0.065263493 | 0.767433333 | 0.433766667 | 0.333666667 | 0.565217391 | 0.085041253 | 0 | 0.195652174 | 0.673913043 |
| 8 | 0.05014623 | 0.567233333 | 0.266933333 | 0.3003 | 0.470588235 | 0.088404943 | 0 | 0.264705882 | 0.735294118 |
| | 0.04876048 | 0.633966667 | 0.333666667 | 0.3003 | 0.526315789 | 0.076913318 | 0.09840929 | 0.236842105 | 0.710526316 |
| | 0.039284451 | 0.583916667 | 0.316983333 | 0.266933333 | 0.542857143 | 0.067277496 | 0.02538505 | 0.2 | 0.714285714 |
| **avg** | **0.059484427** | **0.687492361** | **0.357301389** | **0.330190972** | **0.516106796** | **0.089046577** | **0.01171373** | **0.242184177** | **0.704044092** |

**Table 7.** Salamander 4 strides on glass.

| video # | Stride lengths (m) | stride duration (s) | stance duration (s) | swing duration (s) | duty factor | stride foot velocity (m/s) | slip distance (m) | percentage into stride max foot velocity occurs (swing phase) | percentage into stride min foot velocity occurs (stance phase) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.07147412 | 0.95095 | 0.6006 | 0.35035 | 0.63157895 | 0.119004529 | 0.031200082 | 0.25 | 0.722222222 |
| | 0.079742522 | 0.867533333 | 0.567233333 | 0.3003 | 0.65384615 | 0.140581515 | 0 | 0.205882353 | 0.676470588 |
| 2 | 0.081271496 | 0.734066667 | 0.367033333 | 0.367033333 | 0.5 | 0.110714053 | 0 | 0.272727273 | 0.772727273 |
| | 0.075558116 | 0.7007 | 0.383716667 | 0.316983333 | 0.54761905 | 0.107832333 | 0 | 0.214285714 | 0.69047619 |
| | 0.055743363 | 0.55055 | 0.283616667 | 0.266933333 | 0.51515152 | 0.101250319 | 0 | 0.212121212 | 0.757575758 |
| 3 | 0.073009308 | 0.467133333 | 0.233566667 | 0.233566667 | 0.5 | 0.156292225 | 0 | 0.214285714 | 0.714285714 |
| | 0.087309241 | 0.7007 | 0.367033333 | 0.333666667 | 0.52380952 | 0.124602884 | 0 | 0.238095238 | 0.714285714 |
| 4 | 0.087789982 | 0.917583333 | 0.467133333 | 0.45045 | 0.50909091 | 0.095675214 | 0 | 0.254545455 | 0.709090909 |
| | 0.097507347 | 1.084416667 | 0.55055 | 0.533866667 | 0.50769231 | 0.089916865 | 0 | 0.215384615 | 0.738461538 |
| 5 | 0.058056813 | 0.984316667 | 0.483816667 | 0.5005 | 0.49152542 | 0.058981845 | 0 | 0.305084746 | 0.779661017 |
| | 0.086220021 | 1.034366667 | 0.583916667 | 0.45045 | 0.56451613 | 0.083355375 | 0 | 0.241935484 | 0.629032258 |
| | 0.081000758 | 0.967633333 | 0.467133333 | 0.5005 | 0.48275862 | 0.083710177 | 0 | 0.206896552 | 0.724137931 |
| 7 | 0.074692906 | 0.784116667 | 0.383716667 | 0.4004 | 0.4893617 | 0.095257389 | 0.142618343 | 0.276595745 | 0.744680851 |
| | 0.06267231 | 0.85085 | 0.433766667 | 0.417083333 | 0.50980392 | 0.073658471 | 0 | 0.235294118 | 0.666666667 |
| **avg** | **0.076574879** | **0.828208333** | **0.440916667** | **0.387291667** | **0.530482** | **0.102916657** | **0.012415602** | **0.238795301** | **0.717126759** |

**Table 8.** Salamander 4 strides on gravel.