# A STUDY ON APHONOPELMA SEEMANNI BIOMECHANICS OF MOTION WITH EMPHASIS ON POTENTIAL FOR BIOMIMETIC ROBOTICS DESIGN

by

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## ABSTRACT

With a stable center of mass, pneumatic-aided movement, and the ability to scale multiple terrain types, the uniquely efficient and lightweight form of spiders has changed the way we think about robotic design. While the number of papers on arachnid biomechanics and spider-based biomimetic robots has been increasing in recent years, the style of analysis and the motion-types analyzed have barely changed since the 1980s. Current analyses are based on a force plate and treadmill design, in which the spider is induced into an escape run. This environmental change can affect the movements of the spider. Here I propose a novel method of testing the biomechanical and kinematic properties of spiders using a tank with a built-in sensor matrix which allows for a more natural environment for the specimens and provides force data from individual legs. The system detects a minimum force of .0196 N and has a sampling rate of 1,000 samples /second, which allows for the analysis of forces during the step. Aphonopelma seemanni, a tarantula commonly used in such research, but whose forces during movement have to date not been analyzed, was recorded walking across the matrix, and the forces, step patterns, joint angles, and center of mass deviations were recorded. Walking indicated significantly different step pattern traits than current literature, and forces per leg (.07281 N±.0235) recorded were much smaller than expected in comparison to other spiders. Statistical analysis also indicated no changes in walking movement over a range of temperatures, which also varies from literature. These findings indicate that further research on spiders should be done with respect to walking gaits in order to improve upon current biomimetic models.

## 1. INTRODUCTION

#### **1.1** Biomimetics and the Field of Robotics

Scientific advancement has always been influenced by nature. Innumerous scientific breakthroughs have come from analyzing the creative ways that natural selection and evolution have designed the world as we know it. These bio-inspired solutions classify as biomimetics; synthetic methods of replicating natural phenomena. Biomimicry can be seen everywhere; from the shape of new styles of windmills, modeled after the fins of humpback whales for noise reduction, to slug-inspired glues that have properties which allow them to adhere even on wet surfaces [1][2].

One significant area in which biomimicry is influencing advancement is in the field of robotics. The multitudes of ways in which animals and insects walk, crawl, swim, and fly have already led to innovative solutions to many of the problems modern robotics have faced, such as the ability to move on smooth surfaces, or to bend around corners. These robots range from NASA's Snakebot, which can dig and slither through Martian terrains that other robots cannot, to bacteria-inspired robots that sense slight chemical variations [3][4].

Despite great advances over the last 50 or so years, many challenges still exist, including the need for better bio-inspired robots, improved power sources, navigation of unmapped environments, improvement of brain-computer interfaces, and increased autonomy of medical robots [5][6]. Soft robotics has provided the answer to many of the problems conventional, rigid robotics have. With compliant inner-workings, non-linear modeling, and soft materials, soft robotics are challenging the way we think of robotics and providing new avenues for research.

These systems closely resemble the systems found in nature, with both hard and soft components, such as musculoskeletal systems or endoskeleton systems, which use soft actuation along with hard elements to produce complex movements. Nearly all species use a system like this, and natural selection has produced organisms that are typically at least four times more efficient in energy use than man-made systems [7]. Compared to typical robotic systems, which operate through the use of electrical motors, pneumatic-based systems also tend to require much less mass, and have a greater flexibility on where the actuation force is generated from, which allows for lower inertia and as such, less energy consumption [8].

This trend towards soft robotics has been highly beneficial for a myriad of other reasons as well, including lighter-weight designs, increased range and variability in motion, and decreased risk of injury in human-robot interactions [9]. Researchers have already created soft robotics that can produce 3D limb movement, snake through winding tunnels, or gently grasp complex shapes without damaging them [10]. Soft robotics provide solutions to many of the greatest challenges facing current robotics, and by using biomimicry as a foundation for these robots, researchers can take full advantage of evolution's careful selection of efficient systems.

### **1.2** The Spider as an Ideal System

One of the most common biomimetic robot forms is the spider (Family: Araneae). With a lightweight, elegant design, and the ability to move and climb across various terrain types, turn quickly, and fit through small holes, spiders are an ideal candidate for bio-inspired design. All spiders have common features, which include two segmented bodies, 8 legs, chelicerae, a lack of antennae, a centralized nervous system, and are air-breathing arthropods [11][12]. These common features are shared by all species of spider worldwide; however, there is ample diversity in functional form among species. Some examples of this diversity can be seen in Figure 1.



Figure 1: Examples of variation among Araneae. From left to right: marble spider (*Araneus marmoreus*), goliath bird eating spider (*Theraphosa blondi*), diving bell spider (*Argyroneta aquatica*), trapdoor spider (*Ctenizidae ummidia*) [13][14][15][16].

These variations in features include hunting style, preferred terrain, and type of prey. For example, *Argyroneta aquatica*, actively hunt their aquatic prey underwater, whereas *Ctenizidae ummidia*, or trap door spiders, use unique cork-shaped tunnels with a "trap door" entrance to ambush attack their prey. Spiders are found on every continent, with the exception of Antarctica. As a species with an estimated eight million years of evolution and survival, and with significant variations between genus, these creatures are an excellent prototype for simple, lightweight, and

efficient design [17][18]. Even the largest spider, the goliath birdeater tarantula, or *Theraphosa blondi*, which can have a leg-span of nearly a foot, weighs only about 170 grams on average [19].

There are two main features within spiders that allow for this lightweight design. The first is the lack of an interior skeletal system. The chitin-based exoskeleton provides a thin, hard outer shell for the arachnid and is more lightweight than mammalian skeletal systems [20]. Additionally, spiders reduce both their space and weight using a unique pneumatic system for movement rather than a more traditional muscular system. Some joints within the spider leg have only flexion muscles, instead of both flexion and extension muscles. These joints are instead controlled by pneumatic pressure from the hemolymph, a blood-like liquid that makes up a spider's circulatory system. This hemolymph typically fills whatever space is not muscle or nerve within the spider leg, and changes in its pressure allows for the extension of each individual joint within the leg. By reducing the amount of muscle within the legs, the legs can be narrower, and weigh less overall than if they required more musculature to function [8].

Mechanically, this eight-legged design provides an extremely stable system for the spiders' center of mass. In order to maintain their position, only half of the legs typically move at any given time, and they tend to move in a set of two pairs- two even-numbered legs on one side, and two odd-paired legs on the other [21]. However, this pattern has been shown to be used only about 66% of the time, indicating that this is not inherently a perfect rule. Even with the loss of limbs, spiders tend to maintain this stability. Research dating as far back as the 60's shows that amputating half of the spiders' legs did not result in loss of ambulation, and that the remaining legs would develop new gaits to adapt [21].

Having a biological specimen that is not only well-designed for a multitude of terrains, but also provides a sleek-legged, lightweight design and a propensity for quick, powerful movements provides a fantastic basis for biomimetic robots. The pneumatic features lend themselves well for translation into man-made devices and increase the potential for low energy, lightweight robotics and the wide variety of hunting and movement types within spiders allows for a wide selection of variables to modify individual robotics projects to the needs of the engineers designing them.

#### **1.3 Relevant Arachnid Anatomy and Physiology**

The main body of a spider consists of two components; the prosoma, also known as the cephalothorax, and the abdomen. Between these two main sections is the pedicel, which connects

the two segments and allows for blood flow throughout the spider. The prosoma consists of a tergum and sternum, with an unsclerotized, soft region separating the two on the lateral sides. It is from this unsclerotized region in which the legs extrude [22]. These subparts can be clearly seen in Figure 2 below.



Figure 2: Gross tarantula anatomy with indications for the prosoma and abdomen

The legs of arachnids consist of seven segments, which are proximally to distally the coxa, trochanter, femur, patella, tibia, metatarsus, and tarsus. Depending on the species of spider, a claw might extend from the tarsus [23]. This can be seen below in Figure 3.



Figure 3: Segments of the leg with simplified diagram (shown in yellow)

Within the arachnid leg, there is a complex hybrid pneumatic-muscular system, as previously mentioned in Section 1.2. This system is driven by the heart, which resides in the abdomen. A singular large aorta extends through the pedicel, and into the prosoma. This aorta provides hemolymph flow to the peripheral systems.

The legs are mainly filled with muscle, with a small section containing nerve. As spiders have an open circulatory system, the empty space surrounding the muscles, referred to as lacunae, is entirely filled with hemolymph. At the joints between leg segments are flexible membranes which can inflate. This inflation allows for the extension of these joints. Since pneumatics are used for the extension of leg segments, the majority of the leg is filled with flexion muscles. This phenomenon is most present in the main joints of the arachnid, the femur-patella joint, and the tibia-metatarsus joint, and is not necessarily the main actor in smaller articulations of the less mobile joints [8]. It has been theorized that this system has evolved as a way to maximize flexion forces within the spider, allowing for the strong prey-catching response observed [24].

The pressure within the legs is generated by the prosoma, which does not have a system for individually pressurizing the legs. As such, the pressure in all legs is increased simultaneously. In order to combat this, spiders tense their muscles before the pressure increase, and relax only at the joints they desire to extend [24]. Each joint within the leg functions differently in terms of its degrees of freedom, joint type, and angles it can extend and contract to. Most joints have limited degrees of freedom, and as such, for most analyses and computational models built off of arachnid biomechanics, the 7-segment legs are typically reduced to 3 or less functional sections [23][25][26][27][28]. To this extent, the 7-segment system will be discussed in this paper, with some emphasis on the joints found in the 3 section models.

#### **1.4 The Striped Knee Tarantula**

The striped knee tarantula, *Aphonopelma seemanni*, is an ideal model for biomechanical research. Its large size and striped pattern make movement tracking easier than in smaller, less distinct arachnids. These traits also make it ideal for biomimetic robot design, as the dimensions give more tolerance for the size of current technology. Additionally, the striped knee tarantula is available through the pet trade industry and has been used in similar studies in the past, allowing for a comparison of current literature to our system. These studies, reviewed in Chapter 2, measured the angles and speed of the legs during movement, but did not provide force data for the spiders.

## 2. LITERATURE REVIEW

#### 2.1 Arthropod Biomechanics (1900s-present)

As spiders have fascinated scientists with their unusual number of limbs and their quick speeds for centuries, there is a long history of analysis of arachnids and their biomechanics. However, it was only in 1909 that the lack of extension muscles in spiders was first noted by Alexander Petrunkevitch. D.A. Parry of Cambridge University carefully dissected the individual legs of *Tegenaria atrica* in the 1950s. He and other researchers further confirmed the lack of extensors in a larger spectrum of spider species [29]. A few years later, Parry and R.H.J Brown attached individual *Tegenaria* legs into an apparatus to measure the pressures and angles within the leg. This determined a positive correlation between joint angle and the change in joint volume. This established the relation between extension torque and leg blood pressure, as well as presented evidence that the pressure within the legs is controlled by the prosoma while having no effect on the pressures within the abdomen [22].

John F. Anderson and Kenneth N. Prestwich of the University of Florida began testing the aerobic capacity of the tarantula *Brachypelma smithi* in the 1980s. They determined that the heart rate of these spiders reached up to about 58 beats/min, and that the D-lactate concentrations increased vastly during the test times. The running tests were done on a physiograph to mimic a treadmill, which was then enclosed in wooden frame, and the spiders were forced to run for 10 minutes for the readings. They noted that the spiders differentially alter their stride frequency compared to stride length when exposed to the different running speeds of this experiment [30].

Dr. Robert Full's work on cockroach biomechanics began at this time as well. Nearly every paper from the past few decades is based off of Biewener and Full's "Force platform and kinematic analysis", which detailed a force plate that involved a non-stick surface placed across two force beams covered in strain gauge elements in vertical, horizontal, and mediolateral directions. It effectively uses Wheatstone bridge configurations to create a platform sensitive enough for biomechanical analysis [31]. Figure 4 shows the original drawing for this force plate.



Figure 4: Biewener and Full's force plate design [31]

No insect or arachnid biomechanics paper would be complete without a nod toward Dr. Full's decades of research on the topic. In 1989, Full and Tu published two papers on the mechanics of insects, focusing in on the cockroaches *Blaberus discoidalis* and *Periplaneta americana*. They modified the aforementioned force plate to be enclosed in Plexiglass, with a cardboard track surface to allow for traction. The forces were sampled at 1000 samples s<sup>-1</sup>, and the videography was performed at 60 frames s<sup>-1</sup>. In order to perform their calculations, all runs in which the cockroach bumped against the walls or otherwise did not go straight down the track were discarded. This allowed for the calculation of leg displacement, force, velocity, displacement, and energy for the insects. They noted a loosely linear correlation between stride length and speed, as well as speed and power [32][33].

The year 1997 brought further work on *Blaberus discoidalis*, which made use of a clear treadmill to analyze the insects. Video was captured at 1000 frames s<sup>-1</sup>, and only straight-ahead running at near constant speed. Special note was taken to the joint angle, roll, yaw and pitch angles, and kinetic energy of the cockroaches [34]. Dr. Full's work on the topic continues through current time, where the work has expanded to mechanics of righting motions, in geckos as well as cockroaches, but continues to use a similar set-up as those mentioned here [35][36]. Most current papers on spider biomechanics continue to cite his work as the basis for their experiments.

A comprehensive work on arachnid kinematics was performed in 2002 by A. Sensenig and J. Schultz. This work covered *Eremopus gigasellus*, *Aphonopelma seemanni*, *Hadrurus arizonensis*, *Heterometrus spinifer*, *Mastigoproctus giganteus*, and *Leiobunum formosum*. These animals were

placed on a small treadmill and walking gaits were captured at 60-120 fields s<sup>-1</sup> with .5 mm resolution. They also used a force transducer to test the forces of amputated individual legs. These experiments did not measure the force throughout the walking gait, but rather focused on the internal pressures of the amputated legs [37].

A more recent examination of spider kinetics came out in 2011, "Biomechanics of octopedal locomotion: kinematic and kinetic analysis of the spider *Grammostola mollicoma*.", utilized a similar treadmill and camera setup, with 50 frames s<sup>-1</sup>, which was based on the tarantula *Grammostola mollicoma*. It focused mainly on the center of mass (COM) and the geometry described by the legs on the ground, which is known as the support area. They determined an oscillatory nature for the COM during movement, and a linear relationship between stride frequency and speed, as well as between work and speed for slow speeds, and a non-linear relationship at higher speeds. This paper also claims to be the first attempt to calculate internal mechanical work in spiders [27].

In contrast, Spagna et al. determined that spiders, even at high speeds, produced a linear relationship between speed and frequency, as well as an inverse linear relationship between stride length and duty factor. They used two spiders; *Hololena curta* and *Hololena adnexa*. These spiders also moved in an alternating-tetrapod fashion [38].

2012 brought the novel paper "Hydraulic leg extension is not necessarily the main drive in large spiders" by Weihmann, Günther, and Blickhan, which focused on *Ancylometes concolor*, which indicated that the activity of the flexors allows for much of the force in the hind legs of large spiders, rather than the hydraulics mainly powering all movements, as had been assumed for decades. Markers were glued to the spiders, and the spiders were set to run on a force plate similar to Biewener and Full's. They were able to measure the forces at approximately  $1.1\pm0.38$  times the body weight of the spider using this method, with a maximum vertical force of about 56 mN [23].

The following year, Friedrich-Schiller University wrote a paper on the high-speed locomotion of *Cupiennius salei*, which notes a lack of research on fast spider locomotion. This study used high-speed video and motion-analysis during provoked escape runs. This paper also focuses on the COM during the swing phase, and video data was captures at 308 frames s<sup>-1</sup>, and 1024 X 512 pixel resolution. It was noted that spiders running down the track mostly strived to scale the sides, distorting the gaits. To prevent this, the spiders were prodded into escape runs using hand waving, touches, or air to startle the spiders [26].

With the knowledge gained on the pneumatic properties of spider legs, Booster et. al of Harvey Mudd College hypothesized that spider kinematics might be affected by changes in temperature. To analyze this possibility, *Aphonopelma hentzi* was kept in terrariums at temperatures ranging from 15 to 40 °C and prodded into running using puffs of air. This research gave indication that stride frequency is positively correlated to temperature, but stride length has no correlation to temperature [39].

#### 2.2 Spider-Inspired Robotic Systems

The papers mentioned above in Section 2.1, among others of similar nature, have been the basis of a multitude of arthropod-based biomimetic robots, some more similar to their inspiration than others. In the early 2000s, Dr. Robert Full used his work on cockroach biomechanics to develop two hexapedal robots: RHex and Sprawlita [40][41]. RHex is a cockroach-inspired model which was developed with the intention of navigating difficult terrain with limited effect on speed. This robot can stand, creep, or walk, and develops a dynamic bouncing gait at high speeds, which makes it remarkably similar to living systems. The system operates using 6 passive legs actuated by servos. These legs have a small amount of "spring" to them, which allows for passive posture control in the robot. Overall, the system can scale obstacles up to three times its height with relative ease, and uses much less power than other robotic systems [40].

Sprawlita focused more on the dynamic stability of cockroaches during running and achieved speeds of up to 3 body-lengths per second. This robot more closely resembles a cockroach than RHex, with a self-stabilizing posture, and compliant leg joints on all six independently operating legs. All servos and wiring were embedded within the system to give a more natural look and provide more aerodynamic external features [41].

Worth noting also is the development of the arachno-bot in 2011. This 3D-printed biomimetic spider robot was intended for search-and-rescue missions. Articles from around this time cite its spider-like gait and pneumatic accordion-style joints [42] [43]. However, the original source from the Fauenhofer Institute could not be found.

Another hexapodal system was developed by Chen et al. in 2014. This robot was based on the "typical" insect leg, which the authors determined was a 3-jointed system with a coxa, trochanter, tibia, and tarsus. They focused on a swing-based movement which revolved around a distilled version of a musculoskeletal structure combined with existing engineering techniques for robotic

movement. This robot limited the jerking movement using nonlinear programming and the natural tripod-balancing system of insects. Overall, this robot is based on the external anatomy of 6-legged insects and the movement of such insects, but does not provide a fully biomimetic system [44].

At the IEEE International Conference on Advanced Computing in 2012, the 'Tarantula Bot', is an urban search and rescue robot design to allow for the discovery of injured or trapped individuals in disaster zones. It was proposed as a way to minimize the potential of injury for rescuers and to allow for access to areas that are otherwise unavailable to them [45].

A fascinating study in 2014 by Yang et al. provides a different take on biologically inspired robots; it uses engineered aspects to control a living spider, instead of creating a robot to mimic the spider. This system used *Holconia venatoria*, and electrical stimulation to move the spider in different directions and at different speeds based on which legs were stimulated. The reaction time of the spider was noted to be a maximum of 3 seconds. To prove the practicality of their system, they led the spiders down a v-shaped path. Only 30% of the tested spiders finished the path, and half of the spiders did not even complete the first half of the path [46].

The next big breakthrough with spider robotics was Scorpio, a robotic system based on *Cebrennus rechenbergi*, a type of huntsman spider with a unique rolling mechanism to escape predators. The robot uses only four legs with one major joint each. These legs are curved so that one set can rotate upwards, allowing for the robot to roll. The robot utilizes a wireless camera network to determine when to roll vs. when to crawl without the need for human intervention. An Enhanced Vector Polar Histogram (VPH+) is used to aid in the navigation of the robot. When complete, it is intended for security uses [28][47].

Outside of fully robotic systems, much research has also been done on only mimicking the leg or joint structure of spiders. Landkammer et al. analyzes previous biological research and provides insights on trends and different joint formations. This article states that for pneumatic systems, three-folded bellows are typically sufficient to mimic spider joints well. This is indicated in the trend towards a bellows system since 2006. Becker et al. provided a double bellows system in 2011, with one side of the bellows expanding further than the other side, which allowed for the bending of the individual joints. Landkammer et al. in 2013 provided a similar system, however it much more closely mimicked biological joints, as it provided an exoskeleton and controlled pneumatic and muscular system to control a single-sided bellows which extended the leg from its naturally contracted state [24].

#### 2.3 Novelty of Research

Most kinematic analysis of spiders and insects is based on a generalization of the 7-segment legs into 3-segment legs, under situations in which the animal is placed under stress in an unknown environment. As tarantulas and other spiders have the tendency to hide or attempt to escape unfamiliar environments, most trials were done with prompting of the researchers on moving surfaces. This is entirely unlike how they would move in the wild, and while this provides ample information on the max forces, it creates an unrealistic basis for biomimetic robotics, as the animals cannot sustain this movement over periods of time.

This research provides kinematic analysis of a previously analyzed subspecies of tarantula as a means of comparing our system to previous research, with the addition of force analysis on the spider. It provides a more sensitive and fast means of data acquisition for such studies and sets a precedent for analysis to occur in a more natural environment for the specimens. As most studies found involved a "treadmill" system with initiated escape responses, this stationary system will hopefully provide new information which could vastly affect our understanding of how arachnids and other small creatures move around their environments and provide a new data set to base biomimetic robots on.

## 3. METHODS

#### 3.1 Tank Development

In order to provide the most natural movements for analysis, a customized terrarium was developed with both the natural habitat of the spider and ability to track its movement in mind. This was done by creating a tank out of clear, non-tinted plastic with a breathable mesh top, which can be seen in Figure 5. To one side of the tank, a long offshoot that contains the sensor matrix is attached. This offshoot does not have a mesh upper like the main portion of the tank does, rather it is completely enclosed in the clear plastic in order to provide an unobstructed view of the spider in motion. A small flap door at the distal end of the offshoot allows the researcher to bring food sources into the tank to entice the spider down the tunnel for observation. The angle of this offshoot can be altered for experimental variety. As tarantulas require at least 4" of dirt for burrowing, this offshoot is supported by a black box, which also contains the electronics for the sensors.



Figure 5: Basic terrarium setup as a diagram (left) and as a physical system (right)

Along the bottom of the offshoot is a 24-sensor matrix, as indicated by the light grey rectangle in Figure 5. This electronics behind this matrix are described in Section 3.3. The ends of the sensors protrude from a thin slit along the side of the offshoot. The sensors are secured to a sturdy cardboard surface, which has a grid surface printed across it. Each sensor is 1.5 cm apart from the next, in a staggered pattern.

#### 3.2 Spider

The spider, following the protocol set by the papers mentioned in Section 2 and online care guides, was given appropriately sized crickets weekly, and water was provided ad libitum [26][30] [39] [48]. A wooden structure, moss, and a water dish allow for a natural environment for the arachnid, and a consistent feeding schedule helped maintain normalcy and prevented disturbance from normal movement patterns during tracking. The system was kept in an incubator, which was set at 25°C, the median temperature of the spider's natural environment [49].

#### 3.3 Temperature

Along with the 25°C trials, trials were also performed at 20 and 30°C to compare tarantula walking speeds to the sprinting speeds in previous papers [39]. For these runs, the spider was maintained at the desired temperature for one hour before testing began. Throughout the trials, the temperature varied less than  $\pm$ 1°C.

#### 3.4 Sensor System

The sensor matrix which resides along the offshoot has been developed with 24 small forcesensing resistors (FSRs). These sensors are small resistive pads that decrease their resistance proportional to an increase in force applied to the pad. From a calibration curve, the force applied can be back calculated from this change in resistance. The FSRs chosen for this experiment were the FSR 400 from Interlink Electronics. These sensors have an approximate sensitive range of .2N to 20 N, and have a small diameter (5mm), which minimizes the probability of two legs applying force to the FSR at the same time. The sensors are approximately .3 mm thick, which negligibly hinders the spider's ability to walk across the surface [50]. The resistance to force curve and the suggested sensor setup from Interlink Electronics can be seen in Figure 6.



Figure 6: FSR 400 response to force and general layout per sensor, taken from the FSR 400 Series Datasheet [50]

Test resistors were analyzed to maximize sensitivity of the setup for the force range of interest and set at 300,000 ohms. As this varied greatly by sensor, for the purpose of this experiment each sensor was individually calibrated using a series of calibration weights and given i's own calibration curve for force calculations. Figure 7 shown below is the sensor output of one weight, as well as an example calibration curve for the sensor.

The resistive divider circuit output is sensed by a 12-bit Analog Digital Converter (ADC). Unity-gain buffer circuits were implemented using Microchip's MCP604 op-amps and offer a buffer between the FSR and the low input impedance (2,000 ohms) of the ADC.



Figure 7: Example MCU voltage output for a 21 g calibration weight and calibration curve for forces ranging from 0 to .23 Newtons

This system was set up for each FSR, and each set of eight FSRs was connected to a microcontroller unit with an on-chip 12-bit ADC(TM4C12BGH6PM). This setup is shown in

Figures 8 and 9. Each MCU is outputted to the computer using a USB in real-time. To maximize the accuracy and reduce the number of skipped data points, the software driver kit used to program the standard USB peripheral on the MCU were optimized to increase the speed of transmission of the sampled data values, and the data rate per MCU was set to 1,000 samples per second, or one per millisecond.



Figure 8: FSR sensors along offshoot floor and designated MCUs 1,2 and 3



Figure 9: Layout of sensor system with sensor matrix, buffer board (unity gain buffer), MCUs, and computer

To further protect against missing bits, the data was sent to the computer in packets of 8 with a start and stop bit identifier. Data packets without 8 values were discarded. This data was sent to the computer in hexadecimal form, then translated into decimal form in Matlab, then converted to force using the previously mentioned calibration curves. The code for the sensor analysis is seen in APPENDIX A. As data packets may be dropped, the force graphs were matched up with video analysis manually, and only force data from moments when the spider is fully stepping on the center of the sensor was included for this experiment.

#### 3.5 Camera Setup

To minimize the space taken up within the incubator as well as to provide relatively high pixel counts, high speed analysis of the spider, three GoPro Hero8 cameras were procured. These cameras provide 1080p video quality at 30-120 fps with a linear lens. One camera was set in the xy plane (frontal plane of the spider) and the other two were set on opposite sides of the offshoot to capture the leg motions in the xz plane (sagittal plane), seen in Figure 10. A one cm mark was created in each plane (x,y, and z) in order to offset any variation in camera tilt that may occur throughout the experiment, as well as to provide a pixel to cm calibration.



Figure 10: Layout of cameras as seen from above, with direction of spider movement during trial indicated in green

#### **3.6** Initial Analysis of Data (Painting spider/tracker system)

In order to easily track the spider, and to avoid large variation between experimental runs, the spider painted with dots along the axes of the spider. This was done using bright-colored nail polish and a nail polish application tool for creating evenly sized dots. The colors were set up in an order to minimize the probability of the tracking system mistaking which segment was being tracked, as seen below in Figure 11. The pink and green dot sets on the back correspond to the x and y axes respectively. The z axis is painted in orange, and the center of mass is indicated in blue.



Figure 11: Spider with painted dot design for tracking system detection

Tracker, an Open Source Physics Java platform, was used for initial video analysis of the footage. This program was chosen due to ease of use and accessibility across multiple computer types. Tracker has both frame-by-frame and automatic point tracking abilities, which allowed for correction of point identification and adjustment for any frame tilts [51].

For data collection, each leg was given a 2-character classification, with R representing the legs on the right side of the body, and L representing the left, and 1-4 representing the individual legs, labelled cephalically to caudally. Individual points within each of the legs, from the cephalothorax to the tarsus were labelled distally to proximally 'A' to 'H', as seen in Figure 12 below. For each point, X, Y, and Z data was collected using the 3-camera system.



Figure 12: Labelling schematic of all 8 legs and the individual joints

#### 3.7 Kinematic Analysis

Data from Tracker was transferred into custom Excel sheets, and Matlab R2018b was used to analyze the data [52]. Due to the sheer volume of data, the analysis was separated into multiple codes that could be run independently. The Spider\_moving code simply provides a graphic of the spider moving. This allows for visual analysis of gait patterns and brings attention to any errors the Tracker system may have incorporated from misplaced analysis points. A link to this code, as well as all of the code following, can be seen in Appendix A, and an example of the graphic is shown below in Figure 13.



Figure 13: Snapshot of spider movement

The next code, Angles\_Code, analyzes the points from an angular perspective. The slopes of each of the joints is calculated on a frame-by-frame basis. The xy, xz and yz angles are then calculated from the slopes of the previous joint using Equation 1 below. The angles of each joint over the trial period are then plotted, as well as the average, minimum and maximum angle of each joint with their standard deviation.

$$\tan(\theta) = \left| \frac{m_1 - m_2}{1 + m_1 m_2} \right|$$

Equation 1:Angle between two slopes

The Speed\_COM code provides information about the center of mass, support area, speed, and duty factors of the walk cycle. A duty factor is a metric of the amount of time a creature is putting weight on a limb. This spans from 0 to 1, with 0 being the limb is never on the ground throughout its gait cycle, and 1 being the limb never leaves the ground, and as such is always helping maintain balance and supporting the body weight. This number is calculated by the following equation, Equation 2.

$$Duty Factor = \frac{Time \text{ on ground}}{Total \text{ trial time}}$$

**Equation 2: Duty Factor Calculation** 

The center of mass fluctuations were plotted over time for each trial. Tarsus heights were manually denoted as 0 or 1 for each leg, with 0 being off the ground, and 1 being on the ground. By calculating the number of frames that the foot remains below the line, the duty factor can then be calculated for the run. Speed was calculated based off of the center of mass of the spider over the distance. Using the binary code for feet on the ground mentioned above, the areas under the feet could be calculated, from which the centroid of the shape could be calculated. This is shown in Figure 14 for clarification.



Figure 14: Demonstration support area of a stationary and moving spider

Deviations of the spider's center of mass from the centroid were calculated and plotted as a gif for visual and numerical analysis of this deviation. Snapshots of this can be seen in Figure 15.



Figure 15: Centroid of support area (red square) vs center of mass of spider (green circle). Feet on the ground are indicated in black

The pitch and yaw of the spider was also calculated throughout the experiment. Pitch is determined by the angle the spider's body tilts upwards (xz direction). The yaw is the tilt of the body in the xy direction. The roll of the spider, in the yz direction, could not be accurately calculated as there was no camera in that direction. These directions and their relation to the spider can be seen more clearly in Figure 16 below.



Figure 16: Pitch, yaw, and roll angles of a spider

These measurements were calculated using the painted markings on the side and back of the spider. With two markings in each field, the angle of the spider relative to the axis can be calculated using Equation 3, where  $\Delta$ rise is the change in z between the two points for pitch, and the change in y for the yaw, and  $\Delta$ run is the change in x for both pitch and yaw.

$$\tan(\theta) = \frac{\Delta rise}{\Delta run}$$

Equation 3: Angle from a given slope

#### **3.8 Biomechanical Analysis**

Force data was manually lined up with the individual frames at which the force peaked, and the data from the chosen leg and frame were inputted into Matlab for analysis, see Appendix A. Once the angles of the leg were calculated, the leg's position along with the force could be used to calculate the force in the individual leg segments.

As the legs remained relatively extended at a perpendicular to the body, a simplified twodimensional statics diagram could be used to calculate the forces and moments about the members. An example of the changes from 3D to 2D can be seen below in Figure 17.



Figure 17: Example of leg in xyz coordinates, approximate yz coordinates, and full yz coordinates (left to right)

Below in Figure 18 are two examples of the statics calculations done to interpret the results. With two unknowns,  $F_{Friction}$  and  $R_1$  for the first sub-image, and 2 equations, we can calculate all forces on the tarsus. With  $R_1$  calculated, each following limb segment's forces can be calculated.



Figure 18: Tarsus and metatarsus calculation setup

### 4. **RESULTS**

#### 4.1 Limb Measurements

The 3-year-old female *Aphonopelma seemanni* was found to weigh 18.31 grams. Measurements of each of the leg segments, taken over 6 trials. Variances within segment length were noted to be due to camera shift and the spider's movement in the y direction away from the cameras. To balance this, significant outliers were removed, resulting in Table 1 below, and the majority of the subsequent calculations were based off of slope in place of distance when possible to mitigate the effect of these discrepancies.

| Segment/Leg | R1     | R2     | R3     | R4     | L1     | L2     | L3     | L4     |
|-------------|--------|--------|--------|--------|--------|--------|--------|--------|
| AB          | 0.8290 | 0.6962 | 0.7651 | 0.8014 | 0.6502 | 0.6713 | 0.6887 | 0.5372 |
| BC          | 1.5300 | 1.3862 | 1.4538 | 1.4791 | 1.0843 | 0.9662 | 0.9900 | 1.4344 |
| CD          | 0.9899 | 1.1827 | 1.0258 | 0.9478 | 1.3706 | 1.2474 | 1.1954 | 1.4735 |
| DE          | 0.2512 | 0.2490 | 0.1576 | 0.1810 | 0.1262 | 0.1265 | 0.1088 | 0.1298 |
| EF          | 0.6540 | 0.9996 | 0.9999 | 0.9552 | 1.1885 | 0.9219 | 0.7535 | 1.1573 |
| FG          | 0.8664 | 0.8188 | 0.6580 | 0.9691 | 1.0707 | 0.8241 | 0.6905 | 0.6444 |
| GH          | 0.3410 | 0.3296 | 0.3782 | 0.5264 | 0.4257 | 0.5131 | 0.5182 | 0.4887 |

Table 1: Limb lengths of spider in centimeters±.2 cm (N=5)

#### 4.2 Limb Height

The height was analyzed for all joints of the spider per each trial. Two segments of interest, the tarsus and the femur-patella joint, are highlighted in the following subsections. These give a good indication of how the leg is moving overall, as well as the timing of the individual movements and steps of the spider.

#### 4.2.1 Tarsus

The tarsus' movement throughout the walk cycle varied per leg. The front legs tended to move up quite high, then slowly come down after other, smaller steps with the back three legs. The 2<sup>nd</sup> set of legs tended to mimic the first set, but with less height achieved during the movement. Both the front and the second legs also had a tendency to falter instead of smoothly completing a

step, in that they would dip a short distance down, then rise again without ever fully stepping down. An example of this motion can be seen in Figure 19 below, in which the R2 leg dips up and down three times, but never reaches ground.



Figure 19: Graph of tarsus height throughout a trial, with smooth movements on the left side of the body, and slightly more erratic movement on the right.

Shown below in Table 2 are the average maximum heights achieved by the tarsus over the trials, with standard deviation. It is worth noting that the first leg pair has a much higher peak height than the other pairs.

Table 2: Table of average maximum tarsus heights in cm with standard deviation (N=7)

| Limb | Max Height(cm) | Stdev  |
|------|----------------|--------|
| R1   | 5.4879         | 1.6799 |
| R2   | 3.7787         | 1.5983 |
| R3   | 2.9784         | 1.0653 |
| R4   | 2.5817         | 0.6986 |
| L1   | 4.3177         | 0.8520 |
| L2   | 3.5990         | 0.7455 |
| L3   | 2.4911         | 0.3747 |
| L4   | 2.1136         | 0.3419 |

Analysis of the maximum height of the tarsus over all trials showed no significant differences between the right and left sides for pairs 1,2, and 4, but showed significant variation

between the L3 and R3. Pairs 3 and 4 were also not significantly different (P>.05). Tarsus height ANOVAs can be seen in Appendix B.

#### 4.2.2 Femur-Patella Joint

The femur-patella joint is the highest-sitting joint on the spider. As such, it has a relatively dramatic change in positioning over the walk-cycle as the spider extends its legs. Shown below in Figure 20 is an example of femur-patella joint height over a trial. In this example, the left side is achieving faster variation in height than the right, and multiple legs are moving at the same time.



Figure 20: Height of femur-patella joint throughout a trial

Like with the tarsus, the first and second pairs of legs tend to act similarly, as do the third and fourth pairs. The hind legs in particular tended to experience a short increase in height, following by a slow decrease over time, as the hind legs would be extended fully before movement occurred again. An example of this slow descent can be seen in Figure 21.



Figure 21: Example of hind leg change in height over time

As in the previous section, the maximum heights of the joint were averaged over all trials, and are presented below, in Table 3. Unlike the tarsus, which had significant variation between limb pairs, the differences in heights of the femur-patella joint were not statistically significant at a 95% confidence limit, which is provided in Appendix B.

| C    |                |        |
|------|----------------|--------|
| Limb | Max Height(cm) | Stdev  |
| R1   | 5.1584         | 1.4551 |
| R2   | 4.8848         | 1.3075 |
| R3   | 4.7087         | 1.1671 |
| R4   | 4.9132         | 1.3002 |
| L1   | 4.2805         | 0.4442 |
| L2   | 3.9802         | 0.4639 |
| L3   | 3.8525         | 0.3920 |

Table 3: Average maximum height and standard deviation of the femur-patella joint in cm (N=7)

#### 4.3 Angle Analysis

3.8869

0.4351

L4

The angle between each limb segment was also calculated. This provides information on how the legs move throughout the trial, as well as aids in the calculation of force in Section 4.8.



Figure 22: Three-dimensional angles of femur-patella joint

The average angle of each joint can be seen below in Table 4, which separates out each leg of the spider and each joint into the three coordinate systems; xy, xz, and yz. Further, the maximum angles of each joint were compared to determine if there were differences within the extension and flexion of the individual segments. Despite having a P value of <0.001, a Tukey test determined that only one angle, the first leg pair's angle C, was statistically significant from the rest, with all of the other values remaining within the same grouping. As such, it was concluded that the maximum angle each joint can move from the joint before it is not significantly different from the other joints and resides between 65 and 90 degrees. See Appendix C for further analysis.

| Limb | Dir. | В       | С       | D       | Ε       | F       | G       | Н       |
|------|------|---------|---------|---------|---------|---------|---------|---------|
| R1   | ху   | 25.4876 | 18.8860 | 15.0024 | 24.3249 | 29.6378 | 30.9102 | 32.4183 |
|      | xz   | 24.9365 | 21.1764 | 29.7573 | 42.4823 | 20.6109 | 33.3387 | 32.3827 |
|      | yz   | 27.1367 | 21.8925 | 31.5505 | 45.2733 | 24.9055 | 31.6588 | 38.2540 |
| R2   | ху   | 25.5646 | 20.5977 | 19.0759 | 27.7014 | 23.4926 | 33.6068 | 37.8828 |
|      | xz   | 16.7509 | 18.4495 | 28.4747 | 41.1528 | 14.9249 | 32.9458 | 39.3457 |
|      | yz   | 14.6441 | 18.1631 | 31.4614 | 50.6825 | 17.7529 | 38.9631 | 39.9344 |
| R3   | ху   | 35.0853 | 37.4948 | 19.1359 | 29.0462 | 25.5999 | 35.1055 | 45.1832 |
|      | xz   | 11.9442 | 16.2337 | 39.2308 | 44.9557 | 19.0189 | 37.2815 | 41.1184 |
|      | yz   | 13.8539 | 28.0206 | 43.6415 | 52.0514 | 21.7074 | 37.9575 | 42.6653 |
| R4   | ху   | 23.7174 | 26.0801 | 9.4641  | 21.8878 | 28.3303 | 40.7407 | 38.2425 |
|      | xz   | 19.3964 | 49.3986 | 27.1689 | 51.2550 | 20.0365 | 31.6497 | 41.7922 |
|      | yz   | 10.2354 | 25.5861 | 39.5078 | 50.6205 | 17.1721 | 33.5606 | 26.0233 |
| L1   | ху   | 21.3900 | 15.2298 | 14.8897 | 28.8093 | 32.0525 | 34.7719 | 41.9213 |
|      | xz   | 15.2348 | 15.3570 | 10.7320 | 12.4999 | 18.9319 | 28.2847 | 31.5746 |
|      | yz   | 24.9489 | 18.9629 | 15.1827 | 26.1387 | 26.5713 | 21.1304 | 35.9978 |
| L2   | ху   | 26.1295 | 23.7578 | 17.3304 | 28.3630 | 26.3199 | 33.2628 | 41.9855 |
|      | xz   | 22.6089 | 22.2217 | 18.9907 | 22.7525 | 24.9811 | 35.4981 | 25.9244 |
|      | yz   | 17.7336 | 23.7544 | 12.9563 | 17.6673 | 21.9135 | 23.1154 | 24.6508 |
| L3   | ху   | 32.1575 | 32.2708 | 19.3078 | 32.9833 | 25.6843 | 33.6251 | 43.8495 |
|      | xz   | 22.8333 | 24.0369 | 17.7423 | 25.6800 | 27.3957 | 25.6749 | 36.0255 |
|      | yz   | 24.1085 | 30.1792 | 18.8930 | 15.2977 | 23.0621 | 18.1865 | 23.0128 |
| L4   | ху   | 28.1270 | 27.3822 | 7.4716  | 23.1569 | 26.4494 | 35.1491 | 43.5362 |
|      | xz   | 24.9011 | 27.0132 | 13.9062 | 17.5891 | 27.1878 | 23.2070 | 32.1950 |
|      | yz   | 23.3946 | 25.6535 | 18.3823 | 24.6982 | 33.2371 | 18.3817 | 20.3304 |

Table 4: Average angle in degrees for each joint and limb

## 4.4 Step Patterns

Each trial was analyzed for maximum and minimum number of feet on the ground, as well as the movement pattern of the spider. The following figure, Figure 23, shows the visualization of the movement of the feet across one of the trials. The line indicates that the foot is fully on the ground, while empty spaces mean that the foot is traveling. For consistency, as the hind legs tended to drag along the ground instead of fully lifting up, the unhindered movement of the hind leg tarsus was considered "in the air" for a step.



Figure 23: Visualization of feet on ground across a trial

In the above figure, the minimum number of feet on the ground occurred at around 130 frames, at which time only R1, R4 and L3 were on the ground. Towards 270 frames, all feet are placed on the ground and remain there. Throughout the trials, the average number of feet on the ground at a given time is 5 ( $5.279\pm.357$ ), and the minimum over all trials was 3.

While the times of the step and times between each step varied, as well as the order of the feet, the spider seems to follow a distinct set of "rules" throughout its walk cycle. For instance, the maximum number of feet changed instantaneously per side was two, and this was typically only seen between feet 2 and 3, where it would put one foot down in the exact same frame as it lifted the other. Whenever the spider had only three feet on the ground, it tended to also put its pedipalps down, most likely as a balance. The spider also had a strong tendency to favor specific leg patterns when only three feet were grounded. In every single trial (100%), the leg that was alone on its side was the third leg, and in 66.67% of the trials, the spider supported itself on the other side with legs 2 and 4. The other two leg placements, representing 16.67% each, was leg 3 and leg 4 of the opposite side, and legs 1 and 4 of the opposite side. A visualization of these foot schematics can be seen in Figure 24.



Figure 24: Schematic of the feet in the three 3 feet positions. Green indicates the foot is on the ground. Position A was recorded in 2/3 of all 3-foot instances

Patterns outside of the three-foot range varied greatly during, and between, trials, and as such will not be discussed fully here. However, with respect to "Stepping Patterns in Tarantula Spiders", which states two thirds of tarantula movement is done in an alternating fashion [21]. In order to see how the movement of this spider compares, two additional styles of movement were added to the analysis. Should the spider be alternating movement in a paired fashion, there would be significant amounts of time in which the feet are either in the air or on the ground at the same time. As such, times for which the feet on both sides were alternated, and times for which one side's set of feet alternated were counted, and percent of time in position-style was calculated. In Figure 25 below, some examples of each style of footstep are shown. Sub-images A through C would be counted as fully alternating, as every other foot on both sides is in motion. Sub-images D through F shows the same pattern, but only on one side.



Figure 25: Examples of fully alternating and partially alternating step styles. A through C indicate full alternation, while D through F indicate half alternation.

From this, the percent time in which the feet were in a particular pattern was calculated, and the results can be seen in Table 5 below. A fully alternating leg pattern occurred only 3.41% of the time, less than only three feet on the ground, while a partially alternating pattern occurred nearly one third of time.

| Style       | Percentage |
|-------------|------------|
| Alternating | 3.41%      |
| Partial     | 32.61%     |
| 3 Feet      | 4.34%      |

Table 5: Walking style with percentage of time in use

#### 4.5 Duty Factors and Speed

Duty factors were calculated for 13 trials of the spider's movement. The averages per leg, along with the standard deviations, can be seen in Table 6 below. No significant differences were detected between leg pairs with 95% confidence( $\alpha$ =.05). No significant differences were found between leg pairs 2 and 3, or 3 and 4, but significant differences were found between 1 and 3, and 1 and 4. See Appendix D for full ANOVA tables.

| Leg | Average   | Stdev    |
|-----|-----------|----------|
| R1  | 0.422905  | 0.174705 |
| R2  | 0.5811151 | 0.211012 |
| R3  | 0.7525359 | 0.067818 |
| R4  | 0.8459836 | 0.098193 |
| L1  | 0.4868854 | 0.161184 |
| L2  | 0.6849051 | 0.191233 |
| L3  | 0.723953  | 0.120595 |
| L4  | 0.7847755 | 0.100392 |

Table 6: Average duty factor and standard deviation by leg (N=13)

Speed of the spider, based on the distance the center of mass travelled over time, was calculated as  $2.760 \pm .725$  cm/s, which solidly places the speed of the spider throughout the trials as a walking speed; escape runs with tarantulas have shown an average of 20 cm/s [39].

#### 4.6 Center of Mass Deviations, COM vs Speed

The deviation of the center of mass from the centroid of the shape under the feet averaged .505 cm in the x direction, and .620 cm in the y direction. Shown below in Figure 26 is a graph of average distance from the centroid vs. the speed of the spider.



Figure 26: Comparison of the center of mass deviation from the centroid and the speed of the spider

This graph indicates that the speed of the spider is positively correlated to an increased deviation of center of mass from the centroid, which indicates a decrease in overall stability the faster the spider moves.

The center of mass' height over time was also recorded and analyzed. It tended to oscillate over time, though did not always reach the same amplitude. An example of this can be seen in Figure 27, in which as the spider moves towards the end of the offshoot it lowers its' body before coming to rest.



Figure 27: COM height in cm over time

#### 4.7 Pitch and Yaw

Pitch and yaw over the trials showed no statistically significant differences over 7 trials ( $\alpha$ =.05). Average pitch was 9.88±4.18 degrees, and the average yaw was 11.46±5.34 degrees. A graph of these values in relation to each other over a trial is shown in Figure 28.



Figure 28: Pitch(blue) and yaw(green) angles over time

#### 4.8 Forces Applied During Trial

Due to the spider's tendency to kick dirt from the main portion of the tank into the offshoot, and given the sensors' lack of sensitivity towards the edges, only force data from when the spider was stepping onto the center of a clean, non-dirt covered sensor was used for this analysis. This provided four steps to analyze. One such step can be seen below in Figure 29. The sensors these

forces were applied to were calibrated and a line of best fit was determined for each sensor using an exponential curve, as the resistance of the sensor changes at a rate of  $\frac{Rtest}{Rtest+FSR}$ , which mimics closest to an exponential curve at the values recorded. These curves were considered well-fit, with the lowest R<sup>2</sup> value being 0.976. See Appendix E for all calibration curves.



Figure 29: Voltage change during the spider stepping on sensor

Throughout all trials, the signal to noise ratio (SNR) minimum was 13.14, with larger forces reaching upwards of a 100 SNR. As such, the step was easily identifiable to the naked eye in all cases. The average force applied was calculated by finding the average voltage across the duration of the step, excluding the values on the ends of the step. From this, we get the following table.

| Limb | Force (mN)  | stdev    |
|------|-------------|----------|
| R4   | 49.09991281 | 3.029166 |
| L2   | 56.85067909 | 9.741518 |
| L2   | 87.21515245 | 11.91255 |
| L3   | 98.06526105 | 18.37    |

Table 7: Calculated millinewton forces per leg

Calculations of the frictional force, force at each joint, and moment about each joint were then performed using the quasi-static assumption. These values can be seen in Table 8 below.

|   |                  | Leg 1    | Leg 2    | Leg 3    | Leg 4    |
|---|------------------|----------|----------|----------|----------|
|   | Force Detected   | 0.098070 | 0.049100 | 0.087215 | 0.056850 |
|   | Frictional Force | 0.047410 | 0.000510 | 0.048760 | 0.023556 |
| В | Force(N)         | 0.108930 | 0.049100 | 0.099921 | 0.061537 |
|   | Moment (Ncm)     | 0.150763 | 0.047752 | 0.063859 | 0.045907 |
| С | Force            | 0.661480 | 0.008311 | 0.138820 | 0.046900 |
|   | Moment           | 0.792852 | 0.006830 | 0.145340 | 0.033676 |
| D | Force            | 0.093940 | 0.000856 | 0.117300 | 0.015827 |
|   | Moment           | 0.139618 | 0.008401 | 0.118306 | 0.044639 |
| Е | Force            | 0.056870 | 0.000572 | 0.050987 | 0.011321 |
|   | Moment           | 0.110100 | 0.000516 | 0.182666 | 0.007372 |
| F | Force            | 0.080140 | 0.002719 | 0.072000 | 0.015451 |
|   | Moment           | 0.010756 | 0.000487 | 0.108177 | 0.019489 |
| G | Force            | 0.060550 | 0.011068 | 0.049477 | 0.009171 |
|   | Moment           | 0.003899 | 0.000182 | 0.014965 | 0.007825 |
| Н | Force            | 0.089930 | 0.000309 | 0.049213 | 0.009536 |
|   | Moment           | 0.033724 | 0.001770 | 0.009742 | 0.000628 |

Table 8: Moments in Ncm and Forces in N for the four legs analyzed

#### **4.9** Effect of Temperature on Movement

As stated in Section 3, three temperatures were chosen for this experiment, 20°C, 25°C, and 30°C, and temperature varied by less than  $\pm$ 1°C across all trials. Six trials were analyzed for 30°C, and four were analyzed for 25°C. The analyses for these trials can be seen below.

#### **4.9.1** Temperature Effect on Steps

The average speed of the spider for the 30°C trials was 1.946±.557, and the average speed of the spider for the 20°C trials was 1.233±.230. For  $\alpha$ =.05, the 30°C and 20°C trials were not significantly different, and only the 20°C was significantly different from the 25°C. See Appendix

The duty factors calculated for all temperatures, and the standard deviation between them can be seen in Table 9 below.

| Leg | 20C Avg | 25C Avg | 30C Avg | Stdev  |
|-----|---------|---------|---------|--------|
| R1  | 0.3720  | 0.4229  | 0.5567  | 0.0954 |
| R2  | 0.7914  | 0.5811  | 0.5877  | 0.1196 |
| R3  | 0.7047  | 0.7525  | 0.7508  | 0.0271 |
| R4  | 0.8918  | 0.8460  | 0.8686  | 0.0229 |
| L1  | 0.4757  | 0.4869  | 0.7733  | 0.1687 |
| L2  | 0.3432  | 0.6849  | 0.5524  | 0.1723 |
| L3  | 0.8283  | 0.7240  | 0.6672  | 0.0817 |
| L4  | 0.7808  | 0.7848  | 0.8948  | 0.0647 |

Table 9: Duty factors per leg across temperatures

The 20°C trials followed a similar pattern to that mentioned in Section 4.4, in that the 2<sup>nd</sup> and 3<sup>rd</sup> leg pairs, and the 3<sup>rd</sup> and 4<sup>th</sup> leg pairs were not significantly different from each other. However, there was significant differences between pair 1 and pair 2 that were not seen at 25°C. At 30°C however, only leg pair 4 was statistically different from pairs 1 and 2, and the differences between pair 3 and 4 were not significant.

The leg pairs were also compared across all temperatures. There was no statistical difference between any pair across temperatures except for leg set 1 at 30°C. Leg set 1 remained on the ground approximately 20% more of the time than it did at 20 or 25°C. See Appendix F for full ANOVA tables.

While there was not much change in duty factor, some changes can be observed in the step patterns of the spider. Table 10 below shows the changes in time spend in the aforementioned patterns. There was not enough data to confidently perform full statistical analysis, however, it is clear that the 30°C trials had significantly less alternating and 3-feet patterns than 20 and 25°C trials did.

| Style       | 20C    | 25C    | 30C    |
|-------------|--------|--------|--------|
| Alternating | 3.69%  | 3.41%  | 0.66%  |
| Partial     | 20.34% | 32.61% | 17.19% |
| 3 Feet      | 9.14%  | 4.34%  | 0.99%  |

Table 10: Step pattern percentage by temperature

Changes in three-foot patterns were also observed at the 20 and 30°C temperatures. For 30°C, only one trial contained a three-foot sequence, and while it maintained the same alternating pattern as the 25°C, the solo leg was leg 4 on the opposite side in place of the third. For 20°C, 50% maintained the same common pattern as 25°C, with alternating on one side and the third leg on the

other. The other 50% of the time had leg 4 down instead, with 25% having an alternating pattern, and 25% having the front and hind leg up, and the middle two legs down. Further analysis would be needed to analyze why these differences occur, as none of the preferred patterns maximize the support area, and thus the stability, of the spider.

Table 11 also indicates that the number of feet on the ground at any point during a walk cycle is negligibly affected by the temperature of the environment. This is confirmed with P=.179, indicating no significant differences between the groups. See Appendix D.

| Temperature | Average | Stdev  |
|-------------|---------|--------|
| 20C         | 5.5700  | 0.3806 |
| 25C         | 5.2787  | 0.3573 |
| 30C         | 5.1879  | 0.2493 |

Table 11: Average number of feet on the ground at a time by temperature

#### **4.9.2** Temperature Effect on Other Variables

Center of mass deviations; in overall distance and broken down into x and y components, did not vary significantly from 25°C runs. Pitch and yaw were also not significantly different from the 25°C runs. These results can be seen in Appendix F.

## 5. DISCUSSION AND CONCLUSION

#### 5.1 Step Analysis

The spider moved at an average speed of 2.76 cm/second. This is a 10 fold decrease in average speed over "Effect of Temperature on Leg Kinematics in Sprinting Tarantulas", which cited an average speed of 21 cm/second [39]. This gives strong indication that the spider remained in a walking gait throughout all trials. Despite literature citing 2.4-fold increase in speed across temperatures 14°C to 40°C, with the largest speed increase from 16.8°C and 24.3°C, our trials did not indicate any significant increase in speed between 20°C and 30°C [39].

Duty factors remained relatively unique for the first and last set of legs but maintained only insignificant differences between leg pairs 2 and 3, and leg pairs 3 and 4. This is due to the varied pattern of the front and hind legs within the spider. The front legs tended to spend significantly more time in the air, reaching forward over multiple other steps before finally resting on the ground, while the hind legs tended to maintain their position on the ground even during movement, typically dragging along the floor.

Tarsus height also varied between leg pairs, with the front two leg pairs having the greatest change in tarsus height over the step, and with the hind leg having the smallest. The height of the femur-patella joint however, moved at similar amplitudes despite which leg was moving, and had insignificantly different variances in max height for all eight limbs.

Unlike the step patterns suggested by "Stepping Patterns in Tarantula Spiders", the spider did not exhibit a preference for an alternating walking pattern. The spider showed this pattern only 3.69% of the overall time, which is about 1/18<sup>th</sup> of the predicted time and spend the majority of the time in 5-legged patterns as opposed to 4. Figure 30 shows a comparison of 10 second clips of spider gaits. Clear differences exist in the number of steps, as well as the amount of time in alternating patterns.



Figure 30: Comparison of Wilson's 10-second step patterns vs 10-second experimental step patterns

The major significant differences in spider movement over temperature arise from the choice of legs during movement. 3-foot patterns maintained strong ties to the third leg pair and an alternating fashion for the 25°C trials, but for temperatures warmer and colder varied between leg pair 3 and 4. More analysis should be done to interpret these changes further.

#### 5.2 Angle Analysis (limbs, pitch yaw, etc)

From the calculations, it appears that there is little to no significant different in the maximum extension of individual leg segments, and no segments would bend more than 90° with respect to the limb before it. The greatest angle in the xy plane was at the coxa, with an average of  $40.63\pm4.20^{\circ}$ . The greatest angle in xz and yz was found at the patella, which had an average of  $32.30\pm14.37^{\circ}$  and  $35.30\pm15.85^{\circ}$  respectively (N=56). The xz and yz planes have a much larger standard deviation from the xy plane, which may be due to the size of the offshoot tunnel. More analysis would be needed to determine if this variation is a normal occurrence.

Pitch and yaw remained relatively stable across all trials, producing no significant differences within temperature groups and among temperature groups. Pitch had a slight oscillatory nature and varied between  $0^{\circ}$  and  $15^{\circ}$ . This oscillation is in agreeance with the changes in center of mass height mentioned in Section 5.1. Yaw tended to have less of a patterned effect, and covered a much larger range of values, typically about  $0^{\circ}$  to  $35^{\circ}$ .

#### 5.3 Force System Analysis

The force system encountered some problems throughout the trial, namely that the resistance on the outside edges of the FSRs does not change as drastically as the center, and that the spider had a tendency to kick clumps of dirt onto the sensor, making it impossible to see the force being applied to it. As such, very little force data was able to be acquired. These problems can be mitigated in the future by adjusting the height of the offshoot to limit dirt contamination, as well as increasing the number of sensors along the offshoot floor to increase the chances of a direct hit. For the four forces analyzed the average force was 72.81±23.54 mN. Very little literature exists to compare this value to, outside of "Hydraulic Leg Extension is Not Necessarily the Main Drive in Large Spiders", which calculated hind leg forces for 3 gram *Ancylometes concolor* spiders and determined their forces to reach a maximum of 56 mN [23]. As the spider in this experiment is moving much slower, and weights about 18 grams, no conclusions could be drawn.

#### 5.4 Conclusion

This thesis sets a precedent for a novel method of measuring the forces exerted by spiders and other arthropods during movement. The ability to measure the forces of individual legs without removing the spider from its terrarium, as well as with the ability to record forces throughout the trial instead of just at the edges, should prove beneficial to biomimetic research. Without the disruption of their environment, the spiders should move in a way that better mimics how they would move in the wild.

Analyzing *Aphonopelma seemanni* at low speeds, in place of during forced escape runs, produced walking gaits that varied significantly from existing literature, and that did not vary with temperature as was the case in escape runs. This indicates that walking speeds are less impacted by external factors and may provide a more realistically sustainable gait style than force runs. By analyzing gait patterns outside of those traditionally used in kinetic analysis of spiders, a new knowledge base for the development of biomimetic robots and other pneumatic-based systems can be established.

# **APPENDIX A. GITHUB REPOSITORY**

https://github.com/dlmoryl/Arachnid-Biomechanics

# **APPENDIX B: SELECT HEIGHT ANALYSIS**

| ne-way   | Y AN   | IOVA:     | R1, R2,     | R3, R4     | I, L1, L2, L3, L4 | Grouping Information U |        |           |       |       |      |  |
|----------|--------|-----------|-------------|------------|-------------------|------------------------|--------|-----------|-------|-------|------|--|
|          |        |           |             |            |                   | Factor                 | N      | Mean      | Gr    | oup   | oing |  |
| Factor I | nfor   | nation    |             |            |                   | R1                     | 7      | 5.488     | A     |       |      |  |
| Factor   | Leve   | Is Values | 5           |            |                   | L1                     | 7      | 4.318     | A     | В     |      |  |
| Factor   |        | 8 R1, R2, | R3, R4, L1, | L2, L3, L4 | -                 | R2                     | 7      | 3.779     | A     | в     | C    |  |
|          |        |           |             |            |                   | L2                     | 7      | 3.599     |       | В     | С    |  |
| Analysi  | s of \ | /ariance  | 2           |            |                   | R3                     | 7      | 2.978     |       | в     | С    |  |
| Source   | DF     | Adi SS    | Adi MS      | E-Value    | P-Value           | R4                     | 7      | 2.582     |       | в     | С    |  |
| Factor   | 7      | 60.97     | 8.710       | 8.16       | 0.000             | L3                     | 7      | 2.491     |       |       | С    |  |
| Error    | 48     | 51.23     | 1.067       |            |                   | L4                     | 7      | 2.114     |       |       | C    |  |
| Total    | 55     | 112.20    |             |            |                   | Means t                | hat da | not share | e a l | etter | are  |  |

Figure B.1: Height of tarsus statistics for 25 C, comparison of all legs

|         |        |          |         |         |         | Factor | N | Mean   | Gr | oup | ping |
|---------|--------|----------|---------|---------|---------|--------|---|--------|----|-----|------|
|         |        |          |         |         |         | 30C R1 | 5 | 5 6.89 |    |     |      |
|         |        |          |         |         |         | 30C R2 | 5 | 5.18   | А  | В   |      |
| Analysi | s of \ | /ariance |         | 30C R3  | 5       | 4.360  | A | В      | С  |     |      |
| Courco  | DE     | Adice    | AdiMC   | E-Value | D-Value | 30C R4 | 5 | 3.960  | A  | В   | C    |
| Source  | Ur     | Auj 55   | AUJIVIS | r-value | P-value | 30C L1 | 5 | 2.938  |    | В   | С    |
| Factor  | 7      | 115.43   | 16.490  | 5.31    | 0.000   | 30C L2 | 5 | 2.664  |    | В   | C    |
| Error   | 32     | 99.45    | 3.108   |         |         | 30C L3 | 5 | 1.867  |    | в   | C    |
| Total   | 39     | 214.88   |         |         |         | 30C L4 | 5 | 1.416  |    | -   | C    |

Figure B.2: Height of tarsus statistics for 30 C, comparison of all legs

|            |        |                |        |                | Factor N Mean Group | uping  |   |        |     |   |
|------------|--------|----------------|--------|----------------|---------------------|--------|---|--------|-----|---|
|            |        |                |        |                |                     | 20C R1 | 3 | 8.50   | А   |   |
| Analysi    | s of \ | /ariance       | 2      |                |                     | 20C R2 | 3 | 7.413  | A B |   |
| randi y Si |        | - an inclusion |        |                |                     | 20C R4 | 3 | 5.420  | A B | C |
| Source     | DF     | Adj SS         | Adj MS | <b>F-Value</b> | P-Value             | 20C L1 | 3 | 4.120  | B   | C |
| Factor     | 7      | 121.87         | 17.409 | 7.82           | 0.000               | 20C L2 | 3 | 3.199  | B   | C |
| Error      | 16     | 35.63          | 2.227  |                |                     | 20C R3 | 3 | 2.98   |     | С |
| Total      | 23     | 157.50         |        |                |                     | 20C L3 | 3 | 2.1536 |     | C |
|            |        |                |        |                |                     | 20C L4 | 3 | 2.128  |     | С |

Figure B.3: Height of tarsus statistics for 20 C, comparison of all legs

|         |        |         |        |         |         | Factor | Ν  | Mean  | G | roup | oing |
|---------|--------|---------|--------|---------|---------|--------|----|-------|---|------|------|
|         |        |         |        |         |         | 20C 1  | 6  | 6.31  | А |      |      |
|         |        |         |        |         |         | 20C 2  | 6  | 5.306 | A | В    |      |
|         |        |         |        |         |         | 30C 1  | 10 | 4.914 | A | В    |      |
|         |        |         |        |         |         | 25C 1  | 14 | 4.903 | A | В    |      |
|         |        |         |        |         |         | 30C 2  | 10 | 3.922 | А | В    | C    |
|         |        |         |        |         |         | 20C 4  | 6  | 3.774 | А | В    | С    |
|         |        |         |        |         |         | 25C 2  | 14 | 3.689 | А | В    | С    |
| Analysi | s of V | ariance |        |         |         | 30C 3  | 10 | 3.113 |   | В    | C    |
| Source  | DF     | Adj SS  | Adj MS | F-Value | P-Value | 30C 4  | 10 | 2.997 |   | В    | С    |
| Factor  | 11     | 146.5   | 13.315 | 4.15    | 0.000   | 25C 3  | 14 | 2.735 |   | В    | C    |
| Error   | 108    | 346.2   | 3.206  |         |         | 20C 3  | 6  | 2.567 |   | В    | С    |
| Total   | 119    | 492.7   |        |         |         | 25C 4  | 14 | 2.348 |   |      | С    |

Figure B.4: Height of tarsus statistics for all temperatures, leg pair comparison

|         |        |          |        |         |         | Factor | N | Mean  | Grouping |
|---------|--------|----------|--------|---------|---------|--------|---|-------|----------|
|         |        |          |        |         |         | R1     | 7 | 5.158 | A        |
|         |        | 2012     |        |         |         | R4     | 7 | 4.913 | A        |
| Analysi | s of \ | /ariance | 2      |         |         | R2     | 7 | 4.885 | A        |
| Source  | DF     | Adi SS   | Adi MS | F-Value | P-Value | R3     | 7 | 4.709 | A        |
| Factor  | 7      | 13.27    | 1.8054 | 1 00    | 0.077   | L1     | 7 | 4.280 | A        |
| Freeror | 49     | 45.91    | 0.0544 | 1.22    | 0.011   | L2     | 7 | 3.980 | A        |
| Tatal   | 40     | 40.00    | 0.9344 |         |         | L4     | 7 | 3.887 | A        |
| Total   | 22     | 39.00    |        |         |         | L3     | 7 | 3.852 | A        |

Figure B.5: Height of femur-patella statistics for 25 C, comparison of all legs

|          |    |        |         |         |         | Factor | Ν | Mean   | Grouping |
|----------|----|--------|---------|---------|---------|--------|---|--------|----------|
|          |    |        |         |         |         | 30C L1 | 5 | 3.889  | A        |
|          |    |        |         |         |         | 30C R1 | 5 | 3.843  | A        |
|          |    |        |         |         |         | 30C L2 | 5 | 3.738  | A        |
| Source   | DE | Adiss  | Adi MS  | E-Value | D-Value | 30C L4 | 5 | 3.5784 | A        |
| Source   | Dr | Auj 33 | Aujivis | r value | P value | 30C R4 | 5 | 3.549  | A        |
| Factor   | 7. | 1.015  | 0.1451  | 0.28    | 0.957   | 30C R2 | 5 | 3.529  | Δ.       |
| Error    | 32 | 16.516 | 0.5161  |         |         | 20012  | - | 2 470  |          |
| Total    | 30 | 17 531 |         |         |         | SUC LS | 2 | 3.470  | A        |
| ( with ) | 22 |        |         |         |         | 30C R3 | 5 | 3.440  | A        |

Figure B.6: Height of femur-patella statistics for 30 C, comparison of all legs

|                          |               |                            |                    |         |         | Factor                     | N   | Mean                      | G | roup | ping |
|--------------------------|---------------|----------------------------|--------------------|---------|---------|----------------------------|-----|---------------------------|---|------|------|
|                          |               |                            |                    |         |         | 20C L1                     | 3   | 4.878                     | A |      |      |
|                          |               |                            |                    |         |         | 20C R2                     | 3   | 4.73054                   | А | В    |      |
|                          |               |                            |                    |         |         | 20C R1                     | 3   | 4.620                     | A | В    | С    |
|                          |               |                            |                    |         |         | 20C R4                     | 3   | 4.4945                    | А | В    | C    |
| Source                   | DF            | Adj SS                     | Adj MS             | F-Value | P-Value | 20C L2                     | 3   | 4.397                     | A | В    | C    |
| Factor                   | 7             | 1.8026                     | 0.25751            | 4.78    | 0.005   | 20C L4                     | 3   | 4.245                     | A | В    | С    |
| Error                    | 16            | 0.8611                     | 0.05382            |         |         | 20C R3                     | 3   | 4.1489                    |   | В    | С    |
| Total                    | 23            | 2.6637                     |                    |         |         | 20C L3                     | 3   | 4.0338                    |   |      | C    |
| Factor<br>Error<br>Total | 7<br>16<br>23 | 1.8026<br>0.8611<br>2.6637 | 0.25751<br>0.05382 | 4.78    | 0.005   | 20C L4<br>20C R3<br>20C L3 | 333 | 4.245<br>4.1489<br>4.0338 | A | B    |      |

Figure B.7: Height of femur-patella statistics for 20 C, comparison of all legs

|        |     |        |         |         |         | Factor | Ν  | Mean   | Gro | uping |
|--------|-----|--------|---------|---------|---------|--------|----|--------|-----|-------|
|        |     |        |         |         |         | 20C 1  | 6  | 4.749  | A   | В     |
|        |     |        |         |         |         | 25C 1  | 14 | 4.719  | A   |       |
|        |     |        |         |         |         | 20C 2  | 6  | 4.564  | A   | В     |
|        |     |        |         |         |         | 25C 2  | 14 | 4.432  | A   | В     |
|        |     |        |         |         |         | 25C 4  | 14 | 4.400  | A   | В     |
|        |     |        |         |         |         | 20C 4  | 6  | 4.370  | A   | В     |
|        |     |        |         |         |         | 25C 3  | 14 | 4.281  | A   | В     |
| Sourco | DE  | Adice  | Adi MC  | E-Value | D-Value | 20C 3  | 6  | 4.0914 | A   | В     |
| Source | Ur  | Auj 55 | AUJINIS | r-value | P-Value | 30C 1  | 10 | 3.866  | A   | В     |
| Factor | 11  | 21.87  | 1.9879  | 2.84    | 0.003   | 30C 2  | 10 | 3.634  | A   | в     |
| Error  | 108 | 75.50  | 0.6991  |         |         | 30C 4  | 10 | 3,563  | A   | В     |
| Total  | 119 | 97.37  |         |         |         | 30C 3  | 10 | 3.458  |     | В     |

Figure B.8: Height of femur-patella statistics across all temperatures, comparison of leg pairs

# **APPENDIX C: SELECT ANGLE ANALYSIS**

| 3FG | 14 | 79.57 A |   |   |   |   |
|-----|----|---------|---|---|---|---|
| BAB | 14 | 79.16 A |   |   |   |   |
| 3BC | 14 | 78.04 A | В |   |   |   |
| 3GH | 14 | 77.97 A | В |   |   |   |
| 4AB | 14 | 76.86 A | В |   |   |   |
| 4FG | 14 | 76.39 A | В |   |   |   |
| 3DE | 14 | 74.94 A | В |   |   |   |
| 1FG | 14 | 73.78 A | В |   |   |   |
| 1GH | 14 | 73.73 A | В |   |   |   |
| 3EF | 14 | 73.41 A | В |   |   |   |
| ZAB | 14 | 72.09 A | В |   |   |   |
| 2FG | 14 | 71.56 A | В |   |   |   |
| 2GH | 14 | 70.61 A | В |   |   |   |
| 4EF | 14 | 70.55 A | В |   |   |   |
| 1EF | 14 | 69.40 A | В |   |   |   |
| 4GH | 14 | 69.05 A | В |   |   |   |
| 1DE | 14 | 67.71 A | В | С |   |   |
| 2EF | 14 | 67.68 A | В | С |   |   |
| 1AB | 14 | 65.94 A | В | С | D |   |
| 4BC | 14 | 65.54 A | В | C | D |   |
| 2DE | 14 | 64.11 A | В | С | D |   |
| 2BC | 14 | 63.08 A | В | C | D |   |
| 4DE | 14 | 62.43 A | В | C | D |   |
| 1BC | 14 | 58.47   | В | С | D | Ε |
|     |    |         |   |   |   |   |

Figure C.1: Maximum angle analysis for xy

| Factor | N  | Mean  |    | Grouping | 9   |   |    |       |   |   |   |   |
|--------|----|-------|----|----------|-----|---|----|-------|---|---|---|---|
| 2GH    | 14 | 78.50 | A  |          |     |   |    |       |   |   |   |   |
| 1FG    | 14 | 76.77 | A  | В        | 480 |   | 14 | 68.52 | A | В | C |   |
| 3GH    | 14 | 76.76 | A. | В        | 280 |   | 14 | 67.73 | A | В | C |   |
| 1GH    | 14 | 76.04 | Д  | в        | 248 | 3 | 14 | 66.92 | A | в | С |   |
| 1DE    | 14 | 75.20 | A  | в        | 1 A | в | 14 | 66.66 | A | В | С |   |
| 2FG    | 14 | 74.94 | A  | В        | 2D8 | E | 14 | 66.19 | A | В | С |   |
| 3DE    | 14 | 74.69 | Д  | В        | 3EF |   | 14 | 64.60 | A | В | С |   |
| 3BC    | 14 | 74.01 | А  | В        | 4EF |   | 14 | 63.08 | А | В | C |   |
| 4GH    | 14 | 73.08 | A  | в        | 1 B | C | 14 | 60.71 | А | В | С | D |
| 4DE    | 14 | 72.66 | A  | в        | 4A8 | 3 | 14 | 58.64 | А | В | С | D |
| 3FG    | 14 | 72.43 | А  | в        | 1EF |   | 14 | 57.13 | A | В | С | D |
| 3AB    | 14 | 70.84 | Д  | BC       | 200 | D | 14 | 55.53 | A | В | С | D |
| 3CD    | 14 | 69.62 | А  | BC       | 2EF |   | 14 | 52.85 |   | В | С | D |
| 4FG    | 14 | 69.45 | А  | B C      | 100 | 0 | 14 | 46.98 |   |   | C | D |
| 4BC    | 14 | 68.52 | A  | BC       | 400 | 0 | 14 | 37.57 |   |   |   | D |
|        |    |       |    |          |     |   |    |       |   |   |   |   |

Figure C.2: Maximum angle analysis for xz

| Factor | N  | Mean  | G | roup | bing |     |    |         |   |   |
|--------|----|-------|---|------|------|-----|----|---------|---|---|
| 4DE    | 14 | 78.02 | A | _    |      |     |    |         |   |   |
| 1GH    | 14 | 76.03 | A | В    |      |     |    |         |   |   |
| 1DE    | 14 | 73.78 | A | В    |      |     |    |         |   |   |
| 3FG    | 14 | 70.70 | A | В    | C    |     |    |         |   |   |
| 2DE    | 14 | 70.04 | A | В    | C    |     |    |         |   |   |
| 1FG    | 14 | 70.02 | A | В    | С    | 1BC | 14 | 59.80 A | В | C |
| 2FG    | 14 | 69.92 | A | В    | C    | 2AB | 14 | 59.45 A | В | C |
| 1 AB   | 14 | 69.72 | A | B    | С    | 2EF | 14 | 58.82 A | В | C |
| 3DE    | 14 | 68.91 | A | B    | C    | 1CD | 14 | 56.12 A | В | С |
| 4FG    | 14 | 65.32 | A | В    | C    | 2BC | 14 | 55.22 A | В | C |
| 3BC    | 14 | 63.53 | A | B    | C    | 4GH | 14 | 54.88 A | В | C |
| 3GH    | 14 | 61.54 | A | В    | C    | 4AB | 14 | 54.52 A | В | C |
| 4EF    | 14 | 61.45 | A | B    | c    | 4BC | 14 | 54.40 A | В | С |
| BEE    | 14 | 60.60 | Δ | B    | C    | 4CD | 14 | 53.76 A | В | C |
| 2GH    | 14 | 60.10 | Δ | B    | C    | 3AB | 14 | 50.81   | В | C |
| 1FF    | 14 | 59.89 | Δ | B    | c    | 3CD | 14 | 50.42   | В | C |
| 1BC    | 14 | 59.80 | A | B    | c    | 2CD | 14 | 47.03   |   | С |

Figure C.3: Maximum angle analysis for yz

# APPENDIX D: SELECT DUTY FACTOR AND STEP ANALYSIS

|        |     |        |         |                |         | Factor | N  | Mean     | 1 | Gro | upin | ig |   |
|--------|-----|--------|---------|----------------|---------|--------|----|----------|---|-----|------|----|---|
|        |     |        |         |                |         | 30 C 4 | 12 | 0.8817 A |   |     |      |    |   |
|        |     |        |         |                |         | 20 C 4 | 8  | 0.8363 A | В | С   |      |    |   |
|        |     |        |         |                |         | 25 C 4 | 26 | 0.8154 A |   |     |      |    |   |
|        |     |        |         |                |         | 20 C 3 | 8  | 0.7665 A | В | С   | D    |    |   |
|        |     |        |         |                |         | 25 C 3 | 26 | 0.7382 A | В | С   | D    |    |   |
|        |     |        |         |                |         | 30 C 3 | 12 | 0.7090 A | В | С   | D    |    |   |
|        |     |        |         |                |         | 30 C 1 | 12 | 0.6650 A | В | С   | D    | Ε  |   |
|        |     |        |         |                |         | 25 C 2 | 26 | 0.6330   |   | С   | D    | Ε  |   |
| Source | DF  | Adi SS | Adi MS  | <b>F-Value</b> | P-Value | 30 C 2 | 12 | 0.5701   |   |     | D    | Е  | F |
| Easter | 11  | 2 450  | 0.21265 | 11.50          | 0.000   | 20 C 2 | 8  | 0.5673   | В | С   | D    | Ε  | F |
| Factor |     | 5,450  | 0.51505 | 11.50          | 0.000   | 25 C 1 | 26 | 0.4549   |   |     |      |    | F |
| Error  | 172 | 4.691  | 0.02727 |                |         | 20 C 1 | 8  | 0.4239   |   |     |      | E  | F |
| Total  | 183 | 8.141  |         |                |         |        |    |          |   |     |      |    |   |

Figure D.1: Duty Factor (DF) analysis of leg sets across all temperatures

| Source | DF | Adj SS | Adj MS  | <b>F-Value</b> | P-Value | Factor | N  | Mean   | Grouping |
|--------|----|--------|---------|----------------|---------|--------|----|--------|----------|
| Factor | 2  | 0.4250 | 0.21252 | 4.99           | 0.011   | 30 C 1 | 12 | 0.6650 | Α        |
| Error  | 43 | 1.8327 | 0.04262 |                |         | 25 C 1 | 26 | 0.4549 | В        |
| Total  | 45 | 2.2577 |         |                |         | 20 C 1 | 8  | 0.4239 | В        |

Figure D.2: DF analysis of leg set 1 across temperatures

Leg set 2 across temperatures

| Source | DF | Adj SS  | Adj MS  | F-Value | P-Value | Factor | N  | Mean   | Groupi |
|--------|----|---------|---------|---------|---------|--------|----|--------|--------|
| Factor | 2  | 0.04641 | 0.02321 | 0.51    | 0.602   | 25 C 2 | 26 | 0.6330 | A      |
| Error  | 43 | 1.94124 | 0.04515 |         |         | 30 C 2 | 12 | 0.5701 | A      |
| Total  | 45 | 1.98765 |         |         |         | 20 C 2 | 8  | 0.5673 | A      |

Figure D.3: DF analysis of leg set 2 across temperatures

| Source | DF | Adj SS  | Adj MS   | <b>F-Value</b> | P-Value | Factor | Ν  | Mean ( | Grouping |
|--------|----|---------|----------|----------------|---------|--------|----|--------|----------|
| Factor | 2  | 0.01629 | 0.008147 | 0.81           | 0.453   | 20 C 3 | 8  | 0.7665 | A        |
| Error  | 43 | 0.43462 | 0.010107 |                |         | 25 C 3 | 26 | 0.7382 | A        |
| Total  | 45 | 0.45092 |          |                |         | 30 C 3 | 12 | 0.7090 | A        |

Figure D.4: DF analysis of leg set 3 across temperatures

| Source | DF | Adj SS  | Adj MS  | <b>F-Value</b> | P-Value | Factor | N  | Mean Grouping |
|--------|----|---------|---------|----------------|---------|--------|----|---------------|
| Factor | 2  | 0.03611 | 0.01805 | 1.61           | 0.212   | 30 C 4 | 12 | 0.8817 A      |
| Error  | 43 | 0.48231 | 0.01122 |                |         | 20 C 4 | 8  | 0.8363 A      |
| Total  | 45 | 0.51842 |         |                |         | 25 C 4 | 26 | 0.8154 A      |

Figure D.5: DF analysis of leg set 4 across temperatures

|        |     |        |         |                |         | 25 C R4 | 13 | 0.8460 A |   |   |
|--------|-----|--------|---------|----------------|---------|---------|----|----------|---|---|
|        |     |        |         |                |         | 25 C L4 | 13 | 0.7848 A |   |   |
|        |     |        |         |                |         | 25 C R3 | 13 | 0.7525 A | В |   |
|        |     |        |         |                |         | 25 C L3 | 13 | 0.7240 A | В |   |
| Source | DF  | Adj SS | Adj MS  | <b>F-Value</b> | P-Value | 25 C L2 | 13 | 0.6849 A | В |   |
| Factor | 7   | 2.026  | 0.28941 | 13.12          | 0.000   | 25 C R2 | 13 | 0.5811   | В | С |
| Error  | 96  | 2.118  | 0.02206 |                |         | 25 C L1 | 13 | 0.4869   |   | С |
| Total  | 103 | 4.143  |         |                |         | 25 C R1 | 13 | 0.4229   |   | С |
|        |     |        |         |                |         |         |    |          |   |   |

Figure D.6: DF comparison of all legs across 25C

|        |    |        |         |         |          | Factor  | N | Mean   | Gr | ouping |
|--------|----|--------|---------|---------|----------|---------|---|--------|----|--------|
|        |    |        |         |         |          | 30 C L4 | 6 | 0.8948 | А  |        |
|        |    |        |         |         |          | 30 C R4 | 6 | 0.8686 | A  | В      |
|        |    |        |         |         |          | 30 C L3 | 6 | 0.7778 | A  | в      |
| Course | DE | Adics  | AdiMC   | E Malua | D. Malue | 30 C L1 | 6 | 0.7733 | A  | В      |
| Source | DF | Adj 55 | AUJINIS | F-value | P-Value  | 30 C R3 | 6 | 0.7508 | A  | В      |
| Factor | 7  | 0.7920 | 0.11315 | 3.79    | 0.003    | 30 C R2 | 6 | 0.5877 | A  | В      |
| Error  | 40 | 1.1936 | 0.02984 |         |          | 30 C R1 | 6 | 0.557  |    | R      |
| Total  | 47 | 1.9856 |         |         |          | 30 C L2 | 6 | 0.5524 |    | в      |

Figure D.7: DF comparison of all legs across 30 C

|        |    |        |         |         |         | Factor  | N | Mean   | Gr | oup | bing |
|--------|----|--------|---------|---------|---------|---------|---|--------|----|-----|------|
|        |    |        |         |         |         | 20 C R4 | 4 | 0.8918 | A  |     |      |
|        |    |        |         |         |         | 20 C L3 | 4 | 0.8283 | A  | В   |      |
|        |    |        |         |         |         | 20 C R2 | 4 | 0.7914 | A  | В   |      |
|        |    |        |         |         |         | 20 C L4 | 4 | 0.7808 | A  | В   |      |
| Source | DF | Adj SS | Adj MS  | F-Value | P-Value | 20 C R3 | 4 | 0.7047 | A  | B   | C    |
| Factor | 7  | 1.3284 | 0.18977 | 7.57    | 0.000   | 20 C L1 | 4 | 0.4757 |    | В   | C    |
| Error  | 24 | 0.6013 | 0.02505 |         |         | 20 C R1 | 4 | 0.372  |    |     | С    |
| Total  | 31 | 1.9297 |         |         |         | 20 C L2 | 4 | 0.343  |    |     | С    |

Figure D.8: DF comparison of all legs across 20 C

| Source | DF | Adj SS | Adj MS | <b>F-Value</b> | P-Value | Factor | N  | Mean   | Grouping |
|--------|----|--------|--------|----------------|---------|--------|----|--------|----------|
| Factor | 2  | 0.4587 | 0.2294 | 1.88           | 0.179   | 30 C   | 6  | 5.570  | A        |
| Error  | 20 | 2 4426 | 0 1221 |                |         | 25C    | 13 | 5.2787 | A        |
| Total  | 22 | 2.9013 | 0.1221 |                |         | 20C    | 4  | 5.188  | A        |

Figure D.9: Comparison of average number of steps over temperature

# **APPENDIX E: CALIBRATION CURVES**



Figure E.1: Sensor Set 1 Sensor 3 calibration curve



Figure E.2: Sensor Set 1 Sensor 4 calibration curve



Figure E.3: Sensor Set 2 Sensor 8 calibration curve

# **APPENDIX F: SELECT TEMPERATURE ANALYSIS**

|        |    |         |        |         |         | <b>Factor</b> |        | Mann      | Crouping           |
|--------|----|---------|--------|---------|---------|---------------|--------|-----------|--------------------|
| Source | DF | Adj SS  | Adj MS | F-Value | P-Value | Pactor        | C      | a zeo y   | Grouping           |
| Factor | 2  | 4,922   | 2.4610 | 6.72    | 0.014   | 25 0          | 0      | 2.760 /   | ~ D                |
| Frror  | 10 | 3,663   | 0.3663 |         |         | 300           | 4      | 1.940 /   | 4 В                |
| Total  | 12 | 8 5 8 5 |        |         |         | 200           | 2      | 1.200     | D                  |
| rotar  | 12 | 0.505   |        |         |         | Means ti      | hat do | not share | a letter are signi |

Figure F.1: Analysis of speed over all temperatures

| Source | DF | Adi SS | Adi MS | F-Value | P-Value | Factor | N | Mean Grouping |
|--------|----|--------|--------|---------|---------|--------|---|---------------|
| Factor | 2  | 0.2085 | 0.10/3 | 0.60    | 0.527   | 25 C   | 5 | 0.592 A       |
| Error  | 0  | 1 2614 | 0.1512 | 0.09    | 0.527   | 30C    | 4 | 0.452 A       |
| Total  | 11 | 1.5600 | 0.1313 |         |         | 20 C   | 3 | 0.259 A       |
| TOCAL  |    | 1.3099 |        |         |         |        |   |               |

Figure F.2: Analysis of COM deviations in x over all temperatures

| Source | DF | Adj SS | Adj MS | F-Value | P-Value | Factor | Ν | Mean Grouping |
|--------|----|--------|--------|---------|---------|--------|---|---------------|
| Factor | 2  | 0.3456 | 0.1728 | 1.25    | 0.329   | 25 C   | 6 | 0.620 A       |
| Error  | 10 | 1.3863 | 0.1386 |         |         | 30C    | 4 | 0.442 A       |
| Total  | 12 | 1.7319 |        |         |         | 20 C   | 3 | 0.2071 A      |

Figure F.3: Analysis of COM deviations in y over all temperatures

| Source | DF | Adj SS | Adj MS | F-Value | P-Value | Factor | Ν | Mean Grouping |
|--------|----|--------|--------|---------|---------|--------|---|---------------|
| Factor | 2  | 686.4  | 343.2  | 1.67    | 0.236   | 20.0   | 3 | 28.2 A        |
| Error  | 10 | 2050.2 | 205.0  |         |         | 200    |   | 10.51 A       |
| Total  | 12 | 2736.6 |        |         |         | 30C    | 4 | 13.51 A       |
|        |    |        |        |         |         | 25 C   | 6 | 9.88 A        |

Figure F.4: Analysis of average pitch over all temperatures

| Source | DF | Adj SS | Adj MS | F-Value | P-Value | Factor | N | Mean Grouping |
|--------|----|--------|--------|---------|---------|--------|---|---------------|
| Factor | 2  | 1301   | 650.3  | 1.57    | 0.255   | 30C    | 4 | 80.21 A       |
| Error  | 10 | 4142   | 414.2  |         |         | 25 C   | 6 | 78.54 A       |
| Total  | 12 | 5443   |        |         |         | 20 C   | 3 | 55.5 A        |

Figure F.5: Analysis of average yaw over all temperatures

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