DESIGN AND IMPLEMENTATION OF A CUSTOM FORCE POLE ASSEMBLY FOR THE MEASUREMENT OF PRIMATE LOCOMOTOR KINETICS

by

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Design and Implementation of a Custom Force Pole Assembly for the Measurement of Primate Locomotor Kinetics

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ABSTRACT

The purpose of this research is to design and implement a custom force transducer assembly for the measurement of primate locomotor kinetics. The measurement system incorporates various strain gauges, accelerometers, high-speed video cameras, and a data acquisition system to generate quantitative stability measurements during primate locomotion. The tasks for this research include: (1) designing and constructing Wheatstone bridge circuitry to read outputs from the constructed force transducers, (2) calibrating and verifying force transducer outputs, (3) constructing a compliant force pole base to simulate tree branch mobility, and (4) constructing, wiring, and testing of accelerometers to independently measure force pole movement during animal locomotion on the compliant substrate. This system is used to gather locomotor kinetics of squirrel monkeys (*Saimiri boliviensis*), common marmosets (*Callithrix jacchus*), long-tailed macaques (*Macaca fascicularis*), and pig-tailed macaques (*Macaca nemestrina*). The transducer assembly is applied in two experimental contexts: (1) animals moving over static force poles and (2) animals moving over force poles mounted on a compliant base to simulate tree branch mobility. The design surpasses other similar testing structures through the use of accelerometers to independently measure relative movement and acceleration on compliant substrates. Most importantly, the system allows for adaptation and scalability required for application in other species, such as reptiles and other mammals. Data gathered from this system can be applied to impaired mobility studies in disabled individuals and elderly people.

ACKNOWLEDGEMENTS

I would like to thank my advisory committee and the faculty of the Department of Electrical and Computer Engineering at Youngstown State University and the Department of Anatomy and Neurobiology at Northeast Ohio Medical University, specifically Dr. Jesse W. Young and Dr. Brad Chadwell. Through their combined efforts, I have gained valuable knowledge and skills that have guided me through my education and this thesis work.

I would also like to thank my family and friends. Without their motivation, I would not have been able to complete this endeavor.

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ABBREVIATIONS

A/D	Analog-to-Digital
AR	As Required
DAQ	Data Acquisition
DC	Direct Current
DSP	Digital Signal Processing
EEPROM	Electrically Erasable Programmable Read-Only Memory
IACUC	Institutional Animal Care and Use Committee
MAX	Measurement and Automation Explorer
MEMS	Micro-Electro Mechanical System
NI	National Instruments
NSF	National Science Foundation
PC	Personal Computer
PDP	Product Development Process
UI	User Interface

CHAPTER 1

INTRODUCTION

In recent decades, rapid advances in computer technology have enabled scientists and engineers to collaborate on a diverse range of projects for society's benefit. Continually, these groups are working together to study the world's wonders and analyze information using the latest data acquisition (DAQ) technology. From turtles walking on treadmills [1] to insects running on elastic surfaces [2], biomechanics research relies heavily upon technology used in the electrical engineering field to conduct experiments.

In this research, the area of primate locomotor kinetics is explored using custom force transducers, accelerometers, and high-speed video cameras based upon a collaborative design from Youngstown State University (YSU) and Northeast Ohio Medical University (NEOMED). This system generates quantitative stability measurements of locomotor kinetics for squirrel monkeys (*Saimiri boliviensis*), common marmosets (*Callithrix jacchus*), long-tailed macaques (*Macaca fascicularis*), and pig-tailed macaques (*Macaca nemestrina*). Information collected from this system can be applied to impaired mobility studies in elderly humans. The measurement components can be applied to other locomotor kinetics studies involving reptiles and other mammals.

1.1 History

Long before complex data acquisition systems became standard, scientists and engineers have collaborated on research endeavors using analog signals from simplistic technology. An example of such technology, strain gauges provide a correlation between electrical resistance and strain. This technology has infinite applications, from bone loading to steel strength. A basic staple of the research world, strain gauges have been used to measure principle strain along various axes [3]. In other experiments, ground reaction forces are measured using a system of strain gauges arranged as a force plate [4]. Also, strain gauges can be utilized to measure torque applied to instrumented force poles [5].

As technology progressed, personal computers (PCs) gave rise to an entirely new generation of complex DAQ equipment. An example of such technology, accelerometers are used to measure the change in velocity of a moving body over the change in time. Like strain gauges, this technology also has broad uses, from kinematics of primates to the movement of skyscrapers [6]. Advanced tools capable of producing digital and analog signals, Micro-Electro Mechanical System (MEMS) accelerometers have been used in conjunction with data logging equipment to measure the take-off and landing kinetics of gliding mammals [7]. A more advanced application, a MEMS accelerometer "backpack," high-speed video, and digital signal processing (DSP) filtering have been utilized to measure kinematics of insects running on a compliant substrate [2].

Scientists and engineers consistently utilize strain gauges and accelerometers to gather quantitative measures of natural phenomena. Combined with robust computer-based data acquisition hardware and high-speed video cameras, these devices can be applied to a wide variety of experiments; one such experiment is detailed in this study.

1.2 Motivation

To date, many research applications involve the individual use of strain gauges and accelerometers. Very few studies involve the integration of both technologies. The main goal of this research was to combine custom force transducers (instrumented with strain gauges), accelerometers, and high-speed video cameras in a collaborative system to simultaneously gather kinematic data in real-time. Applied to both stationary and compliant substrates, the system is utilized to measure primate locomotor kinetics (forces, accelerations, and torques) to develop conclusions of arboreal stability. This combined design represents a novel approach in both application of technology and usage of acquired data.

1.3 Organization

This work is divided into five chapters. Chapter 2 provides an overview of the design, including design specifications and development process. Chapter 3 describes the details of the force pole assembly, accelerometer system, and data acquisition hardware. Chapter 4 details the individual testing of components, improvements, and final testing of the entire system. Finally, Chapter 5 provides a summary of this research along with applications and future work. Several appendices provide detailed implementation costs, photographs of the final system design, and animal research approval documentation.

CHAPTER 2

OVERVIEW OF DESIGN

2.1 Background and Overview of Strain Gauges

As defined by National Instruments (NI), strain is the amount of deformation of a body due to an applied force [8]. A dimensionless quantity expressed in relative units of "microstrain," this fractional length change can be positive (tensile strain) or negative (compressive strain). An illustration of tensile strain due to an applied force is shown in Figure 1, with material depth (D), material length (L), and change in length (ΔL) [8].

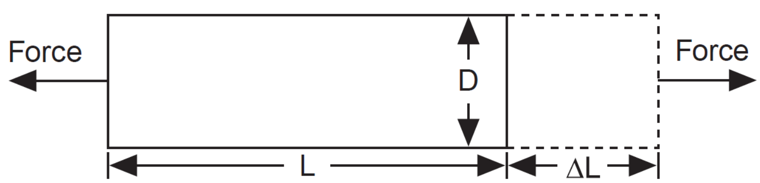

Figure 1: Illustration of Strain

Thus, strain (ε) is given by Equation 1 using definitions from Figure 1.

$$\varepsilon = {}^{\Delta L}/_{L} \qquad (1)$$

Shown in Figure 2, the most common strain gauge is the bonded metallic type which utilizes a metallic foil arranged in a grid pattern mounted on a carrier that is bonded to testing media [8]. Tension or compression of the testing media creates a change in resistance of the gauge which is correlated to a quantitative measure of strain.

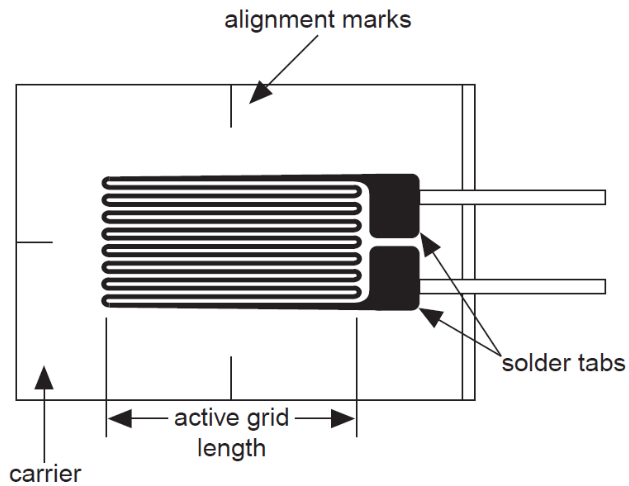

Figure 2: Strain Gauge Diagram

To measure small changes in resistance, strain gauges (modeled as resistors) are almost exclusively used in a Wheatstone full-bridge configuration with an applied excitation voltage (V_{EX}), as shown in Figure 3 [8]. For this circuit, according to fundamental principles of electrical engineering, the strained output voltage (V_O) is defined by:

$$V_O = \left[\frac{R_3}{R_3+R_4} - \frac{R_2}{R_1+R_2}\right] * V_{EX} \tag{2}$$

Using V_O from Equation 2, the strain (ε) is calculated as shown in Equation 3, with indicated gauge factor (K) given by strain gauge specifications and unstrained output voltage (V_{OU}) measured without applied forces.

$$\varepsilon = -\frac{V_O - V_{OU}}{(V_{EX}) * (K)} \tag{3}$$

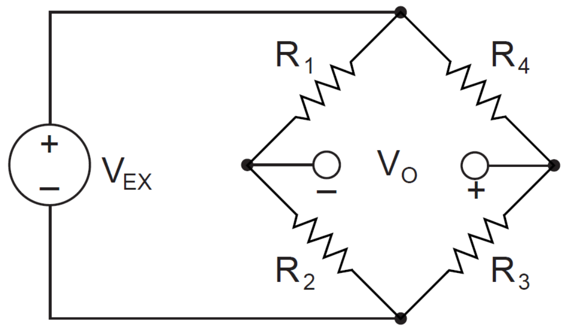

Figure 3: Wheatstone Full-bridge Circuit

2.2 Background and Overview of Accelerometers

Although various types exist, MEMS accelerometers represent the future of a growing industry. As detailed by Analog Devices [9], MEMS accelerometers utilize a sensor constructed from a polysilicon micro-machined structure atop a silicon wafer. Internal signal conditioning circuitry is utilized to measure the static gravitational acceleration and dynamic acceleration due to motion, vibration, or shock. Accelerometers range from single-axis to three-axis systems. Based upon defined characteristics, these testing devices provide voltage outputs correlated directly to changes in acceleration.

Designed specifically for research associated with the Young Laboratory study entitled "The Biomechanics of Arboreal Stability in Primates: an Integrated Analysis" (funded by National Science Foundation (NSF) grant BCS 1126790, awarded to Dr. Jesse W. Young of NEOMED), the design is divided into three categories: force poles, accelerometer array, and data acquisition equipment. As discussed previously, the force poles utilize strain gauges arranged along X (mediolateral), Y (fore-aft), and Z (vertical) axes to convert strain-based changes in resistance into voltages. Then, these voltages are empirically calibrated into units of force. Six identical force poles are placed in series along the custom runway for data acquisition. The accelerometer array utilizes five three-axis accelerometers placed on the instrumented surface to convert voltages into accelerations. The accelerometer array is affixed to the underside of the force pole mounting board for data acquisition. Finally, the DAQ equipment, composed primarily of NI hardware, collects, synchronizes, and conditions the input voltages from strain gauges and accelerometers via various modules and analog-to-digital (A/D) converters. The data set of voltages and high-speed video streams are saved to the custom server from Xcitex Inc. of Cambridge, MA for later analysis and processing. The overall equipment and connections are detailed in Figure 4.

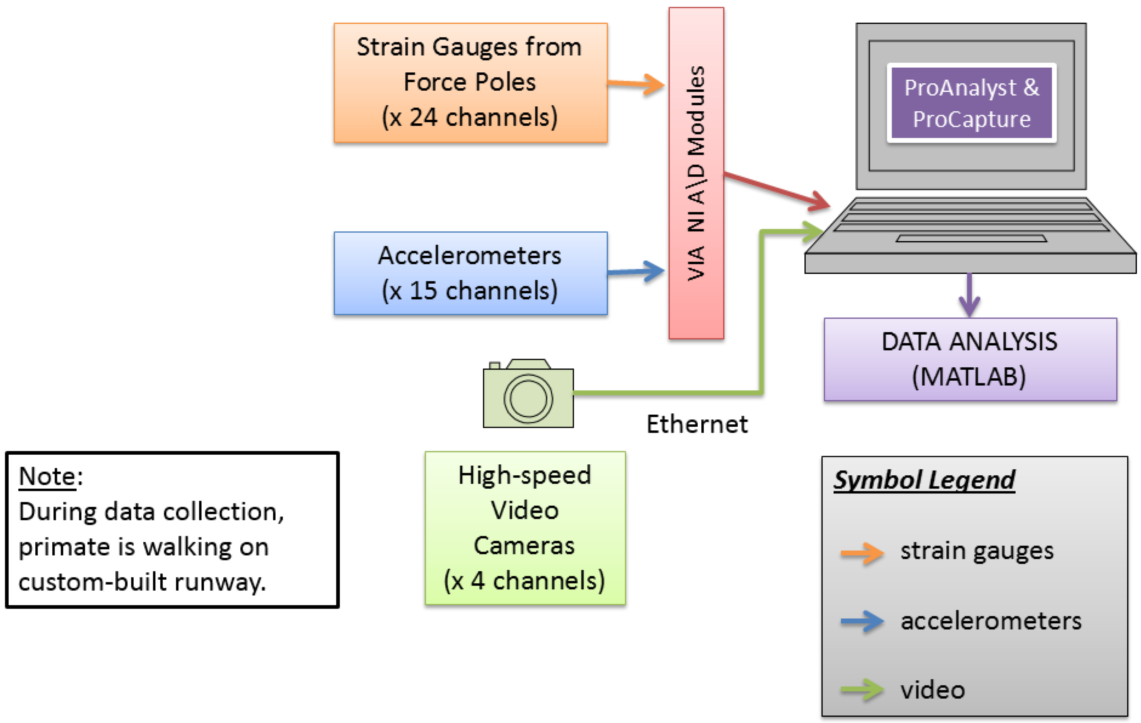

Figure 4: Overall Equipment Connections

2.3 Design Expectations

Based upon consultations with Dr. Young (the Principal Investigator of NSF grant BCS 1126790), the following overall design specifications are used to organize research and construction tasks.

- ***Apply research and development necessary for prototype design.***

  Expectations are met by an in-depth analysis and simulation of similar force pole systems used in biomechanics research. Adaptations are made to assemble a compliant force pole that accurately models real-world "compliant tree branch" behavior. Assumptions are based upon knowledge gained from undergraduate work with Dr. Michael T. Butcher (Department of Biological Sciences, YSU) documented in undergraduate thesis, entitled *The Biomechanics of Turtle Limbs: An Electrical Engineer's Perspective*, corresponding to research regarding bone strain and muscle function in river cooter turtles [1].

- ***Develop engineering thinking process.***

  Expectations are met by careful planning of methodology for specific species of primates used in the study, collection of locomotor kinetic data through repeated trials of primates moving on pole substrates, and data analysis via calculation of forces and torques developed and timed according to the biomechanical events during limb cycle.

- ***Learn generic product development process (PDP).***

  Expectations are met by the assembly and testing of equipment for collection of biomechanical data. The recording hardware is modeled after previous systems that have been successfully used to acquire these types of biomechanical measurements; however, the compliant force pole design on a dynamic substrate is new and not previously tested. Furthermore, the data acquisition software requires testing and customization to collect and synchronize high-speed video and waveform data from primate limbs during locomotion.

- ***Develop oral presentation and writing skills.***

  Expectations are met by a detailed final report of contributions to the study, documented in this thesis. Significant contributions to hardware and software, force pole customization, data collection, analysis programming, and written explanations for the study methodology assist in the authorship of a series of manuscripts to be prepared by Dr. Young and his colleagues.

- ***Participate in group discussions and exchange ideas.***

  Expectations are met by attendance of a weekly meeting in the lab of Dr. Young as well as ongoing interactions with Dr. Young and his colleagues.

- ***Develop team dynamics.***

  Expectations are met by developing a strong working relationship with Dr. Young's postdoctoral scholar, Dr. Brad Chadwell, and students involved in several components of this thesis research. Ongoing interactions and discussions of equipment design, data collection, analysis, and interpretation are critical to the success of this study. Also, the ability to work together to troubleshoot problems reflects successful team dynamics.

- ***Execute project and submit deliverables.***

  Expectations are met by the completion of a working compliant force pole assembly and successful implementation of the device in data collection. Facilitation of a graduate thesis and preparation of scientific manuscripts are the chief goals of the project.

2.4 Product Development Process

Modeled after the design process used commonly in the manufacturing industry, the product development process for this work can be divided into four phases and timeframes with the following tasks:

I. PDP Phase I (September 2012 – November 2012)

For this phase, design specifications were defined and overall concepts were developed. Specific tasks included: discussion of project goals and brainstorming with Dr. Young, planning for types of animals used in the study and data collected, verification of Wheatstone bridge circuitry for strain gauges, and research of three-axis accelerometers for data collection.

II. PDP Phase II (November 2012 – December 2012)

For this phase, a prototype design was created and cost estimates were developed. Specific tasks included: coordination of design tasks with Dr. Chadwell, discussion of budgetary information and cost estimates, ordering final list of remaining parts from various suppliers, and calibration and verification of force pole outputs.

III. PDP Phase III (January 2013 – March 2013)

For this phase, the prototype design was verified and requirements were refined. Specific tasks included: construction of accelerometer circuitry for testing and application, assembly and testing of National Instruments data acquisition equipment and recording hardware, troubleshooting of equipment hardware and software, and training of first set of primates on test equipment.

IV. PDP Phase IV (April 2013 – July 2013)

For this phase, the production design was finalized and released for experimental application. Specific tasks included: testing of force pole assembly as complete unit, programming of data analysis software to synchronize high-speed video and signal data from strain gauges and accelerometers during primate locomotion, collection and filtering of raw data, construction of MATLAB code for data analysis, and production of detailed final report of system design.

2.5 Funding and Material Cost

The overall project budget for this work is $164,200. This budget is separated into four main areas: animal supplies ($38,500), data acquisition devices ($123,200), electrical devices and parts ($1,000), and other supplies ($1,500). Refer to APPENDIX A: SYSTEM IMPLEMENTATION COSTS for a detailed cost breakdown of equipment. The funding for this project is provided by the Department of Anatomy and Neurobiology at NEOMED and NSF grant BCS 1126790.

CHAPTER 3

CONSTRUCTION AND IMPLEMENTATION

3.1 Equipment List

The equipment for this study can be divided into four categories: (1) animal supplies, (2) data acquisition devices, (3) electrical devices and parts, and (4) other supplies. For animal supplies, the equipment includes animals, transport, care, and anesthesia rental. For data acquisition devices, materials include cameras, PCs, NI chassis/modules/terminal blocks, software, strain gauges, and accelerometers. For electrical devices and parts, equipment consists of soldering tools, multimeter, LCR meter, Direct Current (DC) power supply, various wire, D-sub accessories, circuit boards, and resistors. Finally, for other supplies, items include strain gauge epoxy/conditioner/coating, heat gun, heat shrink tubing, clamps, connectors, rods, and beams. Refer to APPENDIX A: SYSTEM IMPLEMENTATION COSTS for a full list of parts, quantities, manufacturers, and model numbers.

3.2 Construction of Force Poles

After reviewing previous protocols on force pole construction, the following improvements are implemented for optimal data collection: (1) test strain gauge values with LCR meter before and after soldering, (2) eliminate "bondable terminals" for wiring connections, (3) solder directly to strain gauge pads, (4) verify applied pressure when curing gauges, and (5) insulate all connections with M-Coat A protective coating.

The initial construction of the force poles had been started in Dr. Young's lab prior to September 2012, according to the following protocol:

I. Use the equations in Biewener [3] to calculate the appropriate thickness of the blade-like elements of the force pole beams needed to measure the range of forces under interest.

II. Typically, aluminum beams are used. However, in this case, steel beams are required to construct small frames appropriate for the desired pole diameters.

III. Mill beams to produce blade-like elements and drill holes in the side to make the beams lighter. In the horizontal beam, place the vertical channel closer to the cover plate (rather than the fore-aft channel) to increase the sensitivity of this channel.

IV. Prepare beams for strain gauge attachment:

    (1) Sand the blade-like elements as smooth as possible using wet Emory 400 grit and then 600 grit sandpaper.

    (2) Clean the blades with alcohol and wooden cotton swabs.

    (3) Clean again with the M-Prep conditioner A, a water-based acidic surface cleaner.

    (4) Clean with M-Prep neutralizer A, a water-based neutralizer.

V. Prepare strain gauges for attachment:

(1) Use Scotch tape to pick up the gauge, with the shiny side of the gauge facing up and the dull side facing down.

(2) Cut strain gauges using a scalpel such that end of wire pads are as close to the end of gauge as possible.

(3) Place strain gauge such that the wires line up with the plane of bending and the ends of wire pads are as close as possible to the edge of the blade-like element.

VI. Prepare the strain gauge epoxy with six parts resin and one part curing agent. Mix epoxy for five minutes and let rest for ten minutes.

VII. Secure the strain gauge to the blade-like element and clamp as shown in Figure 5. An alternative to this setup shown in Figure 6, less gauge slipping occurs for smaller beams with removal of the soft rubber and penny with the gauge secured by custom clamps.

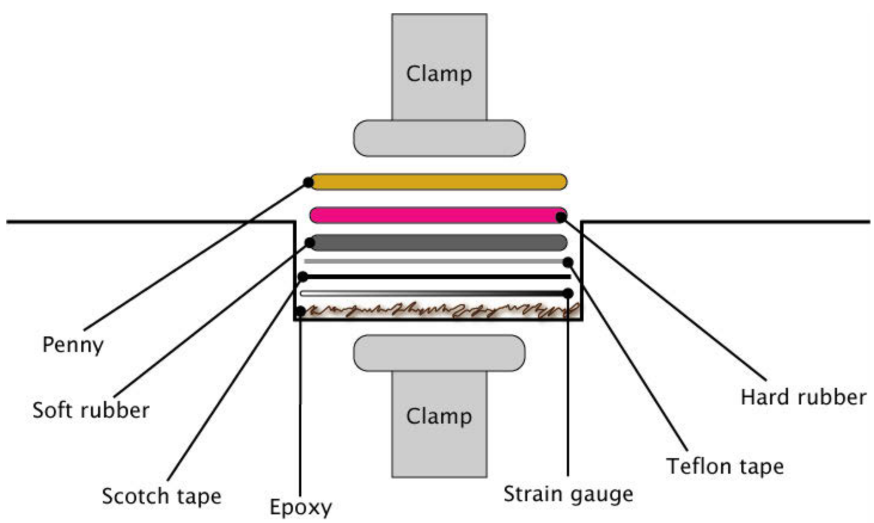

Figure 5: Clamping Setup for Strain Gauge Curing

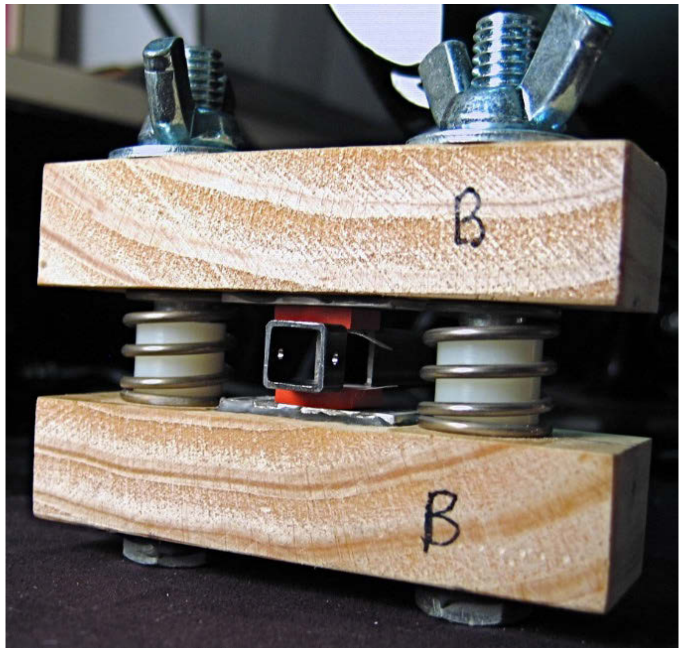

Figure 6: Alternative Clamping Setup for Strain Gauge Curing

VIII. Clamp tightly and bake in a 170°F (76°C) oven for one hour.

IX. Scrape tops of strain gauge soldering pads with a scalpel to make them shiny and ready for soldering.

X. Use rosin paste flux to affix wire and terminal prior to soldering.

XI. After soldering wire leads, test strain gauges for proper resistance and lack of short circuits.

XII. Assemble the force pole using machine screws through pre-drilled holes.

XIII. Grouped by force pole and channel, strain gauge lead wires were placed in heat shrink cable for wire management and organization.

XIV. After assembling each force pole, male and female D-sub connectors were made to allow for ease of equipment setup and troubleshooting. Divided into north and south sections (relative to the orientation of the research laboratory), schematic connection diagrams for each force pole are shown in Figure 7 and Figure 8.

XV. Wheatstone bridge circuitry [10] for strain gauge analysis was constructed according to Figure 9 through Figure 12 for fore-aft, mediolateral, and vertical channels.

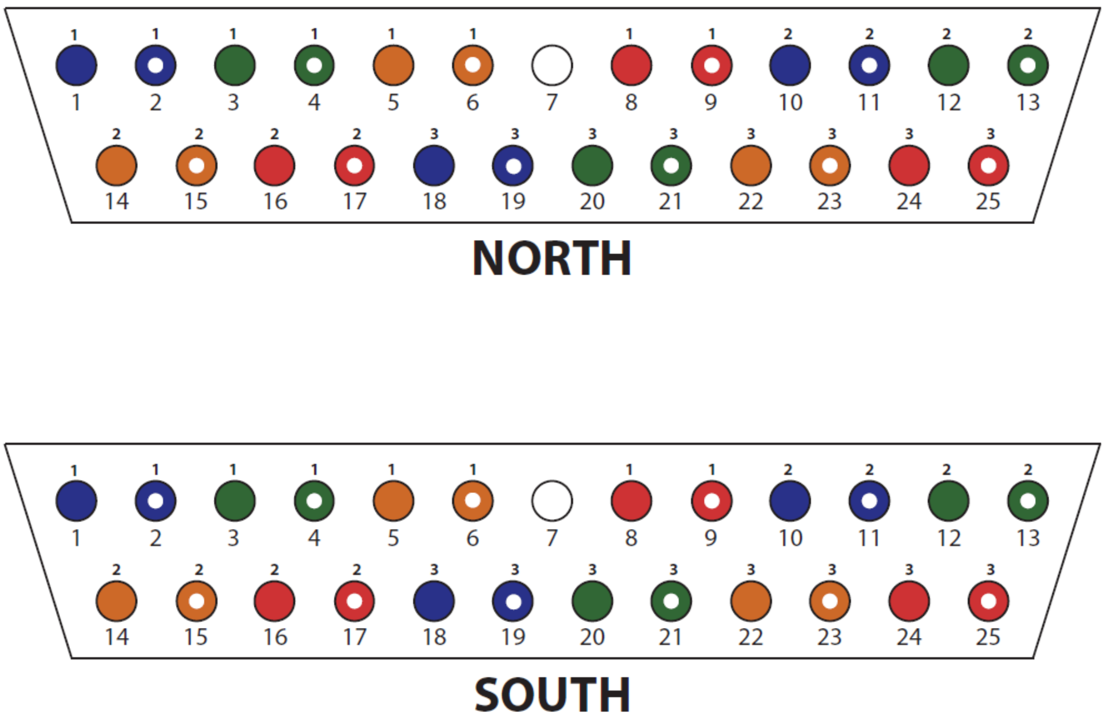

Figure 7: Force Pole D-sub Wiring Diagram - Chassis Side

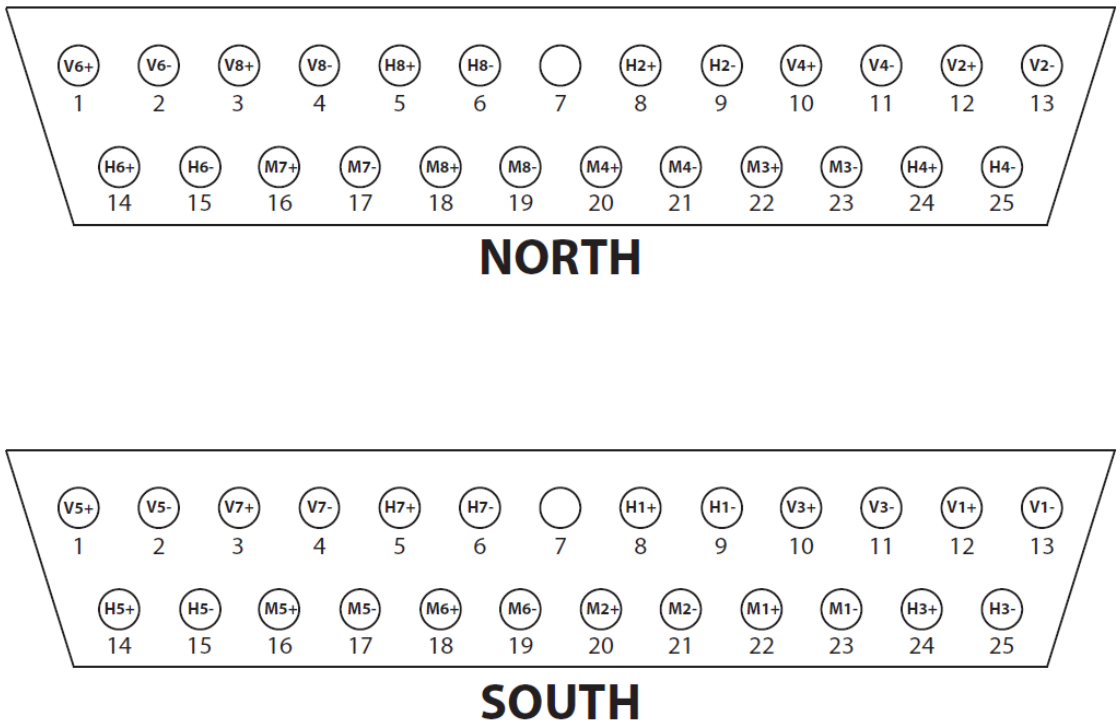

Figure 8: Force Pole D-sub Wiring Diagram - Force Pole Side

As discussed in Chapter 2, Wheatstone bridge circuits are used to measure small changes in resistance of strain gauges arranged as a "full-bridge" circuit. In this type of circuit, gauges are present on all four active arms of the Wheatstone bridge. In Figure 9 through Figure 12, the excitation voltage and output voltage are represented by P± and S±, respectively. In these circuits, strain gauges (or strain gauge pairs) are arranged as two in tension and two in compression. Activating all arms of the Wheatstone, this full-bridge circuit is the most common for utilization in strain measurements. As mentioned previously, the four circuits correspond to one fore-aft (front-back), one mediolateral (left-right), and two vertical (up-down) channels on each force pole. Refer to Figure 9 through Figure 12 for force beam architecture, wiring, and Wheatstone bridge circuitry.

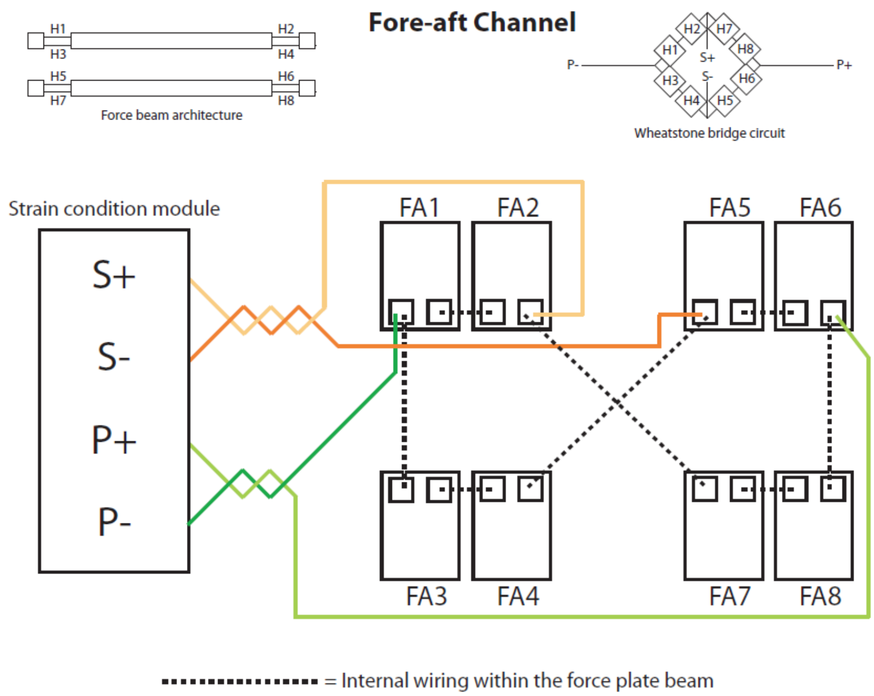

Figure 9: Fore-aft Channel Wheatstone Bridge Circuitry

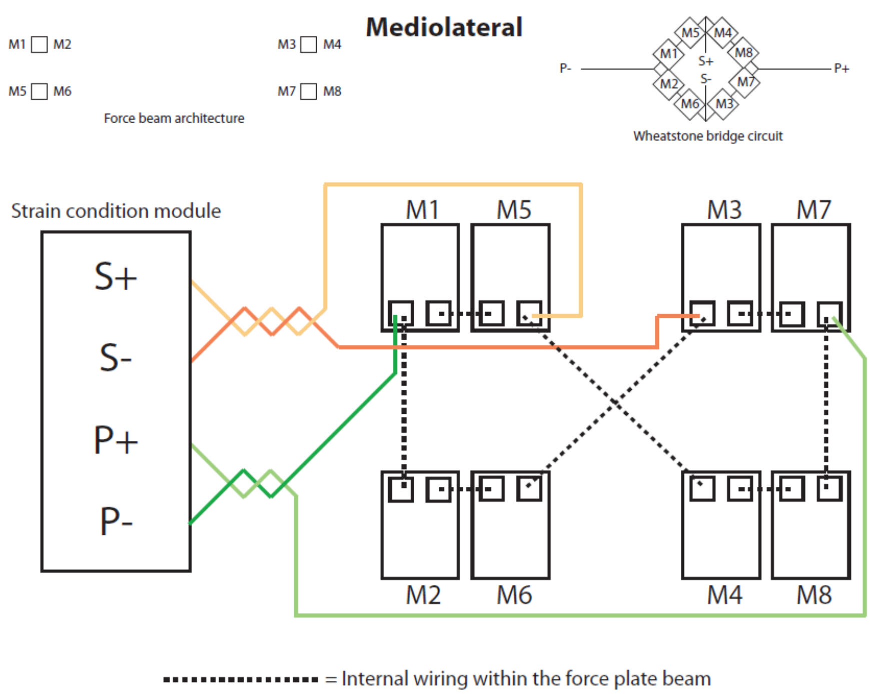

Figure 10: Mediolateral Channel Wheatstone Bridge Circuitry

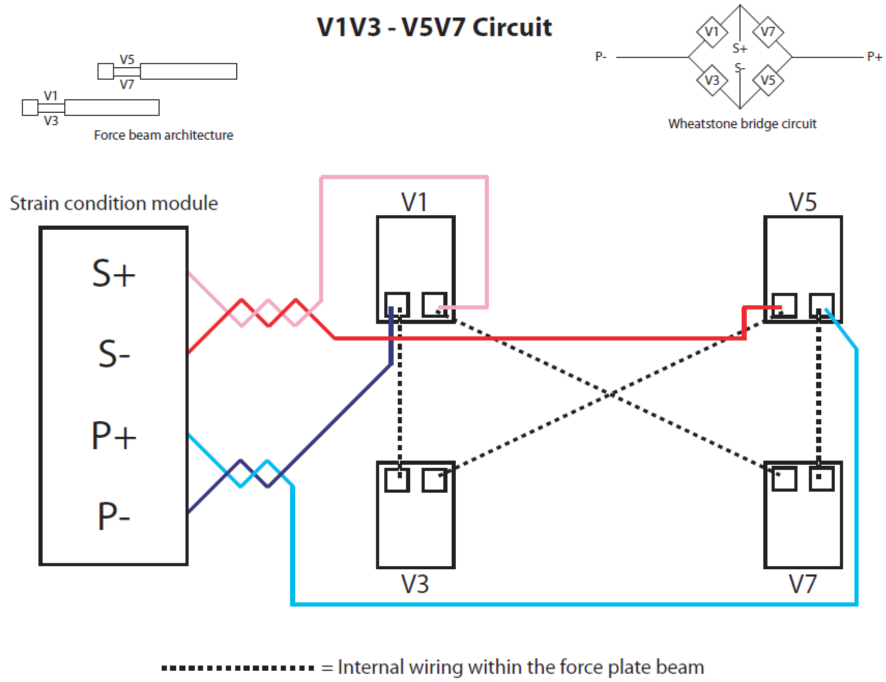

Figure 11: Vertical Channel #1 Wheatstone Bridge Circuitry

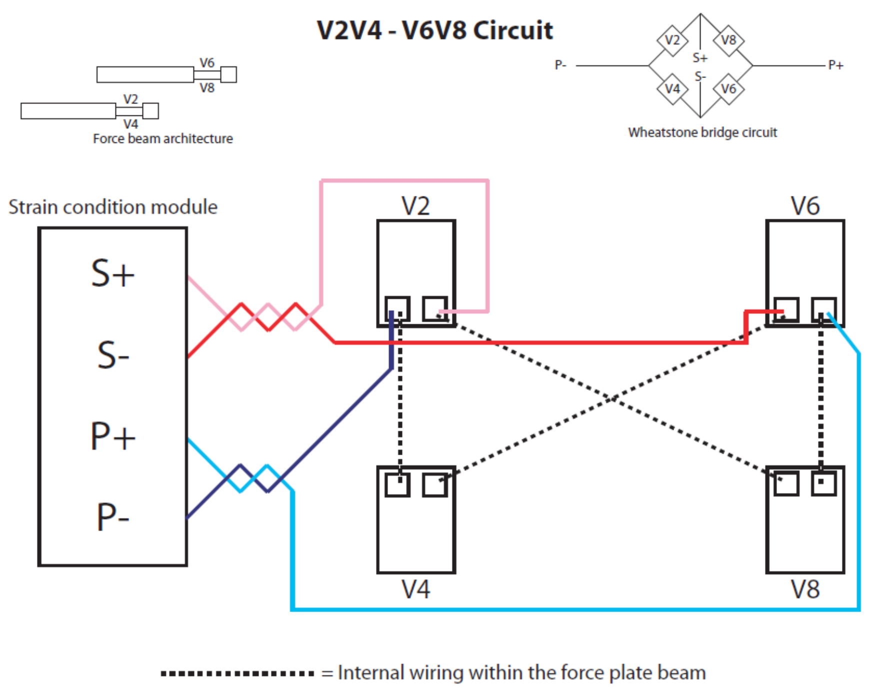

Figure 12: Vertical Channel #2 Wheatstone Bridge Circuitry

Representing the gauge's sensitivity to strain, after constructing force poles, the corrected gauge factor of each strain gauge was calculated [11]. This corrected gauge factor compensates for resistance in the lead wires from the strain gauges and allows for more accurate measurements of resistance. The corrected gauge factor (K_0) for a two-wire (single-element) gauge is calculated using Equation 4.

$$K_0 = \frac{R}{R+rL} K \tag{4}$$

where: R = strain gauge resistance (Ω)

r = total resistance per meter of lead wire (Ω/m)

L = lead wire length (m)

K = indicated gauge factor

Based upon LCR meter measurements and given information from the strain gauge packaging, the experimental values are: R = 350Ω ± 0.3%, r = 0.454Ω/m, L = 0.6604m, and K = 2.150 ± 0.5%. Using these values applied to Equation 4, the corrected gauge factor can be calculated as K_0 = 2.148, which is within the ± 0.5% gauge factor tolerance. Therefore, lead wire resistance has a negligible effect on resistance and strain measurements for this design.

3.3 Construction of Accelerometer System

After evaluating project specifications, the Analog Devices ADXL337Z accelerometer [9] was selected, which requires an external 3V DC Power Supply. After reviewing previous protocols on accelerometer systems, the following steps were taken when constructing the accelerometer array:

I. Using the force of gravity and known specification values, each X-Y-Z channel of five accelerometers was tested and calibrated. Using the measured output voltages and known accelerometer characteristics, linear regression equations of the form $A = m * V + b$ were developed to convert voltages to accelerations, with acceleration (A) in g-force, voltage (V) in volts, linear slope (m), and y-intercept (b). Based upon the gathered data applied to a linear regression model, the average linear equation for conversion of voltages to accelerations is: $A = 3.392 * V - 5.402$. Including a three-axis sensor, amplifiers, demodulator, resistors, and capacitors, the accelerometer block diagram is shown in Figure 13 [9]. Pin connections for the accelerometer chip are shown in Figure 14 [9].

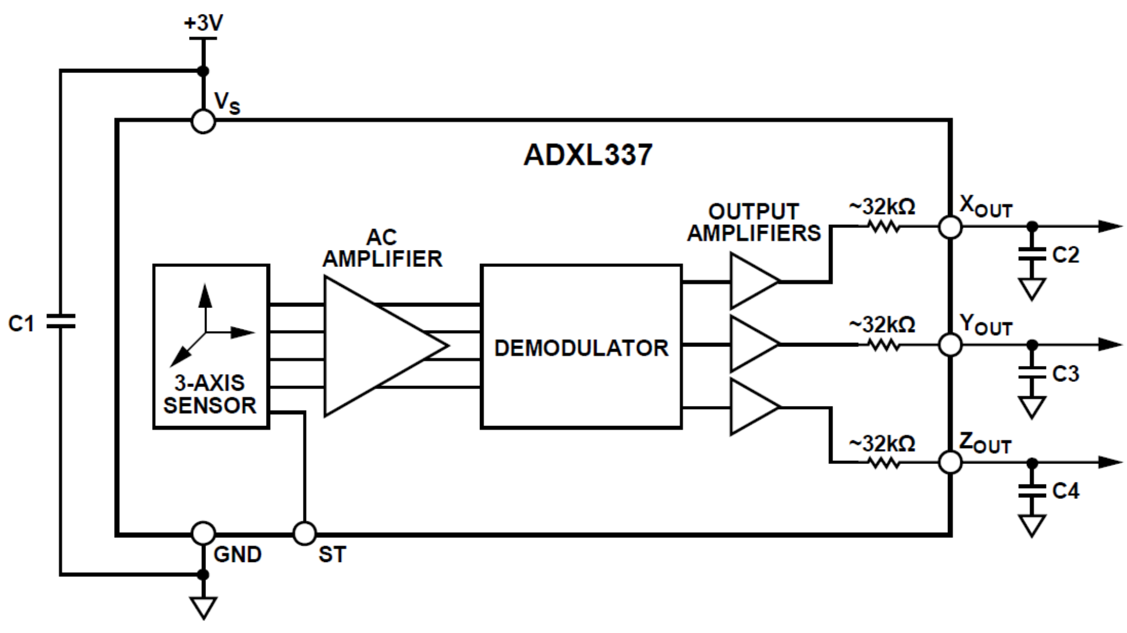

Figure 13: Accelerometer Block Diagram

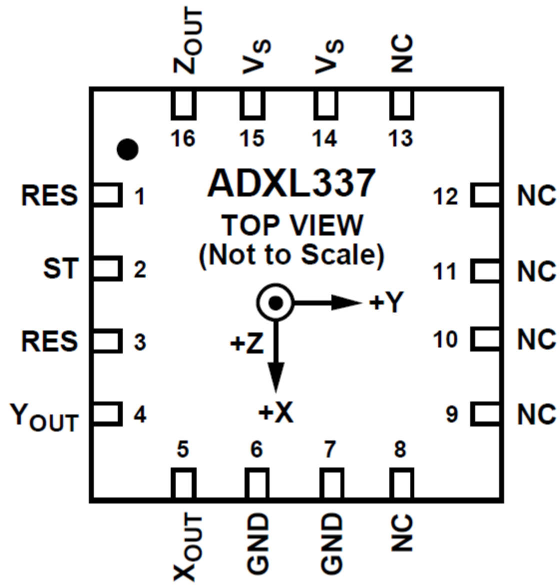

Figure 14: Accelerometer Pin Connections

II. Soldered lead wires for X-Y-Z channels and +/- 3V DC supply for each accelerometer. Accelerometer supply voltages connected in parallel due to low current draw of devices.

(1) Removed insulation from lead wires using wire strippers.

(2) Coated soldered connections in M-Coat A for secure and insulated connections.

III. Grouped lead wires into heat shrink tubing. Used heat gun to shrink heat shrink tubing around cables for easy management and organization.

IV. Soldered +3V supply leads from accelerometers and +3V supply lead from DC power supply together at junction on custom circuit board.

V. Soldered -3V supply leads from accelerometers and -3V supply lead from DC power supply together at junction on custom circuit board.

VI. Soldered 249Ω high-precision bias (pull-down) resistor between –3V supply leads (from accelerometers) and channel grounds (from NI chassis) to eliminate noise and drift in output signals, as shown in Figure 15.

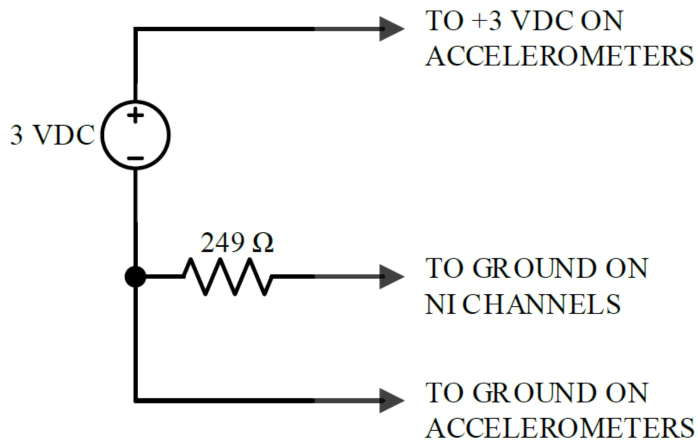

Figure 15: DC Power Supply and Bias Resistor Connections

VII. Connected +/- 3V leads to DC power supply.

VIII. Connected channel negative (common to all channels) to NI chassis with wire jumpers to each channel.

IX. Connected channel positives to each channel on NI chassis.

X. Secured five accelerometers to four corners and center of 1’ x 2’ composite board using bolts, washers, and nuts after using drill press for pilot holes. Accelerometer placement is shown relative to force poles in Figure 16.

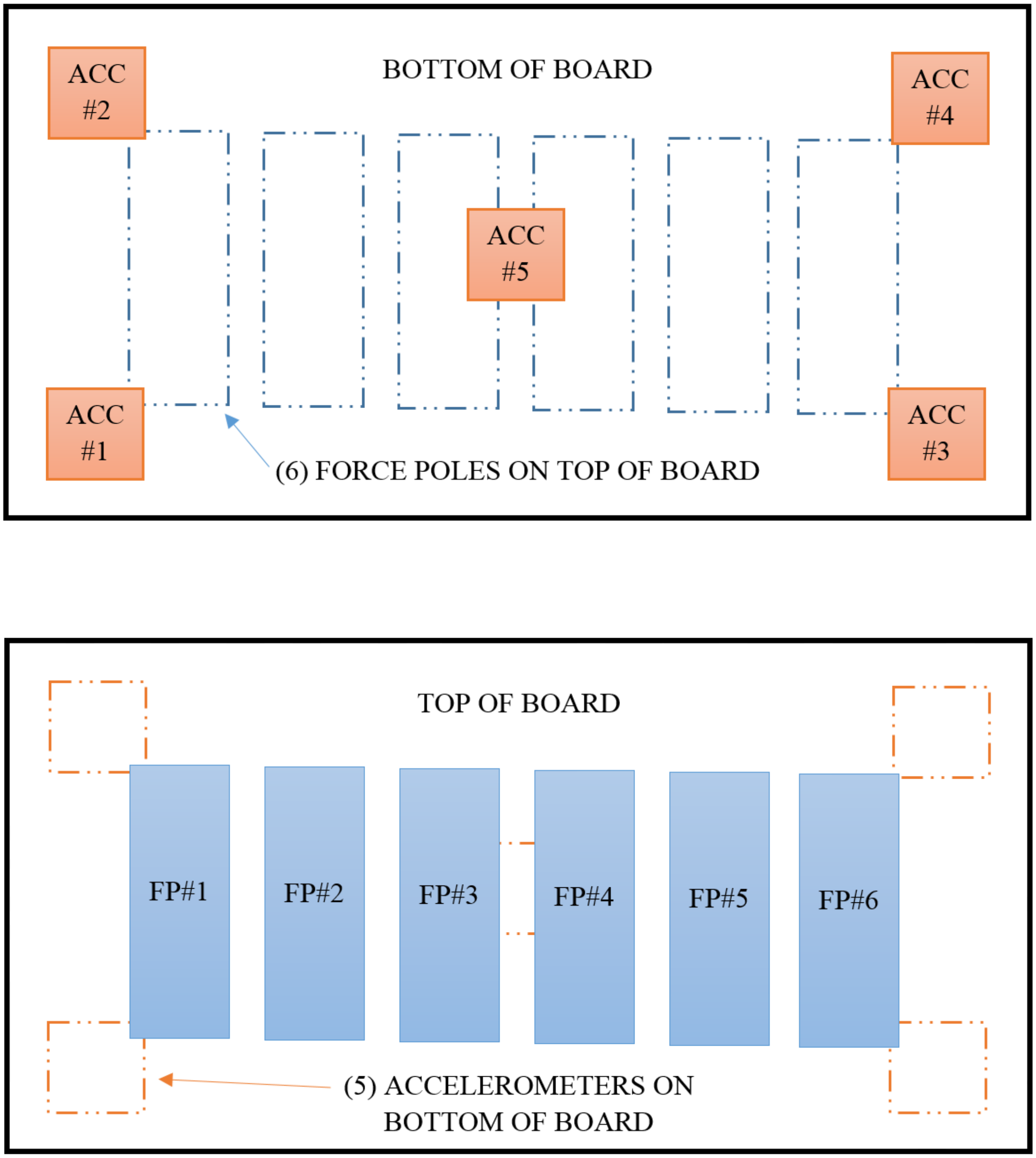

Figure 16: Accelerometer Array Mounting Diagram

XI. After assembling the accelerometer array, male and female D-sub connectors were made to allow for ease of equipment setup and troubleshooting according to diagrams in Figure 17 and Figure 18.

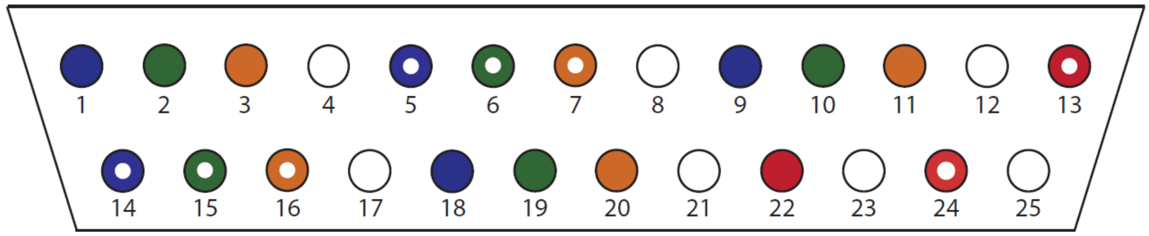

Figure 17: Accelerometer D-sub Wiring Diagram - Chassis Side

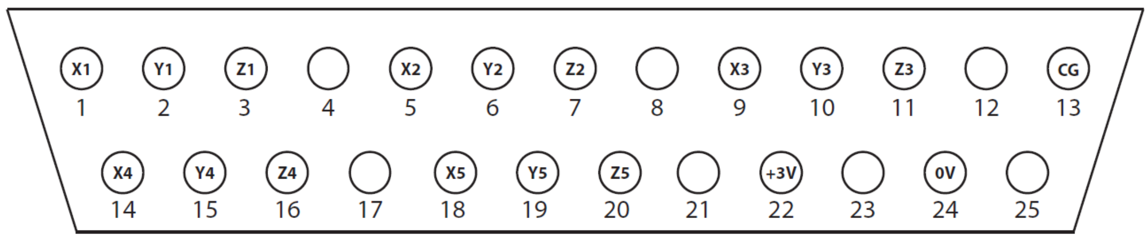

Figure 18: Accelerometer D-sub Wiring Diagram - Accelerometer Side

3.4 Assembly of Data Acquisition Equipment

To gather, process, and store the signals generated by the force poles and accelerometers, a complex data acquisition system is required. Composed primarily of NI equipment, this DAQ system consists of four input modules with terminal blocks housed in a chassis.

To acquire the force pole signals, three strain gauge conditioning modules (NI SCXI-1520,) with three terminal blocks (NI SCXI-1314) are used. To acquire the accelerometer signals, one analog voltage input conditioning module (NI SCXI-1102C) with one terminal block (NI SCXI-1300) is used. These modules contain integral circuitry to condition, filter, and amplify the output signals from the strain gauges, shown in Figure 19 [16], and accelerometers, shown in Figure 20 [18]. This integral circuitry includes amplifiers, lowpass filters, multiplexers, buffers, registers, Electrically Erasable Programmable Read-Only Memories (EEPROMs), switches, and busses.

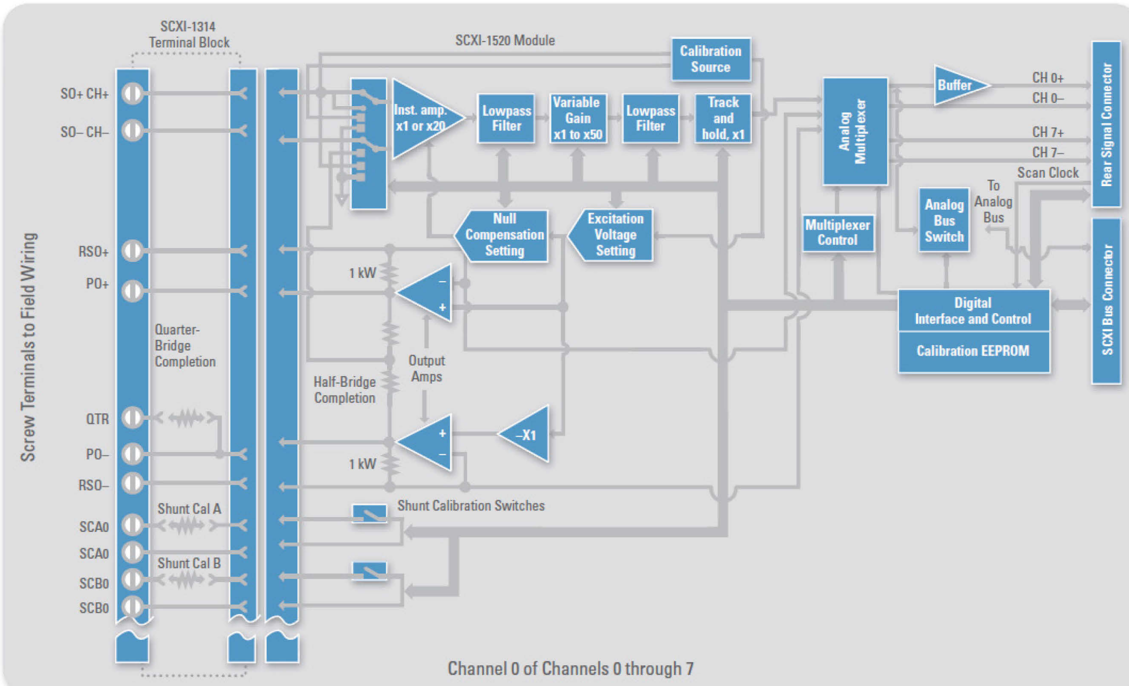

Figure 19: NI SCXI 1520 (Channel 0) Block Diagram

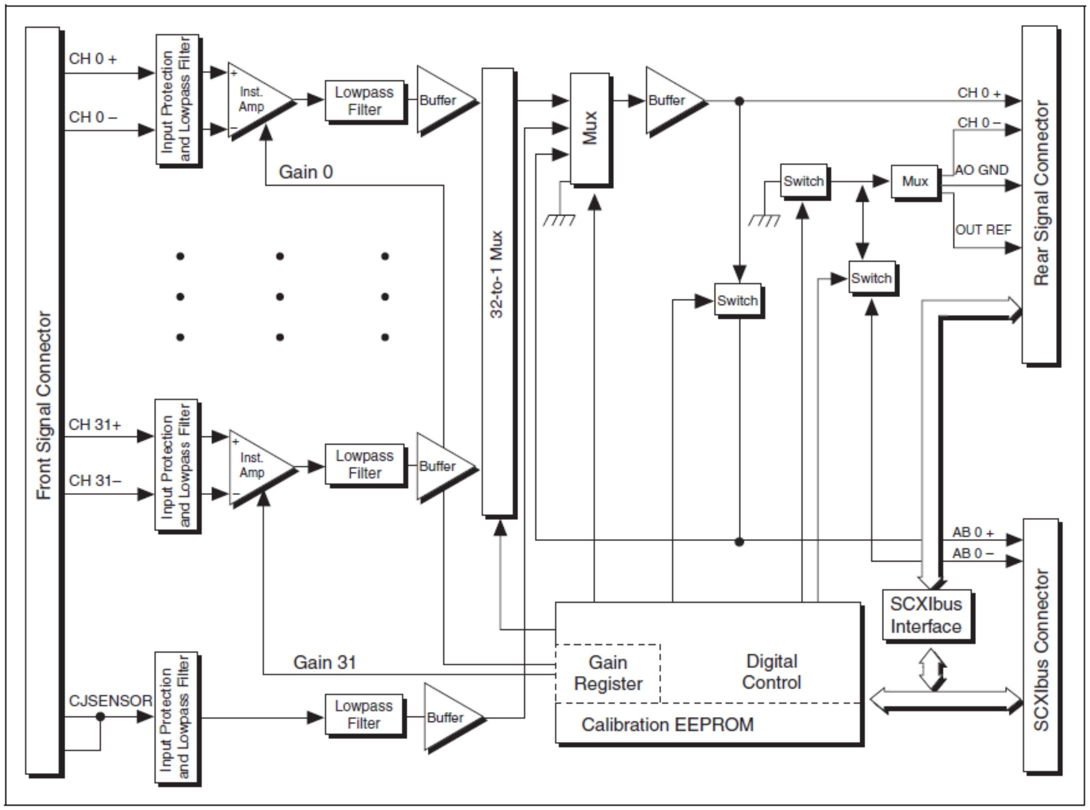

Figure 20: NI SCXI 1102C Block Diagram

Housing each of the conditioning modules, a 12-bay chassis (NI SCXI-1001) with feed-through panel (NI SCXI-1180) facilitates data acquisition of all signals to the recording hardware on a custom server. Connected via proprietary NI cabling and DAQ interface module, the chassis communicates to the server via NI Measurement and Automation Explorer (MAX) software. The final step in the DAQ system, Xcitex ProCapture and ProAnalyst are used to synchronize high-speed video from four Xcitex high-speed video cameras and data signals from the NI chassis. Custom routines in MATLAB are used to facilitate calibration of the high-speed video cameras, permitting animals to be tracked in three-dimensional space during locomotion.

CHAPTER 4

TESTING

4.1 Overview

After assembly of the individual force poles, accelerometers, and DAQ equipment, the entire system is tested and output signals are verified prior to experimental implementation. In the following chapter, the individual testing procedures, improvements, and the full system testing are discussed.

4.2 Individual Component Testing

Before testing the strain and torque measurement capability, the resistance of individual strain gauges and each Wheatstone bridge circuit was verified using a multimeter. After confirming proper electrical behavior, the strain measurement capability of the force pole channels was tested by applying a series of known weights to each of the three axes: vertical, mediolateral, and fore-aft. Using the video cameras to confirm the placement of each weight, strain is extracted from the data output for the applicable axes of each force pole. From this information, a linear regression is performed between the weights and their respective strain. This regression results in a linear slope and y-intercept along with r^2 value of the correlation. If the r^2 value is 0.99 or above, then the strain data represents a desirable fit. Then, using this linear regression, the experimental strain data is converted into forces.

To verify torque measurement, a known weight is placed at different distances from the long axis of the force pole to generate torque about the axis. This known torque and the resulting ratio of north vertical strain to the sum of north and south vertical strain is used to generate a linear regression to calculate torque from the experimental output. After torque verification, each force pole channel was tested for "cross-talk" or the amount of interference between channels. Under ideal circumstances, no cross-talk occurs and noise is eliminated in resulting output voltages. Minor levels of cross-talk can be eliminated in MATLAB during data analysis. As the final force pole verification test, resonant frequency behavior was analyzed by tapping the appropriate side of the supports for each channel. A power spectrum analysis of the resulting waveform characterizes the peak resonant frequency of the force pole system. A resonant frequency at least one order of magnitude greater than the stride frequency of the animals being studied is desirable [3].

After confirming force pole operation, individual accelerometer operation was verified using the linear equations (previously developed in Section 3.3 Construction of Accelerometer System) along with the force of gravity applied to each of the three axes. Shown in Figure 21, the accelerometer output response for each axis is given relative to the force of gravity for various orientations [9]. Using this information, output voltages were gathered using a multimeter and compared to given specifications.

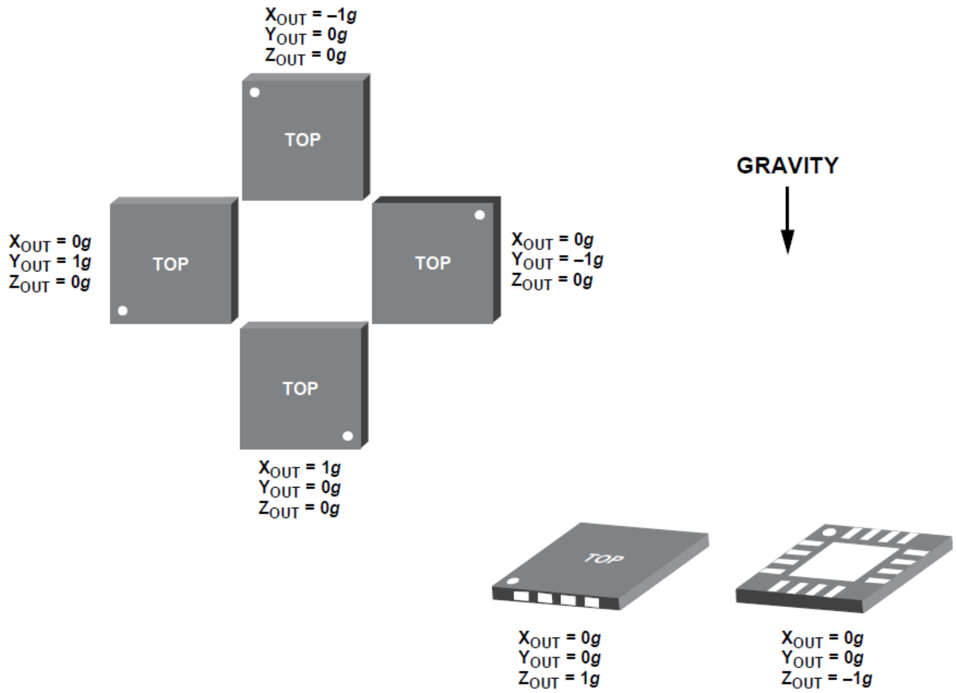

Figure 21: Accelerometer Output Response vs. Force of Gravity

Once assembled as an array, simultaneous signal generation of the accelerometer system was also tested using the linear equations to convert output voltages into accelerations. As a final method of verification, the overall operation of the accelerometer array was tested by moving the system through various patterns along the three axes while captured by the video cameras. Patterns included movements of left/right, up/down, forward/backward, rotation left/right, and rotation forward/backward. Accelerations from the accelerometers and video cameras were compared to confirm proper data collection.

Finally, after testing force poles and the accelerometer array, the DAQ equipment was analyzed. While connected to the server, the NI modules for strain gauge and analog voltage measurement were inserted into the chassis. Using NI MAX software, each component was tested using the "test panel" interface before connecting to the data signals. Overall, the data system behaved appropriately when acquiring force pole and accelerometer signals from virtual channels in MAX. Full-scale system testing will be discussed in Section 4.4 Full System Testing.

4.3 Improvements

Throughout the process of construction and individual component verification, various issues developed that required immediate resolution, either through minor corrections or major revisions in procedure and design. The troubleshooting process related to assembling system components improved the overall validity of collected data and enabled a more robust design approach.

For the force poles, during the initial construction, short-circuits and open-circuits in equipment lead wires were discovered. After wiring corrections, some issues developed while testing the force poles with the data acquisition system. These issues were attributed to incorrect settings on MAX. Finally, individual channels were not behaving correctly. These errors were corrected by fixing a short circuit and adjusting excess strain exhibited by the connecting hardware securing the steel force pole beams.

For the accelerometer array, most issues were associated with unreliable prototype DC power supplies. The first power supply (+3V DC, Acopian Model 3EB50) did not output a steady ground signal and carried such noise into all accelerometer channels. The second power supply (powered breadboard, Sun Equipment Model PBB 4060B) was deemed defective due to an incorrectly-sized protective fuse. Since both of these power supplies were purchased under previous research endeavors, a new variable DC power supply (RSR Model HY1803D) was acquired to power the accelerometers without adverse effects on the project budget. The final DC power supply behaved as desired. After addressing DC power supply issues, fluctuations in accelerometer negative (ground) channels was addressed by using a NI 249Ω bias resistor. Placed between DC power supply negative terminal and negative accelerometer channels on NI chassis, the resistor pulled down the reference negative channels to a true "zero" voltage. Since the force of gravity is constantly measured, the array's central accelerometer was modeled as a fulcrum to accurately subtract the static gravitational acceleration from each accelerometer channel.

For the data acquisition equipment, the main problem was associated with data synchronization from force poles, accelerometers, and video cameras. After weeks of reviewing equipment connections, software settings, and research protocol, the cause of synchronization issues was attributed to software miscommunication between hardware components. A common occurrence when assembling equipment from different manufacturers, proprietary drivers and protocols were causing delays in signal generation and propagation that rendered collected data unusable. Therefore, after reviewing design requirements with NI and Xcitex engineers, a solution was developed by creating custom software versions of ProAnalyst and ProCapture configured specifically for this research.

4.4 Full System Testing

After verifying individual components and troubleshooting various issues, full-scale system testing was performed. First, the NI chassis and modules were assembled. Second, north and south connections from six force poles were appropriately connected to the strain gauge modules. Third, connections from the accelerometer array were made to the analog voltage input module and DC power supply. Finally, four high-speed video cameras were connected to the server via Ethernet cables. Once assembled, all systems components were powered on and checked for final issues. Using the server, twenty-four signals from force poles, fifteen signals from accelerometers, and four streams from high-speed video cameras were successfully acquired, synchronized, and saved during several trials. Therefore, full-scale system testing verifies desired operation of all equipment involved in this research.

4.5 Arboreal Stability Application

Designed to be utilized for biomechanics exploration, the custom force pole assembly designed and tested in this research is utilized as an integral part of an ongoing primate arboreal stability study (NSF grant BCS 1126790) performed by Dr. Young of NEOMED. Specific methodology regarding animals, protocol, data analysis, and results of Dr. Young's study are not detailed as part of this work. All necessary animal protocol approval has been obtained through the Institutional Animal Care and Use Committee (IACUC) at NEOMED. YSU holds no requirements with respect to the animal application of this research; the sole focus of the work is on electrical engineering principles and design. Refer to APPENDIX C: ANIMAL RESEARCH APPROVAL for NEOMED IACUC approval documentation. To date, the custom force pole assembly has been used to gather locomotor kinetics of common marmosets (*Callithrix jacchus*) moving over static force poles. A demonstration of the data acquisition window user interface (UI) during animal testing is shown in Figure 22. Quantifying rolling torque (newton centimeter, Ncm), mediolateral force (newton, N), fore-aft force (N), and vertical force (N), graphs of force pole traces recorded by the DAQ system are shown in Figure 23. Force poles traces (FPI through FP6) are measured versus time (sec) corresponding to primate locomotion events of left forelimb touchdown (Lt FL TD), left hindlimb touchdown (Lt HL TD), right forelimb touchdown (Rt FL TD), and right hindlimb touchdown (Rt HL TD). A similar trace technique is be used to correlate accelerometer outputs to primate locomotion events. In future experimental trials with this adapted UI and trace technique, the locomotor kinetics of squirrel monkeys (*Saimiri boliviensis*), long-tailed macaques (*Macaca fascicularis*), and pig-tailed macaques (*Macaca nemestrina*) will also be examined on both static force poles and force poles mounted on a compliant base to simulate branch mobility.

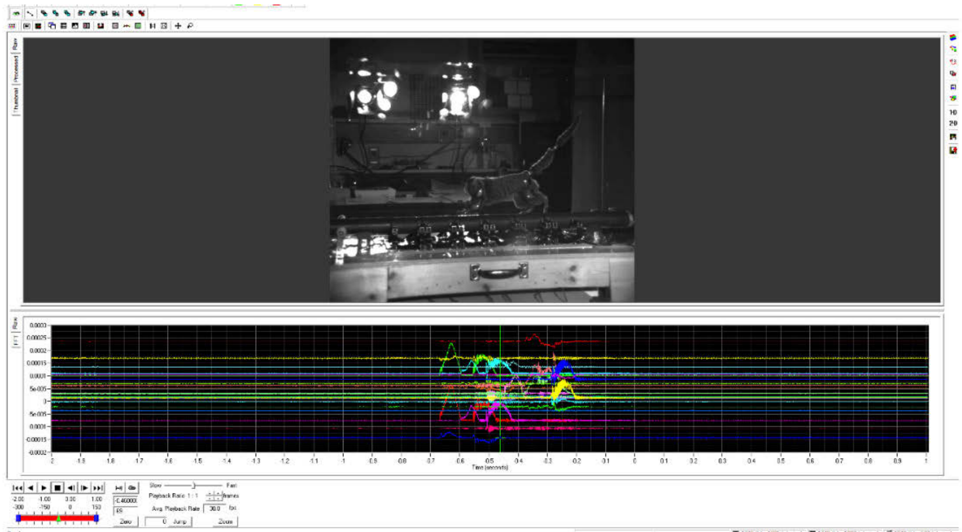

Figure 22: Demonstration of Data Acquisition Window

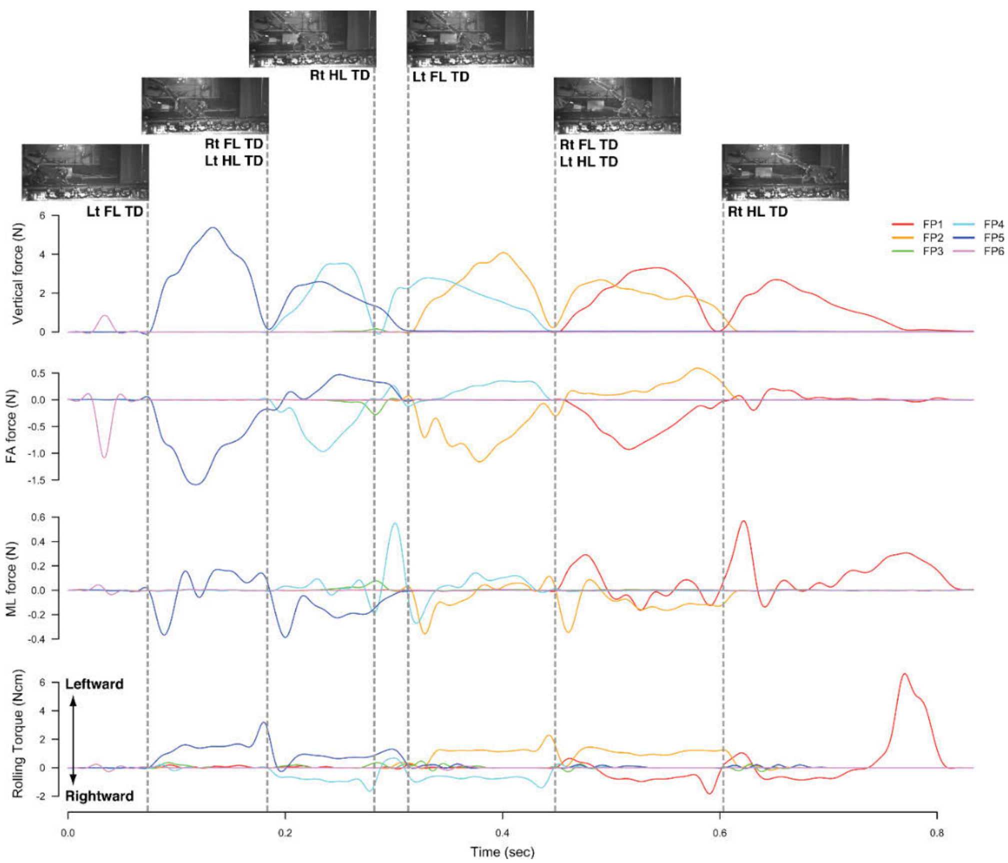

Figure 23: Graphs of Force Pole Traces

CHAPTER 5

CONCLUSION

5.1 Applications in Other Areas

In addition to the current arboreal stability study in the Young Laboratory at NEOMED, the system developed in this work may also be used in impaired mobility studies. A primary focus of quality of life assessments, loss of mobility affects a large segment of the elderly population in the United States. According to a National Health Interview Survey on Disability, approximately 14% of elderly people (aged 65 and over) use at least one type of mobility device (wheelchair, scooter, cane, walker, etc.) due to impaired movement [12]. Thus, studies regarding movement and balance across many age groups have the power to improve quality of life in older individuals. Using a proactive approach rather than a reactive solution, results from these studies could even produce an overall reduction in healthcare costs. Therefore, along with using data from current research in the Young Laboratory, researchers can acquire data regarding human balance and movement using the equipment designed in this study, scaled accordingly.

Along with primate arboreal stability and impaired mobility, the custom force pole assembly designed in this work can be utilized to investigate arboreal adaptation in other species. In particular, non-primates, such as squirrels and chameleons, can be evaluated using almost identical DAQ equipment, force poles, and accelerometers. The scalability of the designed equipment allows for gathering of locomotor kinetics in various animals that exhibit similar movement habits. Therefore, this system can be used to examine almost any animal that moves through static or dynamic environments.

5.2 Conclusion

This work represents a novel design for a custom force transducer assembly to measure primate locomotor kinetics. The design features strain gauges, accelerometers, and high-speed video cameras synchronized by NI DAQ equipment and stored on a custom Xcitex server.

To gather forces and torques, one of the primary objectives of the design was to design and construct Wheatstone bridge circuitry for strain gauge measurements. After assembly, strain gauge circuits were assembled as force transducers and calibrated using proven techniques. To measure relative acceleration and movement, the second design objective was to construct an accelerometer array to independently measure force pole movement during animal locomotion on a compliant substrate. A complete system was constructed using commercially-available components; the design implemented all the functionality of the specifications and proved viable for experimental applications.

Designed for the requirements of NSF grant BCS 1126790, the design presented in this work is used to gather data regarding locomotor kinetics in common marmosets on static substrates. After proving the accuracy and feasibility of acquired data, the instrumented system can be used to gather kinetics of common marmosets on compliant substrates. Finally, a modified version of the system can be applied to squirrel monkeys, long-tailed macaques, and pig-tailed macaques moving on static and compliant substrates to simulate branch mobility.

In summary, a force pole transducer assembly with accelerometers and high-speed video was designed, constructed, and proven feasible. The design surpasses other similar testing structures through the use of accelerometers to independently measure relative movement and acceleration on compliant substrates. Most importantly, the system allows for adaptation and scalability required for application in other species and research areas.

5.3 Future Work

The custom force pole design detailed in this work is fully operational and meets all desired specifications. The system will continue to be used to investigate arboreal stability in primates, as detailed previously. With slight modifications, the system will be utilized in future studies with the runway oriented at various angles to document balance and movement parameters of non-level locomotion.

Improvements can be made to fully demonstrate the adaptability of the system for other applications. Modifications can be made to wiring and interconnections to enable easier data acquisition. Specifically, all wire leads can be lengthened to facilitate better location of DAQ equipment. Also, custom printed circuit boards can be utilized for Wheatstone bridge circuitry in lieu of soldered connections to generic breadboards. This will guarantee accuracy and longevity of component interconnections and wiring.

Although utilized to fulfill a specific design requirement, the MEMS-based accelerometers used in the design measure both the constant acceleration due to gravity and dynamic acceleration due to movement. Another modification is proposed to utilize accelerometers with digital outputs that measure dynamic acceleration only. This will eliminate the central “fulcrum” accelerometer needed to adjust for the static force of gravity. Also, use of rechargeable battery packs in lieu of the DC power supply can be explored to provide the 3V necessary for accelerometer operation. These alterations reduce overall equipment requirements and system complexity while enabling for a more mobile platform of data acquisition.

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APPENDICES

APPENDIX A

SYSTEM IMPLEMENTATION COSTS

With an overall project budget of $164,200, the cost implementation was presented for animal supplies, data acquisition equipment, electrical devices and parts, and other supplies. Table 1, Table 2, Table 3, and Table 4 catalog parts, quantities, and prices used to calculate the cost of implementation for the various project divisions.

Table 1: Implementation Costs for Animal Supplies

Description	Model Number	Quantity	Total Price
Animals	N/A	As Required (AR)	$13,600.00
Animal Transport	N/A	AR	$6,000.00
Animal Care	N/A	AR	$15,500.00
Anesthesia Rental	N/A	AR	$3,400.00
TOTAL			**$38,500.00**

Table 2: Implementation Costs for Data Acquisition Equipment

Description	Model Number	Quantity	Total Price
High-speed Video Cameras	Xcitex MV1-D1312-C030-240-CL-8 [*13*]	4	$60,000.00
Video Server and Monitor	Xcitex (Custom), Samsung 22”	1	$45,185.00
Data Analysis Computer and Dual Monitors	Dell Vostro 420, (2) Samsung 22”	1	(previously purchased for lab use)
Data Acquisition Chassis (12-Bay)	National Instruments NI SCXI-1001 [*14*]	1	$2,175.00
Data Acquisition Feed-through Panel	National Instruments NI SCXI-1180 [*15*]	1	$159.00
Strain Gauge Conditioning Modules	National Instruments NI SCXI-1520 [*16*]	3	$9,525.00
Strain Gauge Terminal Blocks	National Instruments NI SCXI-1314 [*17*]	3	$1,320.00
Accelerometer (Voltage) Conditioning Module	National Instruments NI SCXI-1102C [*18*]	1	$1,770.00
Accelerometer (Voltage) Terminal Block	National Instruments NI SCXI-1300 [*19*]	1	$261.00
Motion Analysis Software	Xcitex ProAnalyst [*20*]	1	(included above)
Data/Video Synchronization Software	Xcitex ProCapture [*21*]	1	(included above)
Data Analysis Software	MATLAB [*22*]	1	$750.00
Strain Gauges	Micro-Measurements Precision Sensors CEA-06-062UW-350 [*23*]	144	$1,400.00
Accelerometers	Analog Devices EVAL-ADXL337Z [9]	5	$150.00
Miscellaneous	N/A (Estimate)	AR	$505.00
TOTAL			**$123,200.00**

Table 3: Implementation Costs for Electrical Devices and Parts

Description	**Model Number**	**Quantity**	**Total Price**
Soldering Station	Weller WES51 [*24*]	1	$150.00
Rosin-core Silver Solder (62/36/2 0.022" diameter)	RadioShack Model 64-013 [*25*]	1	$20.00
Non-spill Rosin Soldering Paste Flux	RadioShack Model 64-022 [*26*]	1	$10.00
Digital Multimeter	Commercial Electric HDM350 [*27*]	1	$20.00
LCR Meter	Agilent Technologies U1733C [*28*]	1	N/A
Variable DC Power Supply	RSR Model HY1803D [*29*]	1	$80.00
Insulated Wrapping Wire (#30 AWG)	RadioShack Models 278-501 (red), 278-502 (white), 278-503 (blue) [*30*]	AR	$50.00
Solid Core Insulated Copper Wire (#24 AWG)	Philcap Electronics Cat5e Cable [*31*]	AR	$150.00
25-pin Male D-sub Connector	RadioShack Model 276-1547 [*32*]	13	$35.00
25-pin Female D-sub Connector	RadioShack Model 276-1548 [*33*]	13	$35.00
25-pin Metalized D-sub Connector Hood	RadioShack Model 276-1536 [*34*]	26	$110.00
Multipurpose Printed Circuit Board	RadioShack Model 276-150 [*35*]	7	$20.00
High-precision Resistor (249 Ω)	National Instruments SCXI Process Current Resistor Kit [*36*]	1 package	$25.00
Miscellaneous	N/A (Estimate)	AR	$295.00
TOTAL			**$1,000.00**

Table 4: Implementation Costs for Other Supplies

Description	Model Number	Quantity	Total Price
Bonding Epoxy	Vishay Micro-Measurements M-Bond AE-10 [*37*]	1 bottle	$110.00
Protective Coating	Vishay Micro-Measurements M-Coat A [*38*]	1 bottle	$15.00
Water-based Acidic Surface Cleaner	Vishay Micro-Measurements M-Prep Conditioner A [*39*]	1 bottle	$25.00
Water-based Neutralizer	Vishay Micro-Measurements M-Prep Neutralizer A [*40*]	1 bottle	$25.00
Heat Gun	RadioShack Model HG-300D [*41*]	1	$25.00
Clamps (Various Sizes)	N/A	AR	$50.00
Thin Wall Heat Shrink Tubing (Polyolefin, Various Diameters)	NTE Electronics (Various) [*42*]	AR	$50.00
Washers, Nuts, Bolts	N/A	AR	$50.00
Dowel Rods (Various Diameters)	N/A	AR	$50.00
Force Pole Steel Beams	McMaster-Carr (Custom) [*43*]	AR	$500.00
Miscellaneous	N/A (Estimate)	AR	$600.00
TOTAL			**$1,500.00**

APPENDIX B

PHOTOGRAPHS OF FINAL DESIGN

Reflecting the complexity of the overall design, detailed photographs of the final system components are shown in Figure 24 through Figure 31.

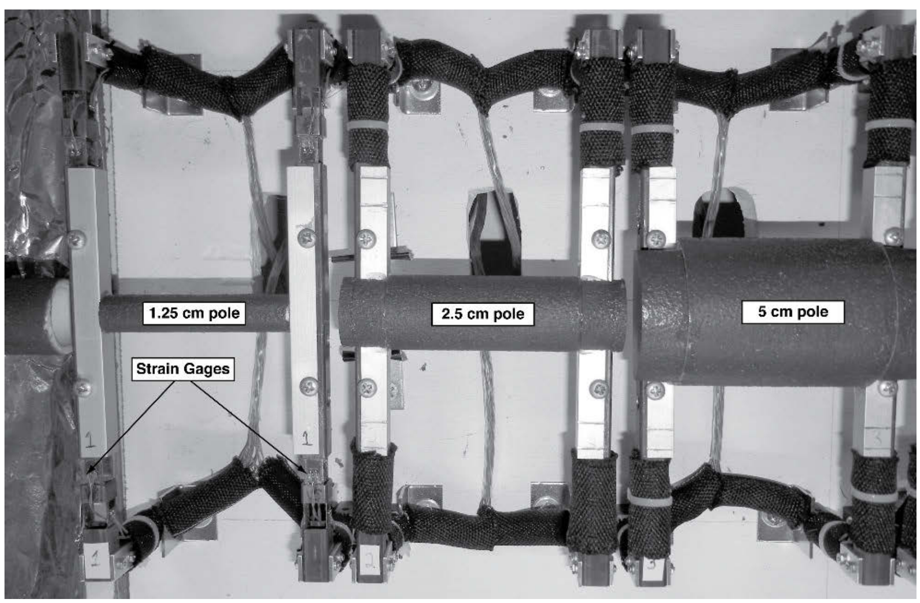

Figure 24: Force Poles of Varying Diameters on Custom Runway

Figure 25: D-sub Connectors for Force Pole Outputs to NI Chassis

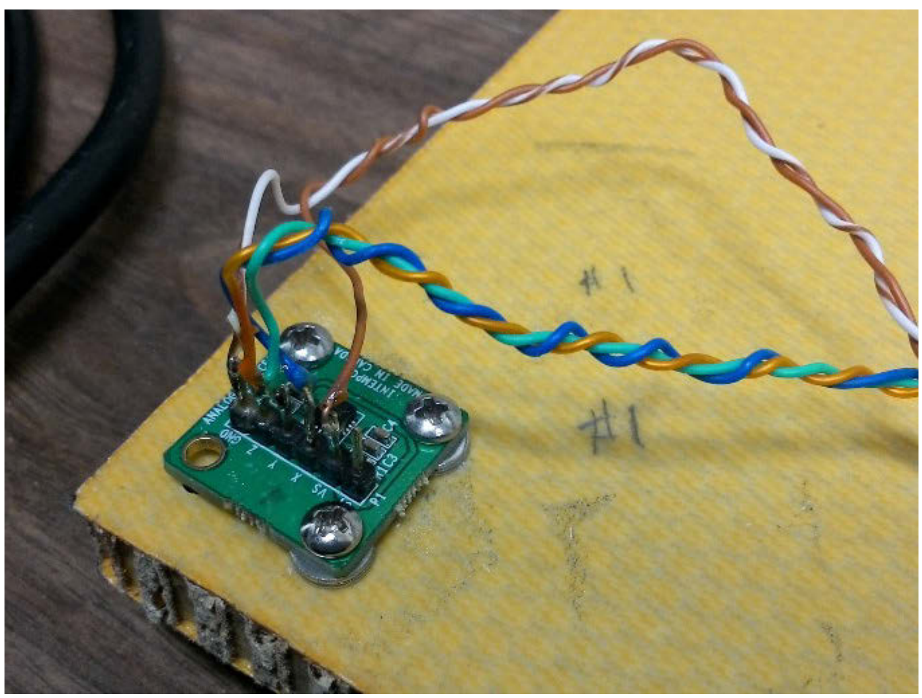

Figure 26: Accelerometer Module and Lead Wires

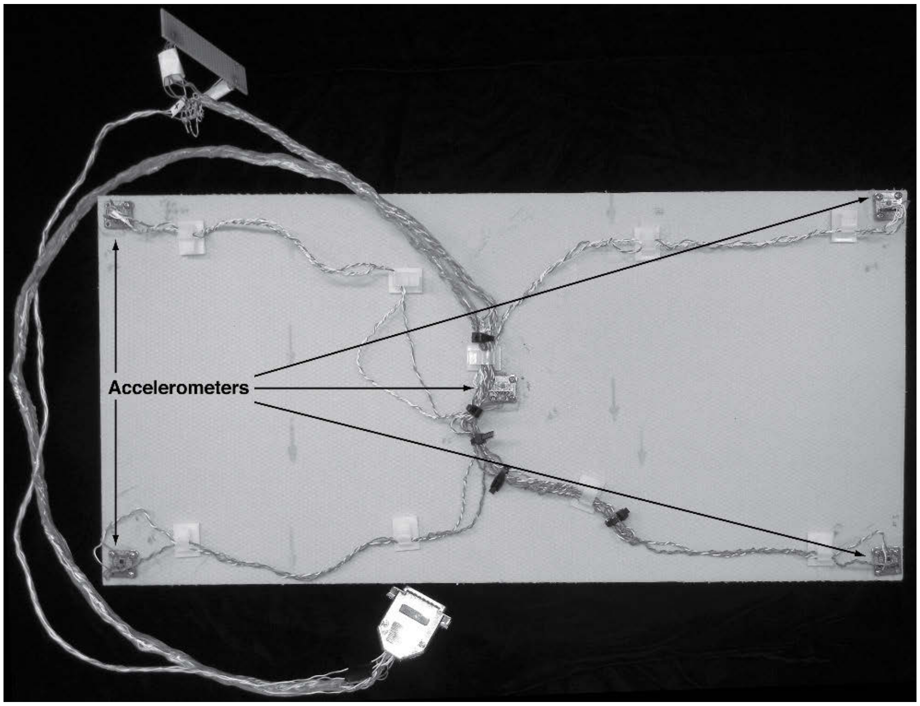

Figure 27: Accelerometer Array Mounting and Wiring

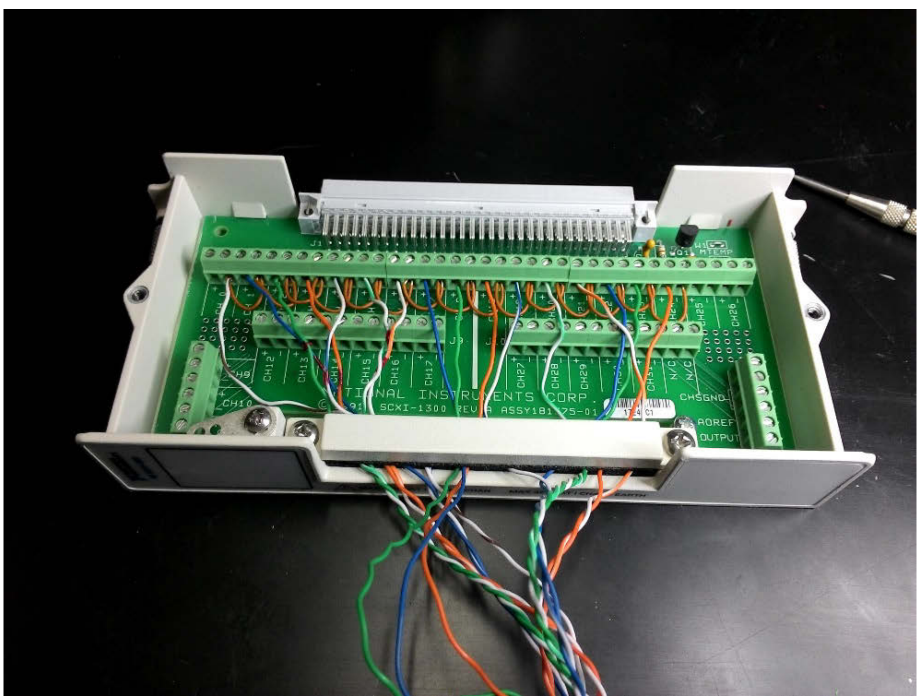

Figure 28: Connection of Accelerometer Channels to NI Terminal Block

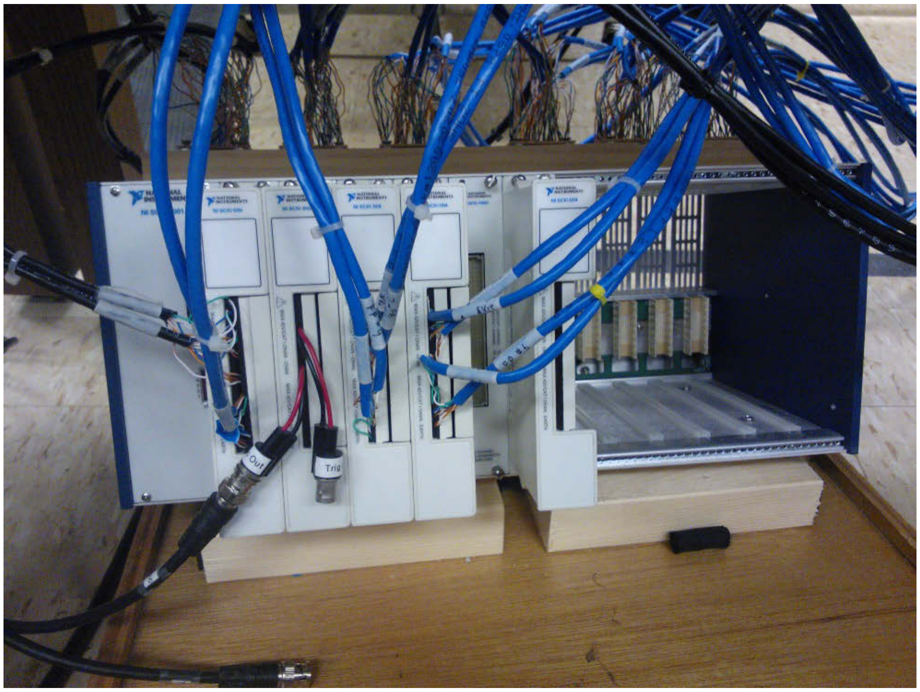

Figure 29: NI DAQ Chassis with Strain Gauge and Accelerometer Modules

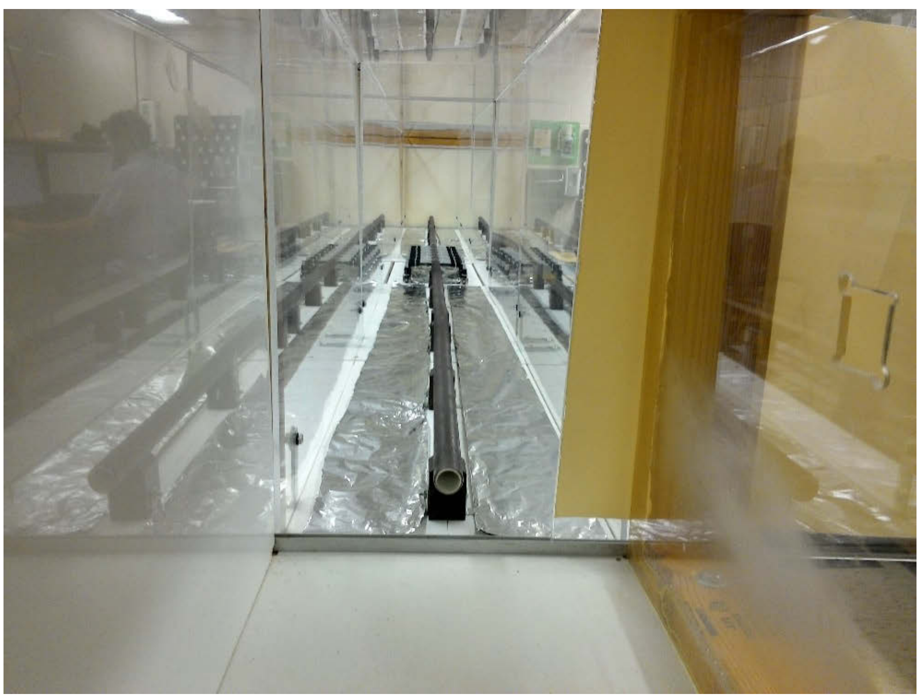

Figure 30: Primate Perspective of Custom Instrumented Runway

Figure 31: Xcitex High-speed Video Camera

APPENDIX C

ANIMAL RESEARCH APPROVAL

As discussed in Section 4.5 Arboreal Stability Application, the Young Laboratory headed by Dr. Young performed all animal research and experimentation according to established guidelines. Shown in Figure 32, prior authorization to perform animal research was obtained and granted by the NEOMED IACUC for Young's NSF grant BCS 1126790.

Northeast Ohio
MEDICAL UNIVERSITY

Institutional Animal Care and Use Committee (IACUC)

MEMORANDUM

TO: Jesse W. Young, Ph.D.
Assistant Professor, Anatomy & Neurobiology

FROM: Erin L. Bailey, Ph.D. EB 8/21/12
Acting Chairperson, NEOMED Institutional Animal
Care and Use Committee

SUBJECT: Protocol Approval

DATE: August 21, 2012

The following Northeast Ohio Medical University (NEOMED) animal use protocol was reviewed and approved by this Institution's Animal Care and Use Committee (IACUC) on August 21, 2012. The protocol is approved for a three (3) year period of time; however, you must submit an annual renewal to the IACUC each year for review.

Any serious or adverse events regarding the use of animals approved in this study must be reported immediately to the IACUC Chairperson or the Attending Veterinarian. Protocols involving the use of human tissues require Institutional Review Board (IRB) approval.

NEOMED Protocol No.:	**#12-018**
Title of Proposal:	**Integrative Analyses of Primate Quadrupedal Locomotion**
Type of Vertebrate:	**Common Marmosets; Squirrel Monkeys; Long-Tailed Macaques; Short-Tailed Macaques**
Funding Agency(ies):	**National Science Foundation**
Protocol Expiration Date:	**August 20, 2015**

This institution has an Animal Welfare Assurance on file with the Office of Laboratory Animal Welfare (OLAW). The Assurance number is A3474-01. This institution is also registered with the United States Department of Agriculture (USDA). The USDA registration number is 31-R-0092.

The Comparative Medicine Unit (CMU) at the Northeast Ohio Medical University (NEOMED) has been accredited with the Association for Assessment for Accreditation of Laboratory Animal Care (AAALAC) International since June 8, 1982. Continued Full Accreditation was last renewed on July 1, 2011.

Thank you.

ELB:lkn

Cc: Walter E. Horton, Jr., Ph.D.
Vice President for Research
NEOMED Institutional Official

Figure 32: NEOMED IACUC Animal Research Approval Letter