CANINE EXOSKELETON
FOR MOBILITY AND REHABILITATION

Final Report
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-Full Report-

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Abstract

Many dogs suffer from common paralytic conditions such as fibricartilaginous embolism (FCE) and degenerative myelopathy, causing paralysis or weakness of the hind limbs. The symptoms appear with no warning and lead to the paralysis and weakness of dogs’ hind legs and sometimes even the front legs. This condition is nonprogressive and dogs can recover their movement over time with physical rehabilitation. Along with this condition, many dogs also face hind-leg paralysis through other diseases, old age, and injury. However, many owners do not have the capability to provide treatment and thus end up using wheelchairs or other relief devices that do not help the dog regain strength. They remain unable to walk properly, and so there is a need for a physical therapy device that pet owners can use. The purpose of this project is to develop an electronically controlled active exoskeleton that improves mobility and rehabilitation in the partially paralyzed/weakened hind limbs of canines.

After extensive research and collaboration with the CSU Veterinary Teaching Hospital veterinarians, customer requirements determined that a fully actuated, wearable hind limb exoskeleton was the best way to load legs for rehabilitation while still providing mobility. A biomechanically accurate hind limb dog model was developed for use with testing the motors in the system. A dog was measured and a custom brace system instrumented with sensors was fabricated. This system was placed on the live dog and sensor data (gyroscope, accelerometer, and pressure) was logged. A second, actuator brace system was created that supported the hind-limb dog model previously fabricated. With the design and manufacturing of a cart attached to the actuator brace system, the data from the live dog brace sensors is inputted into the actuator brace system, with the goal of actuating the fake dog to “walk” and move cart forward. This two-brace system was a strategy for creating a safe testing model that can be used to verify current and future design requirements without endangering a live dog.

This two brace system was tested and deemed a successful working prototype for the first year of this project. Data was collected from multiple sessions with the test animal, and this data was sent to the Motorized Brace System. The Motorized Brace System then moved the fake dog model forward in a biomechanically accurate manner. With more robust motors, the ultimate goal of this proof of concept system is to combine the two systems into a single exoskeleton that will rehabilitate and mobilize a paralyzed canine.
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# Table of Contents

Abstract ................................................................................................................................................. 2  
Acknowledgements ................................................................................................................................. 3  
Table of Contents .................................................................................................................................. 4  
List of Tables and Figures ....................................................................................................................... 8  
Chapter 1: Introduction ........................................................................................................................... 10  
Chapter 2: Review of Previous Work .................................................................................................... 12  
  2.1 Dog Biomechanics Research ........................................................................................................... 12  
  2.2 Dog Wheelchairs .............................................................................................................................. 14  
  2.3 OrthoPets Company ........................................................................................................................ 15  
  2.4 Human Exoskeletons ....................................................................................................................... 15  
Chapter 3: Project Overview and Timeline ........................................................................................... 17  
Chapter 4: Logistical Items ..................................................................................................................... 19  
  4.1 VTH Collaboration ......................................................................................................................... 19  
  4.1.1 Animal Testing Approval .......................................................................................................... 19  
  4.2 OrthoPets Collaboration ............................................................................................................... 19  
Chapter 5: Overall System Objectives/Constraints ........................................................................... 20  
  5.1 General System Customer Requirements and Specifications ....................................................... 20  
  5.2 Project Constraints ....................................................................................................................... 21  
Chapter 6: Mechanical Canine Model .................................................................................................. 23  
  6.1 Preliminary Model Prototype ......................................................................................................... 23  
  6.2 Final Hind Limbs Model ................................................................................................................. 24  
  6.3 Rolling Cart .................................................................................................................................... 26  
Chapter 7: Motorized Brace System ...................................................................................................... 30  
  7.1 Biomechanics Considerations ......................................................................................................... 30  
  7.2 QFD Decision Matrix of Potential Concepts .................................................................................. 31  
  7.3 Preliminary Designs ....................................................................................................................... 33  
  7.3.1 Preliminary Orthotic Brace ....................................................................................................... 33  
  7.3.2 Preliminary Actuator System .................................................................................................... 34  
  7.3.3 Preliminary Model Complications ............................................................................................ 35  
  7.4 Final Linkage System .................................................................................................................... 35  


7.4.1 Stepper Motor Linkage System .......................................................... 35
7.4.2 Knee Linear Actuator ........................................................................ 38
7.4.3 Ankle Linear Actuator ....................................................................... 38
7.4.4 Linear Actuator Placement ................................................................. 39
7.4.5 Attachment Points on Braces ............................................................... 40
7.4.6 Leg Movement ...................................................................................... 42
7.4.7 The Final System ................................................................................ 43
7.5 Power ........................................................................................................ 45
7.6 Coding ....................................................................................................... 45
Chapter 8: Data Collection Brace System .................................................. 47
8.1 System Requirements and Engineering Specifications ......................... 47
8.2 The Sensor System .................................................................................. 47
  8.2.1 Potential Trigger Methods ................................................................. 47
  8.2.2 QFD Decision Matrix of Initial Trigger Mechanism ....................... 48
  8.2.3 Sensor Circuit ..................................................................................... 49
8.1 Mechanical Design and Fabrication ....................................................... 49
  8.1.2 Front Paw Gyroscope Holders Design and Fabrication ................... 50
  8.1.3 Data Collection Braces Design and Fabrication ................................. 50
8.2 Power ....................................................................................................... 52
8.3 Data Collection Sessions ........................................................................ 52
  8.5.1 First Data Collection .......................................................................... 53
  8.5.2 Second Data Collection .................................................................... 54
Chapter 9: System Configuration ............................................................... 56
  9.1 Functional Diagram ................................................................................ 56
Chapter 10: Testing ....................................................................................... 58
  10.1 Batteries ................................................................................................. 58
  10.2 Gyroscope ............................................................................................. 58
  10.3 Pressure Sensors .................................................................................. 58
  10.4 Code ...................................................................................................... 58
  10.5 Biomechanics ....................................................................................... 59
Chapter 11: Design for Requirements ......................................................... 60
  11.1 Safety .................................................................................................... 60
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.2</td>
<td>Rehabilitation</td>
<td>60</td>
</tr>
<tr>
<td>11.3</td>
<td>Mobility</td>
<td>60</td>
</tr>
<tr>
<td>11.4</td>
<td>Usability</td>
<td>60</td>
</tr>
<tr>
<td>12</td>
<td>Chapter 12: Risk Analysis</td>
<td>62</td>
</tr>
<tr>
<td>12.1</td>
<td>FMEA Analysis</td>
<td>62</td>
</tr>
<tr>
<td>12.2</td>
<td>Human/Canine Factors Analysis</td>
<td>62</td>
</tr>
<tr>
<td>13</td>
<td>Chapter 13: Ethical Issues</td>
<td>64</td>
</tr>
<tr>
<td>13.1</td>
<td>Animal Safety</td>
<td>64</td>
</tr>
<tr>
<td>13.2</td>
<td>Global Issues and Ethics</td>
<td>64</td>
</tr>
<tr>
<td>13.3</td>
<td>Environment</td>
<td>64</td>
</tr>
<tr>
<td>13.4</td>
<td>Research Ethics</td>
<td>65</td>
</tr>
<tr>
<td>14</td>
<td>Chapter 14: Conclusions and Future Work</td>
<td>66</td>
</tr>
<tr>
<td>14.1</td>
<td>Results of Project</td>
<td>66</td>
</tr>
<tr>
<td>14.2</td>
<td>Limitations of Current Device</td>
<td>67</td>
</tr>
<tr>
<td>14.2.1</td>
<td>System Speed</td>
<td>67</td>
</tr>
<tr>
<td>14.2.2</td>
<td>Usability</td>
<td>68</td>
</tr>
<tr>
<td>14.3</td>
<td>Plans for future years</td>
<td>68</td>
</tr>
<tr>
<td>14.3.1</td>
<td>Dog Model</td>
<td>69</td>
</tr>
<tr>
<td>14.3.2</td>
<td>Integration</td>
<td>69</td>
</tr>
<tr>
<td>14.4</td>
<td>Final Thoughts</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>70</td>
</tr>
<tr>
<td>Appendix A: Abbreviations</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>Appendix B: Budget</td>
<td>73</td>
<td></td>
</tr>
<tr>
<td>Appendix C: Donations Letter of Interest</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>Appendix D: Project Plan Evolution</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>Appendix E: Detailed Device Testing Plans</td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>Appendix F: IACUC and RICRO Training</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Appendix G: Canine Anatomy</td>
<td>92</td>
<td></td>
</tr>
<tr>
<td>Appendix H: Failure Modes and Effects Analysis (FMEA)</td>
<td>93</td>
<td></td>
</tr>
<tr>
<td>Appendix I: Sensor System Code</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td><strong>Arduino: code</strong></td>
<td>94</td>
<td></td>
</tr>
<tr>
<td><strong>Processing 3 Code:</strong></td>
<td>99</td>
<td></td>
</tr>
</tbody>
</table>
Graphing Function: ........................................................................................................99
Convert Axis Function: .................................................................................................103
Draw Axis Function: ......................................................................................................104
Appendix J: Actuation System Code: ............................................................................110
Arduino Code: ................................................................................................................110
Processing 3 Code: .........................................................................................................112
Appendix K: Hardware Schematic Diagrams ...............................................................113
Appendix L: IACUC Submitted Protocol.........................................................................126
## List of Tables and Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1:</td>
<td>Motion of Hind Leg Throughout Gait Cycle [Goslow 1981]</td>
<td>12</td>
</tr>
<tr>
<td>Figure 2:</td>
<td>Canine Hip Angles from Research</td>
<td>12</td>
</tr>
<tr>
<td>Figure 3:</td>
<td>Canine Knee Angles from Research</td>
<td>13</td>
</tr>
<tr>
<td>Figure 4:</td>
<td>Canine Ankle Angles from Research</td>
<td>13</td>
</tr>
<tr>
<td>Figure 5:</td>
<td>Walkin’ Wheels® Wheelchair Device for Paralyzed Dogs [Dogs in Motion 2012]</td>
<td>14</td>
</tr>
<tr>
<td>Figure 6:</td>
<td>Help ‘Em Up® Dog Harness [2015]</td>
<td>14</td>
</tr>
<tr>
<td>Figure 7:</td>
<td>Dog wearing an OrthoPets Brace [OrthoPets 2015]</td>
<td>15</td>
</tr>
<tr>
<td>Figure 8:</td>
<td>Ekso GT Rehabilitation Exoskeleton [Ekso 2015]</td>
<td>16</td>
</tr>
<tr>
<td>Figure 9:</td>
<td>Year One System Diagram</td>
<td>17</td>
</tr>
<tr>
<td>Figure 10:</td>
<td>Project Plan Flow Chart</td>
<td>18</td>
</tr>
<tr>
<td>Figure 11:</td>
<td>Preliminary Cart Prototype</td>
<td>23</td>
</tr>
<tr>
<td>Figure 12:</td>
<td>The Plans for Making Cuts in Foam Models</td>
<td>24</td>
</tr>
<tr>
<td>Figure 13:</td>
<td>The wooden skeleton plans with assembled hinges</td>
<td>25</td>
</tr>
<tr>
<td>Figure 14:</td>
<td>Final assembly plans for the canine foam leg</td>
<td>25</td>
</tr>
<tr>
<td>Figure 15:</td>
<td>Plans for encasing the foam leg in a fiberglass material</td>
<td>26</td>
</tr>
<tr>
<td>Figure 16:</td>
<td>Isometric view of final cart assembly</td>
<td>27</td>
</tr>
<tr>
<td>Figure 17:</td>
<td>Both the placement for the legs and for the motor can be adjusted vertically and horizontally to achieve any position necessary for testing</td>
<td>28</td>
</tr>
<tr>
<td>Figure 18:</td>
<td>Final model complete and exoskeleton without any actuator attachment</td>
<td>29</td>
</tr>
<tr>
<td>Figure 19:</td>
<td>Illustration of Hind Leg Movement</td>
<td>30</td>
</tr>
<tr>
<td>Figure 20:</td>
<td>Corresponding Linkage System</td>
<td>31</td>
</tr>
<tr>
<td>Figure 21:</td>
<td>QFD of Potential Mechanical Concepts</td>
<td>32</td>
</tr>
<tr>
<td>Figure 22:</td>
<td>System with Two Linear Actuators and One Stepper Motor</td>
<td>33</td>
</tr>
<tr>
<td>Figure 23:</td>
<td>Preliminary Brace for the System</td>
<td>34</td>
</tr>
<tr>
<td>Figure 24:</td>
<td>Side View of the Preliminary Actuator System</td>
<td>34</td>
</tr>
<tr>
<td>Figure 25:</td>
<td>Basic Overview of Linkage System</td>
<td>35</td>
</tr>
<tr>
<td>Figure 26:</td>
<td>CAD Model of Crank Coupler Linkage</td>
<td>36</td>
</tr>
<tr>
<td>Figure 27:</td>
<td>Photographs of Fabricated Crank-Coupler Linkage</td>
<td>37</td>
</tr>
<tr>
<td>Figure 28:</td>
<td>Coupler Attachment to Thigh Brace</td>
<td>37</td>
</tr>
<tr>
<td>Figure 29:</td>
<td>Coupler Link Attachment to Brace</td>
<td>38</td>
</tr>
<tr>
<td>Figure 30:</td>
<td>Linear Actuators Placement</td>
<td>40</td>
</tr>
<tr>
<td>Figure 31:</td>
<td>Actuator Attachment Point Cavities</td>
<td>41</td>
</tr>
<tr>
<td>Figure 32:</td>
<td>Actuator Brace Attachment</td>
<td>42</td>
</tr>
<tr>
<td>Figure 33:</td>
<td>Overview of Motorized Brace System Leg Movement</td>
<td>43</td>
</tr>
<tr>
<td>Figure 34:</td>
<td>Isometric view of the actuated exoskeleton attached to a rolling cart</td>
<td>44</td>
</tr>
<tr>
<td>Figure 35:</td>
<td>Photograph of Final Fabricated Motorized Brace System</td>
<td>44</td>
</tr>
<tr>
<td>Figure 36:</td>
<td>Simplified Code Flow Chart of Control Sequence of Motion</td>
<td>46</td>
</tr>
<tr>
<td>Figure 37:</td>
<td>QFD For Trigger Method</td>
<td>49</td>
</tr>
<tr>
<td>Figure 38:</td>
<td>Canine Metacarpals on Front Paw</td>
<td>50</td>
</tr>
<tr>
<td>Figure 39:</td>
<td>CAD Model of Data Collection Braces</td>
<td>51</td>
</tr>
<tr>
<td>Figure 40:</td>
<td>Photograph of Fabricated Sensor Braces</td>
<td>52</td>
</tr>
</tbody>
</table>
Figure 41: Data Collection Brace System on Live Dog

Figure 42: Gyroscope Walking Data

Figure 43: Pressure Sensor Data

Figure 44: Functional Diagram of the Electrical Hardware System

Figure 45: Design Control Process

Figure 46: Concept Design of Future Combined System
Chapter 1: Introduction

Incredible technological strides have been made over the last ten years to improve the lives of diseased and paralyzed animals. With these strides, orthotic devices have been created to promote mobility in these once degenerate animals. Dogs in particular are prone to compressed discs of the spine leading to weakness and instability of the hind limbs [Coates 2010, Tarlov 1954]. Every day, there are dogs that lose their ability to walk due to hind limb weakness or paralysis from diseases including degenerative myelopathy and fibricartilaginous embolism (FCE) among a number of other conditions [Levine 2014]. These symptoms can appear with no warning and leads to the paralysis of dogs’ hind legs and sometimes even the front legs. Many of these conditions are nonprogressive and dogs can recover their ability to move normally over time with physical rehabilitation. However, many owners do not have the capability to provide treatment and thus end up using the available products such as wheelchairs or other relief devices to increase overall mobility that do not help the dog regain strength or allow any form of physical therapy for the hind limbs. They remain unable to walk properly, and so there is a need for a physical therapy device that pet owners can use.

The Canine Exoskeleton for Mobility and Rehabilitation Senior Design team from Colorado State University (CSU) is comprised of biomedical (BME), electrical and computer (ECE), and mechanical engineering (ME) students. The goal of the project was to create a rehabilitation exoskeleton for dogs suffering from these mobility impairments that would aid in motor functions until the dog regained its strength. The research accomplished for this project can also be applied to modern human physical medicine to ultimately develop a device that will mobilize paralyzed individuals.

For the first year of the project, the team researched the walking movements of dogs to create a device that uses movement signals from sensors on a live dog to replicate the correct hind limb movement of the canine on a model dog.

The team partnered with the Colorado State University Veterinary Teaching Hospital (VTH) in order to have access to world-class knowledge from multiple veterinarians. In order for team engineers to interact with the dogs, the team completed online training provided by the Colorado State University Research Integrity & Compliance Review Office (RICRO) and the Institutional Animal Care and Use Committee (IACUC) in order to ensure the safe and proper handling of the dogs.

OrthoPets™, a canine orthotics company, agreed to provide resources such as dog leg molds and customized orthopedic braces for us to modify into an automated device. Additionally, working with OrthoPets gave team an industry perspective to ensure the project’s long-term goals align with an eventual marketable product.

The following report will give an overview of previous research and existing solutions done in the field (Chapter 2) and describe the project’s overview and overall timeline (Chapter 3). Chapter 4 includes the logistical components of the project including working with the VTH and OrthoPets, while Chapter 5 explains the overall objectives and constraints of the project including the major customer requirements. Chapter 6 discusses the mechanical foam dog model while Chapter 7 will
provide the design of the Motorized Brace System. The Data Collection Brace System will be provided in Chapter 8. Chapter 9 provides information on the electrical system configuration. Chapter 10 describes the testing process followed for the project while Chapter 11 explains designing for safety, rehabilitation, mobility, cost, and usability. Chapter 12, Risk Analysis, provides a Failure Modes and Effect Analysis (FMEA) chart, dog factors analysis, and a mitigation plan. Ethical issues will be covered in Chapter 13, and any future work for uncertainties will be described in our conclusion in Chapter 14.

The appendices list abbreviations, the budget, letters of interest such as the team’s donations letter, the project plan evolution, detailed device testing plans, RICRO and IACUC certifications, canine anatomy, failure modes and effects analysis, sensor system code, actuation system code, the hardware schematic diagrams, and the submitted and approved animal testing process.
Chapter 2: Review of Previous Work

2.1 Dog Biomechanics Research

The scope of this year’s project was to develop a kinematically accurate exoskeleton that successfully actuated a mechanical model of a canine. Therefore, it was imperative that the device followed physiological angles so that, when eventually placed on a live dog, the model would be safe and not move the dog’s leg segments outside of physiological constraints.

Considerable research has been performed investigating the biomechanics of canines [DeCamp, 1997, Goslow 1981, Marsh 2010, Vilensky 1994]. The results of these studies indicate a common joint angle pattern seen in larger dog breeds that can be used as references for the system movement. A standardized motion of the hind leg through one complete gait cycle can be seen below in Figure 1.

Figure 1: Motion of Hind Leg Throughout Gait Cycle [Goslow 1981]

Figure 2 below indicates hind limb hip angle data across three different studies.

Figure 2: Canine Hip Angles from Research

During the gait cycle, the hip flexes to begin the leg movement forward, and then extends as it makes contact with the ground after the swing phase. Figure 3 below exhibits the knee angles of dogs across five different research studies.
The knee angles amongst the five different studies showed slight variations but the overall directions of movement were extremely similar. Ankle angle data can be seen below in Figure 4.

**Figure 3: Canine Knee Angles from Research**

The ankle angle data amongst the two separate studies was very consistent in terms of timing and amplitudes.

Utilizing these previous biomechanics research articles was critical for developing a device that followed physiological angles. This angle data was converted into distances based on actuator attachment locations that were input into the code so that the dog’s three bone segments followed this pattern.

Additionally, during a normal, walking gait, a dog moves one front foot forward, and then its opposite back leg forward (Goslow 1981). This predictable pattern can then be utilized in order indicate if the dog is attempting to walk forward. Refer to Chapter 3 for more information about how this was utilized in the system.
2.2 Dog Wheelchairs

There are now many available products to increase overall canine mobility. Consumers can readily purchase a plethora of wheelchair devices for the dog that attach to the back half of the body, similar to Figure 5 [Creamer 1993, Hill 1993, Hulterstrum 1989, Parkes 2015, Robinson 2009].

Figure 5: Walkin' Wheels® Wheelchair Device for Paralyzed Dogs [Dogs in Motion 2012]

Although these wheelchairs do provide mobility to dogs with hind limb partial paralysis/weakness, their back legs are typically cinched up, limiting their ability to work these legs and potentially increase mobility through physical therapy [Giangregorio 2006]. By not loading these bones and muscles, the wheelchair is inhibiting the dog’s ability to rehabilitate.

There are also simple harnesses on the market, similar to Figure 6, which owners control so that the hind legs can experience loads.

Figure 6: Help ‘Em Up® Dog Harness [2015]

One inherent issue with this harness is the inconvenience of the owner having to constantly grab onto the harness to provide support for the dog. Although this harness could be considered a rehabilitation device, the dependency on the owner causes an unfortunate problem.

Both of the above assistive devices also put a large amount of weight on the dog’s front legs that they are not normally accustomed to, contributing to fatigue and only allowing the dog to use the
device for a short amount of time before it falls forward [Kauffman 2015]. Therefore, current wheelchairs are a short-term form of ambulation, but do not function as a rehabilitation device.

The proposed Canine Exoskeleton for Mobility and Rehabilitation Project aims to increase the dog’s independent mobility and rehabilitate the hind legs so that the dog’s health and strength can be improved. In addition to allowing the hind legs to be loaded and mobilized, the system includes a sensor array in order to determine the dog’s intended movement and physically move the dog accordingly. This will rehabilitate the dog’s nervous system and therapeutically train the dog to use its legs again. To our knowledge, there is no automated pet wheelchair on the market at this time.

2.3 OrthoPets Company

Additionally, working with OrthoPets gave the team an extremely valuable industry perspective to ensure the project’s goals align with a marketable product. As shown below in Figure 7, current OrthoPets products provide stabilization for canine limbs.

![Figure 7 Dog wearing an OrthoPets Brace [OrthoPets 2015]](image)

The goal of this project was to improve the ambulation and health of a canine through the development of an automated assistive device. Current canine orthotics do provide ambulation and health benefits, but act as passive devices that provide stability, not an active actuated movement. Therefore, the team utilized these braces with a new actuator design, to create a device that can allow a dog to receive active help walking forward.

2.4 Human Exoskeletons

Inspiration for this device was partially derived from human exoskeletons currently available on the market from companies such as Ekso Bionics® (Figure 8).
This company along with others has developed an exoskeleton that senses the amount of human input and actuates the mechanism appropriately to drive the person’s legs forward in a walking pattern. These devices have been shown to effectively rehabilitate stroke survivors and those with lower limb weakness, leading to a positive belief that this canine exoskeleton provides similar results [Forrest 2012, Iosa 2012].
Chapter 3: Project Overview and Timeline

Although the ultimate goal of this multi-year project is to develop a single, integrated system to go on a paralyzed/weakened dog, the project was divided into separate years in order to ensure an accurate and reliable device is designed that can safely assist a diseased dog. Therefore, the goal for the 2015-2016 project was to develop two systems: a sensor-instrumented Data Collection Brace System that was placed on a live, healthy dog, and an actuated Motorized Brace System that was placed on a foam dog model that the team also created. These two brace systems were mechanically separate, but were electrically linked so that the healthy dog sensor data was inputted into the Motorized Brace System that then moved the foam dog model forward. A model of this system is shown below in Figure 9.

Data Collection Brace System | Motorized Brace System

Data from pressure sensors on the hind legs and gyroscopes on the front legs was collected from a live dog in the Data Collection Brace System throughout the second semester. As mentioned in the background research, as a dog moves its front left leg forward, it soon after moves its back right leg forward. Therefore, the gyroscope data was able to initialize the walking motion. The pressure sensors were used as a modulation strategy to determine where in the gait cycle the dog was (i.e. if toe off, heel strike, swing phase from the sensors on the bottom of the paw) and also to determine if the dog was resisting motion (the sensors in the braces). This data was stored on a computer, and then sent from the computer into the Motorized Brace System, which appropriately actuated the brace system so that the model dog was able to “walk” forward. This overall project timeline for the year can be seen in Figure 10 below.
As can be seen above, a significant portion of the first semester involved researching this problem and acquiring the customer requirements through many meetings with OrthoPets and the Veterinary Teaching Hospital. A detailed Gantt Chart is also available upon request, but refer to Appendix D for the overall project plan evolution and a simplified Gantt Chart.
Chapter 4: Logistical Items

4.1 VTH Collaboration

Our team worked with members of the VTH in order to help oversee the animal testing as well as provide useful information. These members are Dr. Dean Hendrickson, Dr. Rebecca Packer, Dr. Nic Lambrechts, and physical therapist Sasha Foster. These members provided us with the information regarding the necessary aspects of this product that must be addressed (i.e. customer requirements), the types of conditions that lead to paralysis/weakness of the hind limbs, the current treatments for these conditions, gait information, possible design flaws, and overall feedback throughout the design and fabrication process.

4.1.1 Animal Testing Approval

In order to get approved to work with a live animal, multiple processes were completed before testing could occur.

The Institutional Animal Care and Use Committee (IACUC) provides certification for animal research and testing through CSU. Each member of the team completed this training process. The Research Integrity & Compliance Review Office (RICRO) at CSU offers training to be certified in research ethics and compliance. Please reference Appendix F for the RICRO certifications for each team member.

To work with a live dog, that specific dog had to undergo a neurological examination by experienced veterinarians to ensure the dog could handle the data collection process. The area in which the data collection occurred (the hallway of room B111 in the Engineering Building) also needed to be approved to ensure it was a safe environment. Therefore, a veterinarian visited the area and confirmed that the area was a good place for data collection. Lastly, the protocol detailed how data collection would occur needed to be submitted to the IACUC for approval. The submitted protocol can be found in Appendix L. This protocol was submitted and took six months before approval was given.

4.2 OrthoPets Collaboration

This project worked very closely with OrthoPets, an animal orthotics company, and its engineer, Martin Kaufmann. Martin and his OrthoPets team provided extensive knowledge of brace designs and helped design the mechanical system. He also has a wealth of knowledge concerning animal physiology which helped the team understand the interactions within the dog’s leg. More detail about the brace design and collaboration with OrthoPets can be found in Chapters 7 and 8 of the report.
Chapter 5: Overall System Objectives/Constraints

5.1 General System Customer Requirements and Specifications

The customers in this project included veterinarians and pet owners. For the purposes of this year’s project, the dog will be a full-grown Labrador retriever. Below is Table I to show general customer requirements and specifications.

Table I: Overall Main Customer Requirements and Engineering Specifications

<table>
<thead>
<tr>
<th>Customer Requirements</th>
<th>Engineering Specifications</th>
<th>Desired Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safe</td>
<td>Joint Angle Variability (degrees)</td>
<td>Down</td>
</tr>
<tr>
<td>Provides rehabilitation</td>
<td>Forces that hind legs experience (Newtons)</td>
<td>up</td>
</tr>
<tr>
<td>Provides mobility</td>
<td>Distance dog can walk (meters)</td>
<td>up</td>
</tr>
<tr>
<td>Usable</td>
<td>Operating time (hours)</td>
<td>up</td>
</tr>
<tr>
<td>Cheap</td>
<td>Cost of system ($)</td>
<td>down</td>
</tr>
</tbody>
</table>

Below are tables showing the Mechanical and Electrical customer requirements determined through the team’s collaborations as mentioned in Chapter 4. Since these requirements are meant for the final system, both the Motorized Brace System (Chapter 7) and the Data Collection System (Chapter 8) follow what is listed below.
Table II: Mechanical Customer Requirements and Engineering Specifications

<table>
<thead>
<tr>
<th>Customer Requirements</th>
<th>Engineering Specifications</th>
<th>Desired Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>Mechanism Material Elastic Modulus (Pa)</td>
<td>up</td>
</tr>
<tr>
<td>Lightweight</td>
<td>System Weight (lbs)</td>
<td>down</td>
</tr>
<tr>
<td>Fast</td>
<td>Sum of Actuators No Load Speed (m/s)</td>
<td>up</td>
</tr>
<tr>
<td>Able to handle dog weight</td>
<td>Sum of Actuators Max Load Capacity (lbs)</td>
<td>up</td>
</tr>
<tr>
<td>Simple design</td>
<td>Number of Working Parts/Joint</td>
<td>down</td>
</tr>
<tr>
<td></td>
<td>Number of Microcontroller Outputs</td>
<td>down</td>
</tr>
<tr>
<td></td>
<td>Total Number of Connections</td>
<td>down</td>
</tr>
<tr>
<td>Cheap</td>
<td>Cost ($)</td>
<td>down</td>
</tr>
<tr>
<td>Able to last for long periods of time</td>
<td>Voltage required (Volts)</td>
<td>down</td>
</tr>
<tr>
<td></td>
<td>Stall current required (Amps)</td>
<td>down</td>
</tr>
<tr>
<td>Safe for dog</td>
<td>Low angle variability from published biomechanics data (percentage)</td>
<td>down</td>
</tr>
</tbody>
</table>

Table III: Electrical Customer Requirements and Engineering Specifications

<table>
<thead>
<tr>
<th>Customer Requirements</th>
<th>Engineering Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>Circuit housing, waterproof, concealed wiring, emergency stop circuit.</td>
</tr>
<tr>
<td>Longevity</td>
<td>Battery usage and life.</td>
</tr>
<tr>
<td>Simplicity</td>
<td>Lightweight circuitry, easy to handle hardware, fixable, adjustable, compatible voltage (V) and amperage (A).</td>
</tr>
<tr>
<td>Interdependence</td>
<td>Canine interaction with device should determine movement and level of therapy attention.</td>
</tr>
</tbody>
</table>

5.2 Project Constraints

Because this is the first year this project has been developed, there are many constraints that must be considered in order to produce a device that will be useful for future years.
• **Budget:**
  o The budget for this project was severely limited which affected the quality and accuracy of the sensors, microcontrollers, and actuators that could be purchased. Efforts were made to increase the budget as much as possible. Refer to Appendix B for more information regarding budget details.

• **Using OrthoPets braces:**
  o These braces are vacuum molded and comprise the brace systems on both the Data Collection Brace system and the mechanically actuated Motorized Brace system. This is by no means a limitation (indeed an extreme benefit), but does mean that we had to understand and utilize their specific brace products.

• **Limited access to healthy and unhealthy dogs:**
  o Due to the necessary procedures and training that are required to test on dogs, it was very difficult to get approval. For the purposes of this first year project, only one dog was tested.

• **Inability to test on a paralyzed/weakened canine**
  o Because of the early stage of this multi-year project, it was imperative that the device was designed and rigorously tested for safety. Although it would have been wonderful to mount both the sensor system and mechanically actuated system onto a single, diseased dog, it was determined that this was neither realistic nor safe to perform for the first year device of the project.

• **Availability of collaborators (OrthoPets and VTH) to meet**
  o Martin Kaufmann (OrthoPets) along with the members of the VTH are incredible resources for this project. Unfortunately, they are also extremely busy with other projects and can only meet at certain times and frequencies.
Chapter 6: Mechanical Canine Model

As mentioned earlier, the final goal for the end of the year was to create an automated exoskeleton capable of actuating fabricated dog legs to propel a cart forward. Therefore, creating an articulated dog legs became very important. In order for this project to succeed in future years, the final model needed to closely represent physiological movement, which created a large problem when it came time to manufacture.

6.1 Preliminary Model Prototype

In order to create a durable final model, a preliminary model was created during the first semester to work out some design iterations. Due to the geometric complexity of canine limbs, OrthoPets was able to assist our efforts in creating artificial dog limbs. OrthoPets normally creates artificial dog limbs out of high-density polyurethane foam, as a part of their orthotic manufacturing process. The employees at OrthoPets use sophisticated CAD modeling software to generate an accurate model of dog limbs, and then use a CNC machine to fabricate the models out of foam.

Therefore, in the first semester, the team acquired some of the foam models and articulated them by cutting them into the three leg segments and using hinges to reassemble them. This model served as a baseline for the overall manufacturing process, and allowed the team to practice different manufacturing techniques before producing the final product. In practicing different manufacturing techniques, multiple problems arose that needed to be addressed during the final fabrication process. An image of the initial prototype can be found in Figure 11.

Figure 11: Preliminary Cart Prototype
Preliminary Model Prototype Complications:

1.) Polyurethane Foam Material Properties: The foam was too soft and malleable to accurately use any power tools on, or to place any fasteners into. Therefore, it made holding tolerances impossible, and reassembling pieces together could only be accomplished via use of adhesives.

2.) Alignment: The inability to maintain tolerances allowed for the leg to get out of alignment.

3.) Foam Sheds: The foam shed a lot of material. This was a problem because the team did not want any of the foam dust to influence how the actuators worked, or how the electronics worked.

Although the foam was a design challenge, the team chose to use the foam for the following reasons.

1. **Weight**: Dog limbs weigh very little with respect to the torso. Therefore it was imperative to keep the weight low for both the weight ratio, and for strength of the actuators.

2. **Manufacturing**: OrthoPets was able to create the foam legs in their CNC machine. They were not willing to use another type of material in the machine due to the risks associated with the available cutting tool.

3. **Cost**: Each foam block costs $8.00 and OrthoPets donated the blocks. The budget for project was a limiting factor, and looking for another material and another place to manufacture the material would cost both time and money.

### 6.2 Final Hind Limbs Model

To address the problems associated with the manufacturing challenges discovered in the first semester, the following solutions were created.

**Alignment:**

Each leg was cut into six pieces, and grooves were carefully hand shaved onto the inside part of the limb (Figure 12).

![Figure 12: The Plans for Making Cuts in Foam Models](image)

Sand paper and files were used to create smooth surfaces on both the grooves and the interior of the pieces. This created better contact surfaces for the adhesive that was used.
To assemble the entire leg, a wooden bone structure was assembled first. Two different sizes of square stock were used for the ankle joint and knee joint due to varying diameter between the ankle and knee. Both sizes of wood were cut to the appropriate lengths and then cut in half. Hinges for both the knee and the ankle joint were then sandwiched between the two halves of each length of wood respectively. Brackets were then used to attach the thicker wooden peg to the thinner wooden peg to create the bone structure of the entire leg as can be seen in Figure 13.

![Figure 13: The wooden skeleton plans with assembled hinges](image)

Once the wooden skeleton was aligned, it was glued into the groves that were shaved into the pieces of the foam leg. This process created an assembly for half of the leg. Once the glue dried, the other half of the leg was glued to the first half as shown in Figure 14 below.

![Figure 14: Final assembly plans for the canine foam leg](image)
Shedding Foam:

The legs and torso were encased in a thin layer of fiberglass. The fiberglass was able to protect the integrity of the model, provide more rigidity, and protect the actuators and electrical components from any shedding dust from the legs (Figure 15).

![Figure 15: Plans for encasing the foam leg in a fiberglass material](image)

Tolerances:

A lot of manufacturing by hand took place to ensure that the proper amount of material was removed. Hand tools (files, handsaws, hand drills, etc.) were used with extreme caution to hold tolerances as closely as possible. Tolerances were held more closely than first semester, however due to the nature of the foam, they were not held as tightly as desired.

6.3 Rolling Cart

Due to the fact it is very difficult to recreate the anatomy of a full dog, the team decided to only create the hind limbs. However, in order to simulate the remainder of the body, it was decided to create a cart that the hind limbs could attach to. During the first semester, a preliminary cart was created out of wood to attach the initial foam legs (Figure 11). From the initial cart, it was discovered that in order to create a more functional model that could be used throughout the years of the project, the cart needed to be adjustable. Therefore, a new design for a cart was agreed upon and can be found in Figure 16.
As mentioned earlier, adjustability was important so that a variety of design iterations and dimensions could be tested using the same model. Also, because of the tolerance situation, an adjustable cart would be necessary for fine tuning this year’s final system. Therefore, instead of using wood to create the cart, the cart was made of 80-20 aluminum. 80-20 is a style of extruded T-slotted aluminum that allows adjustability through the use special fasteners that can be purchased through 80-20 suppliers. By cutting the 80-20 extrusions, and using a variety of fasteners, the cart can be adjusted to many lengths and heights in order to fit any dog that may want to be tested. (Figure 17).
Figure 17: Both the placement for the legs and for the motor can be adjusted vertically and horizontally to achieve any position necessary for testing.

After the car was assembled, the final step of the fabrication process was to place the legs onto the tail end of the cart. The front section of the cart that held the large stepper motors and served as the torso of the canine. The front wheels provide a base for the model, as well as behaving as the front legs. A complete assembly of the entire model with the actuator braces on the model legs can be found in Figure 18.
Figure 18 Final model complete and exoskeleton without any actuator attachment
**Chapter 7: Motorized Brace System**

The team’s Motorized Brace System acts as the active component of what would be integrated in the future of this project. This ensured the absolute minimal safety risk to the live dog and provided the team with an appropriate testing environment, allowing the team to interpret dog walk data physically and make adjustments to kinematics as needed.

The Motorized Brace system incorporates a linkage system made of linear actuators and rotary motors. When considering the design goals for the project, the final system had to accomplish the customer requirements and engineering specifications in Tables II and III, Chapter 5.

**7.1 Biomechanics Considerations**

The physiological kinematics of the hind limb throughout the gait cycle (described/shown in detail in Chapter 2.1) were mimicked in the mechanically actuated brace system. A simplified illustration of the movement of the hind leg can be seen below in Figure 19.

![Figure 19: Illustration of Hind Leg Movement](image)

The physiological movements of the above Figure 19 can be described. The paw first makes contact with the ground at heel strike (0% of gait cycle) before going to neutral position (20%). Next, at approximately 50% of the gait cycle, toe off occurs and the knee and ankle flex into a compressed condition. Between 60% and 85% of the gait cycle, the femur swings through, and then the gait cycle finishes by allowing the knee and ankle to extend back down and make contact with the ground at heel strike again.

The hind limb can be considered a three-segment linkage. The hip joint allows rotation but no translation, while the knee and ankle joints can be translated and rotated in the universal coordinate system. This leads to a three degree-of-freedom (DOF) linkage system, indicating that three inputs are required to rotate/translate the segments in a 2D predefined pattern. Figure 20 below shows the translation from the physiological dog leg and bones to the corresponding mechanical linkage system.
Given this three-segment linkage, multiple concepts were developed in order to achieve the desired kinematics. Although a 3 DOF typically indicates that three inputs (i.e. applied forces) must be utilized, a biomechanics analysis determined that, if properly placed, one linear actuator could properly flex/extend the knee and ankle angles because of their dependence on each other. Therefore, the system could have two to three actuators, and could also include linear actuators and/or rotary actuators. Many concepts were considered that utilized a combination of types and numbers of actuators. The following details how the final types and numbers of actuators were determined.

### 7.2 QFD Decision Matrix of Potential Concepts

A Quality Functional Diagram (QFD) Decision Matrix was created in order to determine the best mechanical system concept regarding the number and types of actuators and can be seen below in Figure 21.
### Potential Concepts

<table>
<thead>
<tr>
<th>Specification</th>
<th>2 Linear Actuators</th>
<th>1 Stepper Motor &amp; 1 Linear Actuator</th>
<th>2 Linear Actuators</th>
<th>2 Stepper Motors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weight</strong></td>
<td>5</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td><strong>Length Customization</strong></td>
<td>&gt;30%</td>
<td>5</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td><strong>No Load Max Speed</strong></td>
<td>≥2 in/s</td>
<td>15</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td><strong>Max Force (Per Actuator)</strong></td>
<td>&gt;10 lbs.</td>
<td>10</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td><strong>Working Parts Per Joint</strong></td>
<td>≤2</td>
<td>10</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td><strong>Number of Microcontroller Outputs</strong></td>
<td>≤2</td>
<td>15</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>≤500</td>
<td>10</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td><strong>Voltage Required</strong></td>
<td>≤12.0 V</td>
<td>2</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td><strong>Stall Current Required</strong></td>
<td>≤0.6 amp</td>
<td>3</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td><strong>Total Number of Connections</strong></td>
<td>≤6</td>
<td>10</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td><strong>Angle Deviation from Published Data</strong></td>
<td>≤10%</td>
<td>15</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

**Weighted Sum:**

|                        | 100    | 50    | -10   | 30    | -10   | 20    |

### Figure 21: QFD of Potential Mechanical Concepts

The results of the QFD indicated that the system that best met the weighted customer requirements was a two linear actuator, one rotary motor system. Therefore, this was the chosen actuator system design for the system. A simplified sketch of the system throughout the gait cycle can be seen below in Figure 22.
This three-actuator system utilized linear actuators to flex/extend the knee and ankle separately, and a rotary (stepper) motor with a crank linkage system to actuate the hip. Any three-actuator system will be more expensive and require more electrical and computing power, but should also result in more accurate kinematic accuracy and a simpler mechanical design, as determined by the QFD analysis above.

7.3 Preliminary Designs

The team developed a preliminary prototype brace, actuator system, and model and then iterated the concepts to produce a better, final product.

7.3.1 Preliminary Orthotic Brace

OrthoPets aided our efforts to create the brace shell for the exoskeleton. During the first semester, they provided an initial layout of the orthotic brace for the team to gain an idea of how would look upon final fabrication. The preliminary brace was composed of three separate shells connected by an aluminum side bar that allowed rotation. The purpose of the brace was to not only provide a preliminary idea of what the brace looked like, but also test fixture. A model of the initial brace can be found in Figure 23.
7.3.2 Preliminary Actuator System

During the first semester, after receiving the preliminary orthotics from OrthoPets, the team developed a design for the actuator brace. As mentioned earlier in the report, the team decided to use two linear actuators and one stepper motor to move each leg through its gait cycle. Each actuator was responsible for controlling one joint. The stepper motor controls the hip joint, one linear actuator one controls the knee joint, and one linear actuator controls the ankle joint. Figure 24 shows the initial CAD modeling for what the team wanted the final system to look like.
7.3.3 Preliminary Model Complications.

Upon receiving the initial brace, the team was able to perform preliminary tests using the actuators that were purchased. During testing two major problems occurred. The first problem was that the friction in the hinges was making the joints rather hard to move. The second problem was that in the current design there was no efficient way to attach the linear actuators, or the stepper motor linkage system, to the brace. Therefore, the team approached OrthoPets about the problem, and worked with their engineers to create a solution for each one.

7.4 Final Linkage System

The three actuators for each leg of the dog needed to be attached to the system in order to transfer force.

7.4.1 Stepper Motor Linkage System

It was necessary to convert the rotary motion from the high torque stepper motor into a translational motion, and to do this a four bar linkage system was developed. The below Figure 25 illustrates the basic design of the crank- rocker linkage system on the model dog torso and thigh.

![Figure 25: Basic Overview of Linkage System](image)

The weight of the model leg, the braces, and the two linear actuators, was approximately 5 pounds. The thigh, at its lowest point before the knee joint, was required to undergo a displacement of 5 inches to reach all physiological angles seen during the gait cycle.

It was determined that the stepper motor and its crank only needed to rotate 140 degrees before returning to its initial position to meet the translational constraints of the leg motion. The crank was created out of aluminum stock metal, and was attached to the motor by a motor shaft attachment purchased online that was secured with a set screw.

To prevent shear forces in the crank-coupler pin joint from potentially causing an unwanted moment about the joint, two equal length aluminum coupler links were fabricated and placed on both sides of the crank with a pin joint securing them together. To reduce friction, nylon washers and spacers were utilized. Figure 25 below shows a CAD model of the crank, coupler linkage.
Figure 26: CAD Model of Crank Coupler Linkage

As can be seen, the double link coupler ensures no shear forces cause an unwanted moment at the pin joint. Figure 27 below shows photographs of the final fabricated crank, coupler linkage.
The two aluminum bars used for the coupler link were then attached to the shoulder screw located on one of the extruded cavities on the thigh brace, as can be seen in Figure 28 below.

Figure 8 details how the couple link attached to the brace system. A photograph of this attachment point can be seen below in Figure 29.
Given the 330 oz-in torque of the stepper motor, the crank length was minimized to 3” to provide a little over half of the total thigh movement necessary and to ensure maximum torque. This was done because throughout rotary motion of the motor, the displacement of the coupler would be equal to ~1.8 times the crank length. This resulted in a force of roughly 7 pounds used to propel the thigh forward during the swing phase of the gait.

This stepper motor linkage system successfully underwent close to frictionless motion and was able to move the thigh forward as designed.

### 7.4.2 Knee Linear Actuator

The knee linear actuator connected the aluminum bar on the femur orthotic shell to the bar on the tibia orthotic shell. In order to achieve a walking motion, the tibia must be able to retract and extend. Therefore, as the stepper motor swings the leg forward, the knee linear actuator keeps the tibia retracted. Then, at the proper moment in the gait cycle, the actuator extends the tibia allowing the leg to make contact with ground. The actuator keeps the leg extended as rotation occurs about the hip joint, in order to keep the leg straight and propel the dog forward.

### 7.4.3 Ankle Linear Actuator
The Ankle Linear Actuator connected the aluminum bar of the tibia orthotic shell to orthotic shell of the tarsus/paw. Similar to the movement of the knee linear actuator, the ankle linear actuator will be retracting and extending the foot. It will work in parallel with knee linear actuator, and perform retraction and extension at similar points in the gait cycle. The combination of all three of the actuators working in unison was crucial for the success of the project.

7.4.4 Linear Actuator Placement

During the first semester, the team initially designed for the linear actuators to be placed on an aluminum bar that ran along the lateral edge of the leg. In order to minimize the resistance the linear actuators faced when moving the limbs, attachments points needed to be placed as far from the joint center as possible to maximize torque.

However, after designing the final braces and choosing the optimal positions for the attachment points, final measurements revealed that there was not going to be enough space on the surface of the brace for all of the attachment cavities to be placed on the lateral side of the brace. Therefore, it was decided to place the knee linear actuator on the lateral side of the brace, and the linear actuator that controlled the ankle joint on the medial side of the brace. This final design was considered robust as, on a live dog, placing the knee joint actuator on the medial side of the brace would have interfered with the canine torso. The actuator in control of the ankle joint, however, would not interfere with any other body part if it was placed on the medial side of the leg. Figure 30 shows the placement of each linear actuator.
Once the team addressed OrthoPets about the attachment points and the hinges, it was determined that the final braces would be redesigned. First, the hinges that were used in the preliminary system were not the same as the ones that are used in marketable orthotics. Therefore, the final brace system was manufactured using frictionless hinges which fixed the friction issue at the joints. Second, the material used for the final system was polypropylene plastic, which gave more design freedom to approach the issue of actuator attachment as it can easily be drilled into while still strong enough to undergo forces.

As mentioned earlier, OrthoPets uses a vacuum forming process to manufacture their braces. To create the brace for this system, a polyurethane foam dog leg was cut, using a CNC, to the desired internal shape of the final orthotic brace.

Once the leg was properly carved, it was placed onto a solid tube that was attached to a vacuum. A solid sheet of polypropylene was heated in an oven until it reached a certain level of plasticity that made it very formable. The formable polypropylene was then draped over the foam leg and placed on the vacuum. The polyurethane foam was porous enough that when the vacuum was
turned on, the polypropylene was suctioned directly to the foam, which allowed it to stick to every surface of the foam. The vacuum then remained on as the polypropylene dried and hardened. Once the polypropylene was hardened, it was taken off of the vacuum, cut, shaped, and reassembled in order to fit the canine model leg.

Although the polypropylene was hard after drying, it was thin and did not hold fasteners well. Therefore, it was impossible to create an attachment point where fasteners were only placed into the polypropylene by any sort of threading. Therefore, the team developed a solution that made use of vacuum forming to create a cavity that could better hold fasteners. By building up the foam at strategic points among the leg, cavities were created along the length of the legs (Figure 31).

The cavities were hollow, and the team then drilled a number of holes into the surface of these cavities. Small aluminum pieces were created with threaded holes that matched the holes on the surface of each cavity, and went into the hollow spaces in the cavities. At least one hole in the cavity was used to hold the aluminum piece coincident to the inside of the cavity. Another hole was used to connect a shoulder screw to the aluminum piece. The shoulder screw served as a shaft for rotation of the linear actuators and the stepper motor. Figure 32 shows a cross section of the cavity, actuator attachment assembly.

**Figure 31: Actuator Attachment Point Cavities**
7.4.6 Leg Movement

In order for the cart to move forward, all of the actuators had to move in coordination with each other. Figure 33 below demonstrates the basic leg movement needed for the dog to walk in a biomechanically accurate manner.
Following Figure 33, with the leg starting in a standing position, both of the linear actuators retract to lift the toe off of the ground. Once the toe is out of the way, the stepper motor rotates to swing the entire leg forward. At the end of the arc, the two linear actuators then extend so that the heel of the foot strikes the ground. As soon as the heel strikes the ground, the stepper motor rotates the opposite direction to swing the leg in the opposite direction. The entire dog leg is in contact with the ground as the leg swings backward, which propels the cart forward. Once the leg is pushed to the end of its arc, the linear actuators retract again to begin the next step.

7.4.7 The Final System

In Figure 33, the cycle only shows the motion of one foot at a time. However, like any walking animal, two legs worked together to propel the cart forward. As the left leg swung forward, the right leg swung backward, and vice versa. Therefore, there was an even distribution of steps to push the cart forward. Figure 34 shows a CAD model of the final system that was fabricated.
Figure 34: Isometric view of the actuated exoskeleton attached to a rolling cart. During the presentation at E-Days, the Motorized Brace System was able to successfully and reliably walk forward in a cyclic motion. Figure 35 below shows a photograph of the final Motorized Brace System.

Figure 35: Photograph of Final Fabricated Motorized Brace System
7.5 Power

To power the entire system, three types of batteries were used: 1.2V-2600 mAH NiMH AA rechargeable, 3.7V-2200mAH LiION 18650 rechargeable, and 9V-230mAH NiMH 9V rechargeable. In order to power the linear actuators, two battery holders that consisted of an eight slot and a two slot were connected in series, yielding a voltage of 12. A 12V regulator was placed between the connection of leads and the linear actuator control (LAC) board. The LAC is able to carry a max voltage of 15V. It is important that this is not exceeded or the risk of frying the linear servo is increased.

To power the high torque stepper motors, seven of the 3.7V 18650 batteries were placed in series. Since this was the highest of our voltages with the largest amount of drive power, a switch was put in series with the positive lead of the battery pack. All of these were designed for an operating time of at least one hour based on customer requirements. For the actuation system an external power (batteries just mentioned) had to be applied to the linear actuator control board and stepper motor driver. More detail about the electrical system can be found in Chapter 9: System Configuration.

7.6 Coding

The code controlling the device had to be less than 256k bytes in order to be stored on the Arduino Mega. The program reads in a file that contains the data collected from the Data Collection Brace System. The code mainly consists of while and for loops as well as software interrupts within those loops to ensure fluidity of the device and the safety of the canine. The interrupts were used to exit the loops and stop any movement that could cause any harm. While loops acted as the different stages of the device. The for-loops were within the while loops and were used to move the actuators into position during each of the different stages. Below is Figure 36, which shows a simplified flowchart of the code.
The device waits for the sensors to pick up the trigger signal. Then it decides what foot needs to move forward and which one goes backwards. From there both legs go through their individual cycles and continue to do so until the sensors pick up an anomaly within the pattern. This will either return the legs into a neutral standing position or it will cease all movement depending on the type of anomaly. The entire code can be found in Appendices I and J.
Chapter 8: Data Collection Brace System

A Data Collection Brace System acted as the passive system and was designed and fabricated to be placed on a live dog to ensure maximum safety when working with a live animal. The braces for this system were very similar to those braces used by OrthoPets passive orthotics. Therefore, after getting IACUC animal testing approval, the testing dog was measured and leg scans were performed so that OrthoPets and the team could begin the fabrication process.

8.1 System Requirements and Engineering Specifications

The data collection system of the devices incorporates a system of gyroscopes/accelerometers and pressure sensors that relay feedback to control the Motorized Brace System, accounting for the speed, placement, and controllability of the system. When considering the design goals, the final system must accomplish the customer requirements and engineering specifications in Tables II and III, and Chapter 5.

8.2 The Sensor System

In order to apply motion towards a motorized linkage system, the team designed a system of pressure and gyroscope sensors that were placed on a healthy canine in the spring semester. Coming up with this system required an analysis of the available devices that would read movement data and a general understanding of each device’s role in the system. The sensor system would require a primary trigger mechanism to communicate the beginning of the control sequence of the actuation system as well as a series of checkpoints for the gait cycle.

8.2.1 Potential Trigger Methods

In order to find an appropriate device for the trigger, an understanding of dog walk movement was essential. The team did an analysis of different sensing devices to determine the best ones to use in the data collection brace.

8.2.1.1 Potential Electromyography (EMG) Concept

This system had multiple changes while considering the design constraints found throughout the year. The original goal was to use EMG muscle signals to understand when muscles are activated, which would ideally trigger leg movements much more precisely, and would also potentially have some application with weakened/partially paralyzed dogs [Adrian 2011]. However, there were many conflicts with using this sensor. First, most EMG sensors that are used on dogs for data collection are invasive, which the team would not be able to use without proper veterinary training and oversight. Second, the non-invasive, surface EMG sensors are incredibly noisy and would have been difficult to translate into coding for the both the variability of the muscle, noise, and for the mechanical system. Third, since deciding on using the Arduino Microcontroller for our system, we would have been limited as to what types of chips would interface and gather the EMG data. There were a couple different sensors that were offered to hobbyists, but nothing that’s accurate enough for this application.
8.2.1.2 Pressure Sensors

When looking at pressure sensors, the team found that the accuracy of these pressure sensors was not always incredibly precise, but could still be utilized as a secondary control system. These piezoelectric sensors were cheaper and easier to manipulate in terms of placement, coding, and the variability of the pressures applied, assuming that the pressure would be read from the tibia, femur, metatarsus, and paw. Thus it would not be suitable to trigger the code cycle and trigger the walk for the device. In the end design, the pressure sensors are a useful positioning check, so the device still incorporated these into the design.

8.2.1.3 Gyroscope/Accelerometer

The team’s next option was to consider the front leg movement of the dog, as it is a visual trigger for the gait cycle. The most efficient way to sense this initial trigger was to use the speed and angle of the movement, which is why the Gyroscope/Accelerometer chips were chosen. The gyroscope accelerometer combination would allow the code to understand the front paws’ placement in space and speed. This system reads in muscle pressures, angles, and speeds of the different stages in the gait cycle of a walking dog.

8.2.2 QFD Decision Matrix of Initial Trigger Mechanism

To help make decisions on the trigger mechanism, the team came up with a QFD chart to decide on the appropriate initial trigger, shown in Figure 37. The numbers in the weighted sum came about from the plus and minus signs that showed whether the potential concept helped the specifications or did not. This chart also helped us decide the overall sensor system by showing us the pros and cons of the different sensors.
The QFD chart indicated the best initial trigger of the system is the first front step of the dog, which will be read by a gyroscope/accelerometer chip and will give us the initial change in speed and angles. The initial trigger will then trigger the reading of the opposite side, hind leg angles and pressures to interpret the current position of the gait cycle. This is the gait pattern of a walking canine; refer to Chapter 2.1 for reasoning. These signals are then interpreted by the microcontroller, the Arduino MEGA, and processed into our motorized system.

### 8.2.3 Sensor Circuit

After deciding on the gyroscope/accelerometer as the initial trigger, the team then decided to implement pressure sensors as the checkpoints of the walk cycle since the dog would be leaning against specific points in the brace as it would be walking. These pressure sensors were fitted along the entire brace on the thigh, knee, ankle, and paw of the brace, at locations with bony prominences to get more robust data. For more information on the hardware of the sensor circuit, please reference the functional diagram in Section 9.1.

### 8.1 Mechanical Design and Fabrication

The Data Collection Brace System consisted of the front paw gyroscope holders and the hind limb data collection braces.
8.1.2 Front Paw Gyroscope Holders Design and Fabrication

The gyroscopes needed to be securely fastened to the front paws. This was necessary in order to keep the gyroscope axes consistent while the test dog was walking around in them. A very simple solution was developed by taking a neoprene sleeve and strapping it to the metacarpals on the front paw (Figure 38 below).

![Figure 38: Canine Metacarpals on Front Paw](image)

The metacarpals undergo large changes in angle as the dog’s front leg moves forward. The metacarpals were therefore strategically chosen as the gyroscope attachment point because these large changes in angles were able to be sensed by the gyroscope very easily.

8.1.3 Data Collection Braces Design and Fabrication

The Data Collection Braces needed to envelop a live dog’s leg and hold some sensors. However, the overall design of the Data Collection Braces was much simpler than the design of the Motorized Braces because the Data Collection Braces did not need to hold any actuators and were very similar to products already created by OrthoPets. Therefore, this brace did not contain any actuators cavities that were discussed earlier for the motorized braces. Instead the entire brace was smooth and only contained extrusions where it was necessary to provide support to the animal. Figure 39 represents a CAD model of the final braces that were created.
The leg scan data from the live test dog was inputted into a CNC machine, which carved a foam, anatomically identical leg to that of the test dog. After shaving the foam legs down and placing hinge extrusions on the leg, polypropylene plastic, a thermoplastic, was heated up to deformation temperature, and wrapped around the foam leg, and vacuum formed to its shape, the same process described in Section 7.4.5 for the Motorized Braces. The plastic cooled to a rigid state, and was then carefully removed from the foam, and ground and cut in certain locations to allow for a real dog’s leg to easily slide into the plastic.

Next, this plastic was cut into the three leg segments, and hinges were placed in the extruded hinge locations of the plastic and fastened with screws. Finally, a soft, thin foam was used as a liner inside of the brace to increase comfort for the canine.

The next step was implementing the electrical sensor system into these braces for the data collection process and retrieving healthy walk data for the mechanical braces. This would help the team understand the dog walk and allow for adjustments physically, electrically, and mechanically of the motorized brace design in regards to speed, torque, and kinematics.

A photograph of the final fabricated sensor braces can be seen below in Figure 40.
Figure 40: Photograph of Fabricated Sensor Braces

The red and white chips at the ends of the wires in front of the sensor system are the gyroscopes that attached to the front paw for data collections.

8.2 Power

For the power on the Data Collection Brace System, which includes gyroscope, accelerometer and pressure sensors, power was supplied directly from the Arduino microcontroller. The 3.3 Volt pin on the Arduino powered the gyroscope/accelerometer, a device which could potentially draw 7.6mA. For the pressure sensors, a 5V signal was created by connecting the 5V pin on the Arduino to one end of the sensor while the other connected in parallel with a resistor and Arduino. The resistor was then connected to ground completing the circuit. The 9V batteries were used to power the two Arduino microcontrollers. The functional diagram provides more detail about how the system interacted, refer to Section 9.1

8.3 Data Collection Sessions

After the animal testing protocol was approved (refer to Appendix L for the full protocol submitted and approved), the team was able to work with a female adult black Labrador Retriever to collect the sensor data. The approval required that the dog was only tested in the Engineering building, the hallway by room B111.

The dog was first fitted to the brace and slightly adjustments to strap lengths were made. The owner was then tasked with putting the braces on the test dog for two 20 minute sessions every
day for three days to get the animal accustomed to wearing the braces and walking with a normal gait. Figure 41 below shows the test animal, Maya, wearing the hind limb braces.

![Data Collection Brace System on Live Dog](image-url)

**Figure 41: Data Collection Brace System on Live Dog**

The dog was brought in for two data collections in the second semester, one for purely front paw gyroscope data and the other for the front paw data as well as the hind limb pressure sensor data.

### 8.5.1 First Data Collection

During this trial, the only data collected was the front paw gyroscope/accelerometer data. At this time, the leg braces were not ready and so it was simpler for the team to first test the front triggers on the live dog. Figure 42 below shows the basic trends seen in this gyroscope/accelerometer data.
As can be seen in Figure 42, it was very obvious when the dog’s front paw was taking a step forward. Therefore, this sensing mechanism was deemed accurate and robust for use as the trigger mechanism for the leg motion.

8.5.2 Second Data Collection

This second trial implemented the entire Data Collection Brace System including the gyroscopes and pressure sensors and found valuable data to show the walk cycle. Figure 43 below shows an example of the data recorded with the pressure sensors on the right leg.
As can be seen in Figure 43, the pressure sensors easily detected the different movements as the dog walked forward. This data could then be used as a modulation method to determine two important states:

1. If the dog was resisting movement, in which case the system returns to neural position and shuts off as an emergency cutoff. This data was collected from the pressure sensors on the inside of the braces, i.e. the thigh, tibia, and metatarsus segments.
2. Where in the gait cycle the dog was (i.e. swing phase, toe off, heel strike). This data was collected from the pressure sensors on the bottom of the paws.

The gyroscope and pressure data was successfully implemented in the code to trigger and modulate the actuation in the Mechanical Brace System.
Chapter 9: System Configuration

The system was designed to coherently and accurately follow the requirements of the project. Even though the system was split into two for safety and testing purposes, the goal for the electrical design was to still have a device that accurately collected data and a device that actuated according to said data, thus proving that in future years the system can be integrated.

9.1 Functional Diagram

Figure 44 shows a functional diagram of the electrical hardware of the system.

This functional diagram explains the circuit process of the device.

1. Gyroscope/accelerometer are placed on the front paw of the dog, this determines the position in the gait cycle, but mainly acts as trigger to the cycle of motion. These communicate over SDA/SCL inputs.

2. The Arduino MEGA powers the gyroscope/accelerometer with the 3.3V supply.

3. Pressure sensors act as a system “state” and modulate to help the controller understand positioning and movement. These are connected via analog inputs, and read as a 0-5V input signal.

4. Arduino MEGA communicates via pulse width modulation (PWM) to the linear actuator control board and the stepper driver to guide the position for the linear actuators and stepper motors.
5. Linear Control Board (LAC) and Stepper Driver match the PWM signal with the external power supplied by the batteries. This allows for the proper amount of power needed by the motors.

6. All communications to the motors are done with PWM as a digital output.

7. The stepper motor has high precision, therefore no feedback signal was implemented on this part of the motorized system. Motor rated at 24VDC with a max operating current of 2.8 Amps.

8. The Linear Actuators have a closed loop feedback system implemented, and operates at max speed at 12V with a max operating current of 1 Amp.

9. All data processing and control signals are being done by the Arduino MEGA.

10. 9V rechargeable batteries will power the Arduino MEGA.

11. 12V rechargeable battery will power the linear servo.

12. 24V rechargeable battery will power the stepper motor.

Full hardware schematics can be found in Appendix K of the report.
Chapter 10: Testing

While the team has already written a device testing and validation document (Appendix E), there have been updates to the types of tests that were completed.

10.1 Batteries

The batteries were tested to make sure they were capable of powering the linear actuators and stepper motors. This number was purely based on how much torque the motors needed and how fast they needed to actuate. A multimeter was used to see the voltage and current draw and losses on the batteries from the actuators. Making sure that all batteries are fully charged is important to the functionality of the system, especially the linear actuators since the speed is based on voltage. During the testing of these batteries on the system, the system was able to remain powered on average for one hour and ten minutes, exceeding the team’s goal of an operating time of one hour.

10.2 Gyroscope

Early testing of the gyroscope included checking its accuracy as a constant position monitoring device. Initial results indicated that the gyroscope met the required specifications. The major final test of the gyroscope was placing it on the live dog’s front legs during data collection and analyzing the data afterwards to ensure there were obvious trends and peaks seen during steps vs. when the dog was not moving. Refer to section 8.5.1 for a graph of this data.

10.3 Pressure Sensors

The pressure sensors were first tested by simply applying pressure with fingers and ensuring the pressure data displayed on the computer was proportional to the force applied. These tests supported the robustness of the pressure sensors, and so they were placed under the data collection brace paw and inside the braces at known bony prominences (where pressure would be highest if the dog was resisting motion). Again, the major test of these sensors was placing the data collection braces on the live dog and recording the data. The pressure sensor data from the live dog was not as robust and accurate as the gyroscope data from the live dog, but still had enough variations to be considered a method of modulation for the system. Refer to section 8.5.2 for a graph of this pressure data.

10.4 Code

The code for the system was tested and debugged so that it could use the appropriate input and output signals to trigger/modulate the system whether it’s for the normal gait cycle or with a safety feature like the emergency shut off. This was tested with different data collection trials as well as modifications to these data collections to simulate if the dog were to fall over. The last step in testing the electrical system is testing if the two microcontrollers will be able to communicate with each other in real time so that one can collect the data and the other processes that data. With each of the time stamps the length to collect one section of data, process the data, and then perform the appropriate task was less than half a second. This was within our bounds of real time.
10.5 Biomechanics

The biomechanics of the Motorized Brace System were recorded with video and compared to the biomechanics data discussed in Chapter 2. At all points in time, the Motorized Brace System was within +15 degrees. Although the team ultimately wishes to make this deviation less than 5 degrees, for the first year of the project the goal of 15 degrees was successfully reached.

All of the above testing plans are more thoroughly documented with details in Appendix E of the report.
Chapter 11: Design for Requirements

Sections 7.2 and 8.2 documented the specific reasons for choosing the design of the system through a Quality Functional Diagram analysis. Below illustrates the more general overall goals of the device and how the team designed for these goals.

11.1 Safety

Because the ultimate goal of this project is to place this device on a live animal, it was of paramount importance that the team designed for safety. While future teams will have to consider the safety of the actuation system, this year the team focused primarily on the safety of the Data Collection Brace System which was placed on a live dog. The actuation system was purposely housed on a dog model, eliminating possible safety risk of the motors to the dog for this year. With the constraints of the project in mind, the team did an extensive risk analysis, shown in Chapter 12. This chapter accounts for potential failure modes, severity, likelihood, and the actions that were taken to provide maximum safety.

11.2 Rehabilitation

This being the inaugural year of the project, it proved impossible given safety constraints to assume the team would be able to rehabilitate a live canine within this year. Given the amount of research and design that was necessary before receiving animal testing approval, the project was scaled down for the first year to still design for rehabilitation, but not be able to test this component. The current device does not provide any sort of rehabilitation to a live dog but instead provides proof that the device will be able to move in a kinematically correct manner with real-time signals from a live dog. The model dog legs do undergo loading forces, which would on a live dog provide a form of therapy to both increase muscle tone and bone porosity. The hope is that next year’s team will be able to take signals from a paralyzed dog and still be able to generate a kinematically correct walk. The final device must be integrated to one physical and electrical system and be able to sense movement from a paralyzed dog and then actively rehabilitate the paralyzed dog until the assistance is no longer needed. Ideally this device will be able to lessen its support on the legs as the legs begin to heal.

11.3 Mobility

From a mechanical perspective, the proposed canine model does go through a biomechanically correct gait motion through the help of the actuators. This provides proof of concept that this model dog could be replaced by an actual dog and increase mobility of the diseased animal.

11.4 Usability

There are many different and necessary aspects of a device to make it usable. For the purposes of this first year prototype, the team focused on developing a system that could run for an hour before needing to be recharged. This was done after input from veterinarians who said that twenty minute
sessions in this device would be ideal. Therefore, our device was designed for a minimum of two twenty minute sessions of use.

While ease and comfort is an important factor for the usability of the product, the team enlisted the help of OrthoPets to design custom-made, comfortable yet durable braces and attachments that are adjustable to each individual canine. As for future years, the team will continue to work with OrthoPets to adjust the design to each dog the team works with.
Chapter 12: Risk Analysis

12.1 FMEA Analysis

The purpose of the FMEA Analysis is to identify the ways in which a failure could occur (mode), the corresponding consequences of that failure (effect), and the severity of each effect. A functional FMEA was performed in order to determine potential causes of various failures and identify what prevention and detection methods could be utilized in order to decrease the risk of a catastrophic failure. Please refer to Appendix H for the analysis chart.

12.2 Human/Canine Factors Analysis

Because the focus of this year’s prototype was to simply achieve intended movement due to limited time and resources, a limited human interface analysis was performed during the design process. The below factors were considered when designing the device for human factors:

- Ability for the left brace to be placed on the right leg and vice versa
  - Effect: Mechanical and electrical system would be “inside out” and could actuate the wrong leg forward, resulting in instability leading to a fall.
  - Mitigation plan: The braces were specialized for the right and left leg and do not fit the opposite leg due to their curvature.
- Strapping the dog’s legs too tightly into the device
  - Effect: Constriction of blood vessels and nerves could lead to serious consequences such as amputation or paralysis
  - Mitigation plan: Velcro straps were cut to strategic widths to increase the surface area exposed to dog skin and therefore lessen the force applied to a single location.

Furthermore, for this year a more applicable “Dog Factors Analysis” was performed.

- Dog chewing on the device
  - Effect: Dog could chew on the brace or linkage material, severely decreasing or eliminating the mechanical strength of the device. Dog could also chew on actuators, loose wires, or microcontrollers.
  - Mitigation plan: Minimized loose mechanical components on brace. Allowed the dog to sniff the braces before putting them on and just in general get comfortable around them. The braces were also given to the owner before data collection occurred and the owner allowed the dog to get used to wearing the braces for 20 minute sessions two times a day for three days. Additionally, all electrical components were secured as best as possible.
- Dog attempting to move backward/turn/climb stairs/sit/run
  - Effect: Dog could fall over due to instability since the current device will not allow motions other than forward walking.
  - Mitigation plan: Mechanically actuated system was rigid, not allowing other motions. However, if the dog does try to move backward the pressure sensors in the brace sense this movement and shut the system down.
- Dog fighting actuators during movement
  - Effect: Dog will be put under considerable stress trying to stop its leg from moving.
Mitigation plan: If the dog severely resists the motion, the feedback mechanisms on the actuators along with the pressure sensors in the brace senses this change and stops the device.

Dog urinating
- Effect: System will become wet and electrical components could be damaged.
- Mitigation plan: Walked dog prior to wearing system, and ensured any lower electrical components were in a waterproof encasing.

Besides the risks associated with how the canine uses this device, there are also some inherent risks associated with placing a system like this on a dog, hence why for the current year we plan to have two separate systems with only sensors placed on the live dog. Despite this fact, a risk analysis for the health of the dog was performed and can be seen below in Table IV.

**Table IV: Risk Analysis for a Dog**

<table>
<thead>
<tr>
<th>Risk</th>
<th>Undesirable Effects</th>
<th>Severity (1-10)</th>
<th>Likelihood (0-100%)</th>
<th>Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstable</td>
<td>Could harm dog’s leg or cause dog to fall</td>
<td>8</td>
<td>30%</td>
<td>Structural analysis tests on all components to ensure stability.</td>
</tr>
<tr>
<td>Burns</td>
<td>Could harm dog’s leg</td>
<td>8</td>
<td>20%</td>
<td>Encase circuits in heat resistant material.</td>
</tr>
<tr>
<td>Skin irritation</td>
<td>Cause discomfort to the dog, dog will not walk appropriately will tear off device.</td>
<td>3</td>
<td>80%</td>
<td>Work with Orthopets to ensure that device is attached to canine properly.</td>
</tr>
<tr>
<td>Electrocution</td>
<td>Could harm and potentially kill the dog</td>
<td>10</td>
<td>5%</td>
<td>Ensure no loose wires are present or exposed to the canine. Waterproof and encase the circuits.</td>
</tr>
<tr>
<td>Joint angles</td>
<td>Angles are too extreme, can tear ligaments/break dog’s bones.</td>
<td>8</td>
<td>20%</td>
<td>Work with VTH kinematics lab to acquire proper kinematic data. Test our device with the kinematics lab on models to ensure compatibility.</td>
</tr>
<tr>
<td>Gait</td>
<td>Device influences incorrect gait pattern.</td>
<td>6</td>
<td>50%</td>
<td>Work with VTH kinematics lab to acquire proper kinematic data and gait data. Test our device with models to ensure capability.</td>
</tr>
<tr>
<td>Durability</td>
<td>Dog sitting/falling on hind legs and breaking the device.</td>
<td>7</td>
<td>70%</td>
<td>Use quality materials to construct exoskeleton and casings.</td>
</tr>
<tr>
<td>Bioburden/Nature hazard</td>
<td>Bodily fluids or debris get on device.</td>
<td>6</td>
<td>70%</td>
<td>Design device to be easily cleaned. All circuits and servos will be in protective casing.</td>
</tr>
<tr>
<td>Budget</td>
<td>We run out of money.</td>
<td>2</td>
<td>80%</td>
<td>Create a more accurate cost analysis. Fundraise depending on future design requirements.</td>
</tr>
</tbody>
</table>
Chapter 13: Ethical Issues

The project faced a number of ethical concerns that were addressed. The number one priority of the project was to ensure the safety of the dog both in the instrumented Data Collection Brace System that actually interacted with the dog this year, and in the Motorized Brace System that did not go on a dog this year, but must be designed with safety in mind.

13.1 Animal Safety

To ensure that the animal was not harmed, the team worked closely with canines and a canine physical therapist (Sasha Foster) to gather a variety of preliminary information about how paralyzed/weakened dogs walk. The team worked closely with the Veterinary Teaching Hospital and OrthoPets to determine any/all risks involved both with dog testing and the overall design of the device. The device underwent rigorous mechanical and electrical testing on a test fixture before it was placed on the live dog (see Appendix E). Additionally, team members completed IACUC and RICRO training in order to safely interact with dogs (see Appendix F). A six month long animal testing approval process occurred, and that submitted and approved protocol can be found in Appendix L. All precautions were taken to ensure the health and safety of the canine before the device came into contact with the subject.

13.2 Global Issues and Ethics

From a global perspective, to our knowledge, there is currently no powered mobility device available for canines. Therefore this product, if successful, could become very popular in the concerned population, albeit small. The project device aims to not only provide mobility but also rehabilitation to the canine, so there is the potential that a system like this could get insurance approved. Although individuals can purchase health insurance for their pets, according to the North American Pet Health Insurance Association, only about 0.65% of all of the pets in the U.S. are insured, so most customers would be paying for this device out of pocket. Therefore, despite having insurance potential, this would most likely not lead to a more impactful product.

Although it would be incredible to say that this device will immediately impact the market on a global level, this will likely not be the case. One major reason for this is the level of importance people from different cultures place on their dogs’ health. Frankly, certain cultures would scoff at the idea of paying the cost of this device (see Appendix B) for an animal. With the initial high cost of this device, it is unlikely that it would be readily available to developing countries who do not even have the funds for this level of technology for humans.

13.3 Environment

Based on current projections of the device design and use, this project does have a large impact on the environment. The device requires a custom fitted brace for each dog that will be owned by that owner and used for its lifetime. All batteries used are rechargeable to limit the amount of disposable products associated with the device. Additionally, the team did not use any hazardous material for the construction of the brace systems. The team remained mindful of this as to not contribute to unnecessary waste.
13.4 Research Ethics

For the moment, all intellectual property from this project belongs to the team members and adviser. There is the potential for a patent to be filed by the end of the year, and care will be taken to ensure meticulous records of group effort and individual contributions. It was also incredibly important to maintain proper ethics during data collections with the live dog. The team had to follow the protocol that was submitted and could not deviate from it without requesting approval beforehand. Additionally, a significant research background and literature review was necessary for ensuring all facets of the project are considered. Therefore, it was important that all sources were cited and acknowledged. Finally, while collaborating with a plethora of experts from the Veterinary Teaching Hospital and at OrthoPets, we ensured that they were properly acknowledged for taking the time to contribute their knowledge and resources to this project.

Overall, this project entailed multiple ethical issues that the team worked to successfully resolve. The highest priority was given to the safety of the dog, but other global, environmental, and academic concerns were also addressed. The device could have a positive impact for many pet owners, and therefore all precautions were and will continue to be taken to produce a safe and high quality device that is produced using ethical guidelines.
Chapter 14: Conclusions and Future Work

14.1 Results of Project

The team successfully created a proof of concept system for a Canine Exoskeleton for Mobility and Rehabilitation. Below are the major accomplishments of this year’s project:

- A large understanding of the best methods for designing this device was gained through intense collaboration with OrthoPets and the Veterinary Teaching Hospital.
- A biomechanically accurate hind limb dog model was created along with a cart fixture to provide stability and mobility.
- A Data Collection Brace System was designed, customized to a live dog, and successfully fabricated.
- Multiple data collection sessions resulted in robust data that was used for input into the Motorized Brace System.
- A Motorized Brace System was designed and fabricated with actuator attachment points and linkage systems.
- A robust electrical system of sensors, motor drivers, and actuators was assembled to convey vital information between systems.
- An efficient code linked the two systems together and allowed proof of concept that this system could be combined.
- The Motorized Brace System successfully walked forward based on input from data collected previously.

We created a safe testing model that can be used to verify future design requirements without endangering the dog.

Figure 45 below shows the team’s overall design control process.
As can be seen in Figure 45 above, the five main customer requirements the team attempted to meet were providing mobility and rehabilitation and ensuring safety, usability, and cost effectiveness. These requirements were developed into the main engineering specifications that were used as the design input. After following the design process and performing all technical analyses, a device was created. Upon observing the design output, it was determined the major issue with the current device was the low power and quality of the actuators. Given the low budget for the team this year, this was expected and can easily be addressed. However, verification testing definitely revealed that this was a major issue and must be fixed before this could be considered a successful exoskeleton medical device. Further information about limitations of the current system can be found below.

14.2 Limitations of Current Device

The final two system prototype successfully walks forward based on data collected from previous live dog sessions. However, upon analysis of the final product for this first year, there are certain aspects that could be improved upon for future years.

14.2.1 System Speed

The actuators for this system were fairly inexpensive and therefore not as powerful as the team would have preferred. Due to the weaker motors, the system was unable to move as quickly as a
live dog walks. Given the team’s limited budget this issue was something that was impossible to overcome for the first year, but with a larger budget could easily be fixed.

14.2.2 Usability

The team focused on only one small aspect of usability for the first year: operating time. We successfully reached this goal by having a system that can operate for more than two twenty minute sessions of use. However, usability is a very broad customer requirement that absolutely needs to be fully addressed before this could be a marketable product. Some necessary usability components to consider include, no loose parts that the dog could easily tangle with, ease of assembly for the owner when putting the device on, light enough so that the dog does not feel weighed down, etc.

14.3 Plans for future years

In future years, this device will be expanded upon. The goal is to develop a single system to ambulate an unhealthy dog. This can be readily accomplished with a larger budget as the main setback of the current device is actuator speed. Figure 46 below provides a concept design of what a final combined system may look like on a live dog.

![Figure 46: Concept Design of Future Combined System](image)

The system itself can also be expanded to have a modular speed in order to compensate for running. Additionally, a dog’s leg motion is not strictly 2D, so future research is needed for different planes of motion, such as turning, sitting, and going up and down stairs. The ultimate goal of the system is to fully replicate a healthy canine’s complete range of movement and provide exceptional physical therapy and mobility to a currently diseased dog.

The team also prepared future teams through a variety of research and design strategies.
14.3.1 Dog Model

The biomechanically and anatomically accurate dog model will be available for future use. It is easily modifiable so that any changes the project will have in the future can be easily made to it. The dog model provides a method for testing concepts on a test fixture versus attempting to get approval (which was over a six month process) to put this on a live dog.

14.3.2 Integration

The current system is not completely integrated but is designed with that goal in mind, allowing an easier transition between years. This is because the goal of this project is to gather testing data but also design a mechanical system that electrically connects to the sensors. With a larger budget, these actuators could be placed on the sensor brace system and create a single actuated exoskeleton with embedded sensors.

14.4 Final Thoughts

Future teams will utilize this first year project to further develop a robust device that could one day help canines. The successes and the failures were well documented so that the next year will be able to not only know what did and did not work, they will also be able to understand why they did and did not work. The research done for this project, a large majority of the first semester, was documented extensively so that the new team members are able to reference back to this year’s findings.

The team is very proud of the fabricated device and feels that we have created a successful, “walking” prototype that could one day have an impact on the market and actually help paralyzed/weakened dogs walk again!
References

2. C. Adrian, 'Kinetic, Kinematic and Electromyography Analysis of Canine Cruciate Ligament Rupture Using a Monopolar Radiofrequency', Ph.D, Colorado State University, 2011.
3. C. Creamer Jr., 'Mobile sling for crippled animals.', 2,546,726, 1951.
Appendix A: Abbreviations

1. BME - Biomedical Engineering
2. CSU - Colorado State University
3. DOF - Degree of Freedom
4. ECE - Electrical and Computer Engineering
5. EMG - Electromyography
6. FCE - Fibrocartilaginous Embolism
7. FMEA - Failure Modes and Effects Analysis
8. I – Amperage
9. IACUC - Institutional Animal Care and Use Committee
10. LAC - Linear Actuator Control Board
11. ME - Mechanical Engineering
12. QFD - Quality Functional Diagram
13. RICRO - Research Integrity and Compliance Review Office
14. VTH - Veterinary Teaching Hospital
15. V - Voltage
Appendix B: Budget

Our budget consists of the allowances given by the Electrical Engineering and Biomedical Engineering departments at CSU. Below is a table of our estimated costs of the project.

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The team was allotted $1,200 at the start of the year. Each team member was given $200 from the ECE department, and originally the team had an Open Option student planned to contribute to the project, giving us $1,200. The team approached the School of Biomedical Engineering and was given $400. After a competitive fundraising presentation, Keysight Technologies funded $320 and Haley King’s Honors Thesis Grant was $200. The budget after fundraising was $2,120.

Total money spent on mechanical fabrication was $661.85, the actuation of the Motorized Brace System was $714.72, and sensing system and electronic components was $354.65. Total money spent during the year was $1,731.22, with $388.78 left over.

While the team managed to stay within the budget, certain customer requirements were not achieved. Many of the hardware used was acquired through student discounts as well. On the next page is the team’s budget sheet for the entire year.
### Table V: Budget

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Appendix C: Donations Letter of Interest

To whom it may concern,

Every day, some dogs lose their ability to walk due to hind limb weakness or paralysis from a variety of diseases. These symptoms can appear with no warning and lead to the paralysis of dogs’ hind legs and sometimes even the front legs. Many of these conditions are nonprogressive and dogs can recover their ability to move over time with physical rehabilitation. However, many owners do not have the capability to provide treatment and thus end up using wheelchairs or other relief devices that do not help the dog regain strength. They remain unable to walk properly, and so there is a need for a physical therapy device that pet owners can use.

We are the Canine Exoskeleton for Mobility and Rehabilitation Senior Design team from Colorado State University, comprised of biomedical, computer, electrical, and mechanical engineering students. The goal of our project is to create a rehabilitation exoskeleton for dogs suffering from these mobility impairments. This device would be placed on the paralyzed dog and aid in motor functions until the dog regains its strength. The research accomplished for this project will, one day, also be applied to modern human physical medicine to ultimately develop a device that will mobilize paralyzed individuals. This first year of the project, we are researching the walking movements of dogs and we hope to create a device that will use movement signals read by a sensor system to replicate the correct hind limb movement of the canine. The sensor system will be comprised of accelerometers, gyroscopes, pressure sensors, and Arduino microcontrollers, which will then process the data being collected and will replicate the angles of movement onto a motorized exoskeleton comprised of linear actuators and stepper motors. This motorized exoskeleton will be placed on a movable dog model that will provide proof of concept by “walking” alongside a live dog wearing the sensor system. We are writing to you to ask about possible funding opportunities to aid our efforts in creating this system by the Senior Design Showcase Event in April of 2016. We rely on the support of industry members, consumers, mentors, and those who are interested in the cause in order to be successful.

Movement of the exoskeleton will require powerful, expensive actuators to compensate for large loads since we will be working on modeling a larger dog breed, a Labrador retriever. In addition to load capacity, these actuators must be extremely precise and fast since we are modeling live animal movement. The sensors must also be extremely accurate when it comes to leg angles, speed, and pressures. We are also working diligently with our academic advisor and the CSU Vet
Teaching Hospital to more thoroughly understand what type of conditions and problems our device must be capable of handling. These expensive devices, construction of our moving model, electrical and mechanical device testing, and other device cost conditions will require much more than our starting budget if we want a stable and precise model by the end of the school year. The Electrical Engineering department at CSU is providing us with a $1200 starting budget ($200/team member+$200) and we also received $400 from the School of Biomedical Engineering. OrthoPets, an orthotics company for pets, has also offered to provide certain resources such as customized orthotic braces, foam models of canine hind limbs, and any other orthotic needs we may encounter. Without this support, our estimated budget would be incredibly expensive. Additionally, we are working with the CSU Veterinary Teaching Hospital to ensure we are developing a safe and reliable device that we plan to begin to test on live dogs this year. Please see below for an estimate of our budget in order to produce a robust device. In total, we currently have $1,600, which does not hit the minimum cost of our project.

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Thank you very much for your time. If you have any questions about the project or our funding strategy, please do not hesitate to contact us, our faculty advisor Dr. Anura Jayasumana, or the Head of Senior Design in the ECE Department Olivera Notaros. We appreciate any form of funding you can provide and believe that our project will be a strong reflection of your company. Should you choose to donate, please do so online at https://advancing.colostate.edu/ENG/ECE_SRDESIGN/GIVE and in the comments section say, “Donation to Canine Exoskeleton for Mobility and Rehabilitation.” Thank you for your support and we hope you enjoy our project!

Sincerely,
The Canine Exoskeleton for Mobility and Rehabilitation Team

Team Website: http://projects-web.engr.colostate.edu/ece-sr-design/AY15/canine/
Team Contact Info: Haley King, haley.king11@gmail.com, 574-849-4606
Advisor Contact Info: Dr. Anura Jayasumana, Anura.Jayasumana@colostate.edu
Appendix D: Project Plan Evolution

***Detailed Gantt Charts available upon request. See Chapter 3 for overview of project plan.

Original Project Plan: September 14, 2015

Team Deliverables
- Electrical Engineering Based (Katelyn Harada and Jeremy Valades)
- Mechanical Engineering Based (Daniel Vance and Haley King)

**Jacob Bryant, the computer engineering team member, will be integrating the mechanical and electrical systems and therefore working with both groups.
Revised Project Plan: November 6, 2015

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Revised Project Plan December 7, 2015

Today's Date: 12/7/2015

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# Final Project Plan April 15, 2016

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Appendix E: Detailed Device Testing Plans

*The previous Device Test and Validation Original Document available upon request. The following pages detail how the device components will be tested and validated.

1. **Initial testing of batteries**
   1.1. *The power system needs to power the sensor system and linkage system for at least two hours. This will be accomplished by having two separate power supplies, one for the sensor system and one for the linkage system. Nine volt rechargeable batteries will run the Arduino Mega microcontroller, while a still in development power system will supply the actuators. Test is for longevity of the device.*
   1.2. Testing batteries

We will be testing each battery through the year by using them to power the Arduino and sensors to test the length of time. We will not be able to test the linkage system until it is finalized.

Results (expected): The 9V battery will be able to last for at least three hours, but will not be enough to power both the sensor system and our linkage system. Another power system must be developed for this

2. **Initial testing of Accelerometer/Gyroscope**
   2.1. *The intent of using the accelerometer/gyroscope chip will be applied as an initial trigger to the system. Idea is to put the chips on the legs of the dog to read in the angles and motion of the first step taken to move forward. When certain angles/speeds are hit within the step, it will indicate to the Arduino to initiate motors on the braces of the hind legs to bend to hind leg angles. Test is for the interconnectability and stability of the device.*
   2.2. Testing gyroscope

Testing done for accuracy of the gyroscope involved using pre-made coding and circuit design found online since Arduino code is open-sourced. Test was made to determine accuracy of angles to validate using the gyroscope as an initial trigger. Gyroscope will be used to monitor position of gait cycle by relating front and back leg angles.

Results: Gyroscope proved to be accurate with angle values given of up to four decimal places. While stationary, gyroscope angle varied $\pm 0.0005$. This shows us that using the gyroscope is beneficial as a trigger method for the gait cycle.

   2.3. Testing accelerometer

Using pre-made Arduino code and circuit design found online, test is to determine accuracy of acceleration to validate using the accelerometer as an initial trigger. Data received from accelerometer will be used to trigger leg movements by determining speed of front and back paw movement. Accelerometer will also determine speed of the walk cycle in order to replicate the same speed on the leg model.

Results (expected): Because the gyroscope was accurate and the sensor acquired is a gyroscope/accelerometer combo, it is expected that the accelerometer will be at the same level of accuracy, which will provide useful data of the gait cycle. If the accelerometer proves to be unreliable, the component will not be incorporated the further research into different accelerometer will be performed.

3. **Initial testing of Pressure sensors**
   3.1. *The intent of using pressure sensors in the exoskeleton system is to translate two types of signals in the Arduino microprocessor. Sensors will replicate 1) muscle signals of hind legs to indicate push/pull of gait cycle which will act as triggers for the system for start/stop motion and
2) position of the gait cycle using sensors on the bottom of the paw. Test is for the accuracy and interconnectability of the device.

3.2. Test for accuracy
A test will be performed on a simple circuit design. This design will feed sensor signals into the Arduino to understand the behavior of pressure sensors that are intended to be put on dog legs and paw to read muscle and step activity. This is to ensure they are accurate enough to replicate the muscle signals and paw position.

Results (expected): These sensors are fabricated to react to up to 25lbs. For this reason, we expect extreme values on the paw. The back paws will have at least two pressure sensors to read the “toe and heel” placement of the foot. The maximum weight placed onto each paw sensor will be sent to the microcontroller and coding will read in the position in the gait cycle accordingly. For the hind leg pressures, we expect the sensors to be accurate enough to be used as triggers.

3.3. Further testing on a healthy dog is needed to fully understand if pressure sensors will be accurate enough to replicate appropriate signals for modeling the movement on dog model. This is because the current dog model is made of foam and is too light.

4. Initial testing of the motors for activation
4.1. Because the linkage/actuator design will be provided by the mechanical team, testing the electrical activation of the final system will not be possible until each motor is selected. Until then, simple motors have been acquired to get an idea of the final sensor/motor system. This test is for the speed, strength, and interdependence of the device.

4.2. Test the accelerometer/gyroscope with motor
Test will read in gyroscope angle to the Arduino microcontroller, and then output the required voltage to power the motor.

Result (expected): It is expected that initially the motor will not react appropriately to the signals, which will require adjustments in the Arduino code and possibly adjustments in the circuit.

4.3. Test the pressure sensor with motor
Test will read in pressure(s) to the Arduino microcontroller, and then output the required voltage to power the motor.

Result (expected): It is expected that initially the motor will not react appropriately to the signals, which will require adjustments in the Arduino code and possibly adjustments in the circuit.

5. Testing of sensor system
5.1. The sensor system will consist of accelerometers/gyroscopes, pressure sensors, and Arduino interface. This system is meant to read in all the movement signals of a real-life dog which includes front leg swing movement, back leg toe-off, back leg swing phase, and back leg heel-strike. Each sensor component takes into account one or more of these gait cycle behaviors. Because the credibility of the entire system will not be available until we are able to test the brace on a real dog in spring semester, the goal for this semester is to replicate the correct gait angles using published data and rely solely on the accelerometers/gyroscopes. This testing will ensure that there is a replication of hind leg movement once the sensor system is initialized. This will come about with the testing of the sensors interfacing with the motors. This test is for the interdependence, simplicity, safety, strength, and longevity of the device.

5.2. Test for movement of prototype
The test will be performed by moving the gyroscope/accelerometers at appropriate angles and speeds which will then allow the Arduino to output appropriate voltages to activate the motor to initiate/change angles and speeds of the hind legs. The pressure sensors will also be tested by manually pressing on the sensors to see how the system reacts.
Results (expected): The system will initially not move properly, which will require changes in the programming as well as possible modifications to the circuit. There is a guarantee for debugging the system due to this being a theoretical application of the sensor system.

5.3. Testing Sensor System on a Healthy Canine

Data will be recorded on the developed sensor system by mounting this system on a healthy canine. This will determine if our sensor system is picking up the signals that are necessary and if the trigger methods/fail safes line up with how the canine moves. After this initial testing the system will only be on the canine when debugging the movement program and to finally show our model legs functioning like the canine’s legs.

Results (expected): There will be variability in the canines walking patterns which may necessitate adjusting the sensor placement in the brace in order to receive a higher quality signal. It is also anticipated that there will be issues within the processing code that will need to be debugged as testing goes on.

6. Initial Testing of Microcontroller

6.1. As the main processing component of the entire project, the microcontroller is going to need extensive testing to make sure that it will perform to the best of its abilities. In order to fulfill all the inputs and outputs of the system we needed to use two Arduino Megas. This test is for the interconnectability of the device.

6.2. Initial Structural Testing of Controller

When looking at the structural integrity of the microcontrollers, it will be checked to see if it will operate in the intended environment. Specifically, this is on a living canine and a mechanical replica. To simulate this process, it would be beneficial to test the controllers in different temperature settings along with different angles. Additionally, will the controller work when it is being moved around constantly? To test for this, the controller will be physically picked up and moved around while it’s performing operations.

Results (expected): The controllers are not only expected to control all of the sensors and motors, but to do so under proper conditions. By ensuring that the controller will be able to work under the right conditions, this will act as a sense stress test of the system. If it breaks, that will determine that it is not able to hold up to the required environment.

6.3. Testing Inputs and Outputs

In order to test all the I/O properly, an I/O checkout will be performed. This requires individually going through all of the Analog and Digital pins and attaching an oscilloscope to them. This can be done by moving a sensor from pin to pin and running code specifically to the port.

Results (expected): Throughout the entire procedure, the exact same results should be reported every time on similar inputs. This will validate that each of the pins is working properly, as long as nothing is done to ‘fry’ them.

7. Initial Testing of the Code

7.1. The code will run the mobility system. It is the job of the code to keep the canine and the device in a safe and operable position/motion. Using the information given by different sensors the Arduino needs to know when to shut off the system safely and which sensors need to be active to progress the motors through the canine’s gait cycle. This test is for the simplicity and interdependency of the device.

7.2. Test for Falling Safety

Using the gyroscopes on the back legs, the Arduino will shut off the motors if the roll of the gyros pass 45 degrees past vertical. This will demonstrate that if the dog were to fall over with the device that the system will stop running and not damage the dog or itself and further.
Results (expected): Once one of the gyroscopes used for the back legs is tilted, the motors will shut off. This will act as one of the fail-safes for the system.

7.3. Test for Trigger Method:
Using the gyroscopes and the accelerometers on the front legs and the pressure sensors in the paw, the system will begin its walk cycle once the front paw gyroscope is tilted and the pressure sensors on the back paws are activated. If just one of the sensors is triggered, the system should not do anything.

Results (expected): When the gyro for the left front leg is triggered, if the pressure sensors for the front of the back paw are triggered as well the opposite leg to the gyro, the system will begin to walk. If only one of them are active then it will do nothing.

7.4. Testing the Emergency Cut Off Switch
Once the E-switch is pressed the device will stop all processes and halt the motors. This is to stop the device from hurting the dog and give the owner a manual override to the system should an unforeseen error occur.

Results (expected): The E-switch is pressed and the system comes to a halt and will not reset till the switch is pressed again.

7.5. Testing The Gait Cycle Program
Once the trigger test has been met the one of the legs will begin its gait cycle. This will go from a neutral position to the launch phase, then transition into the swing phase, which then transitions into the landing phase, and then back to swing phase.

Results (expected): As long as none of the fail safes are triggered, the leg should move according to how a normal canine leg moves. If it doesn’t, that means the code for the transitions needs to be debugged.

7.6. Testing Actuator Feedback
The feedback from actuators will act as a safety function. If the torque on the actuators increases then that means the canine doesn’t actually intent on walking and will resist the motor’s movements. The Arduino needs to see if the torque from the motors is past expected values and if so return the legs to a neutral position.

Results (expected): Once significant torque is applied, the system resets to a neutral position. If this is not the case, debugging of the monitorization of the actuators will occur, otherwise it could harm the dog and burn out the actuators.

7.7. Testing Actuator Feedback (2)
Along with a safety factor, the feedback will provide a position and a torque value. This value is very important to the overall function of our system. The best test for this will be to hook up an oscilloscope and look at the output of the pin when proper code is ran. This will be done by using an analog detecting oscilloscope.

Results (expected): This test will ensure that we have the proper signal going into the system. By applying different bits of code, the precise output can be calculated that is created at the pin. This needs to be done after testing all the pins and microcontroller.

7.8. Testing Microcontroller communication
Since a canine will be wearing the device and another device will be controlling the actuators, the signals from the device on the live animal that transmit to the device on the model legs must occur in a timely manner.

Results (expected): Initial tests will show that the devices are not transmitting and receiving data fast enough to keep the device running in real time. This will necessitate looking into how data is
sent and somehow increase the efficiency of the data is processed so that the devices can accomplish their tasks in real time.

8. Initial Prototype:
8.1. In order to gain an initial understanding of how to create a working model, a preliminary model needs to be created. This allows the team to play with joint angles and a variety of actuators to create movement. By creating the initial prototype, the team will gain familiarity with how the future canine model will function. This test is for all customer requirements of the device.

8.2. Testing Tolerances
To fabricate a working model, OrthoPets supplied a polyurethane foam model of the hind legs and torso of a labrador retriever. Due to the nature of the foam, assembling the dog legs became a challenge because of the inability to hold any type of tolerance. Therefore, it was important to test the material to see what type of tooling and fasteners could be use to assemble the model.

Result: After fabricating two legs, it became very clear that it would be impossible to hold any type of machining tolerance because the material was extremely soft. Traditional fasteners such as screws and nails would be unable to be used, so it was concluded that any sort of hind limb assembly would require adhesives.

8.3. Testing Limb Motion
Limb motion is not as concrete as it looks on paper. The preliminary model will be used to test how the final model will move. It will serve as a draft for what the team wishes to create for a final product. It will help attain motion of actuators and also will give practice on how to make fake dog legs.

Result (expected): The motion analysis of the foam models will show where the model needs to improve to more accurately replicate the kinematics and loading of a real canine. The information gathered from this type of testing will be used to fine tune the final model.

9. Final Robust Model:
9.1. In order to prove that the exoskeleton can provide support and help a canine walk, it is important to create a second more robust model of a dog. This model needs to replicate the motion of the dog and be capable of withstanding physiological loads. The initial prototype will be used to help create the final model. This is to test the strength, weight, and speed of the device.

9.2. Robust Model Fabrication:
Research into other types of materials to create the model will be done to see if the polyurethane foam can be replaced. However, regardless of material, the final model will be fabricated.

Result (expected): The model will work as a good representation of the hind limbs of the canine. Due to the nature of the legs, there will be inevitable problems when assembling, however, careful planning before fabrication will take place to avoid as many complications as possible.

10. Mechanical Loading Throughout the System:
10.1. One of the most important aspects of this project is whether or not the exoskeleton can support an animal. Because of this, the mechanical loading that occurs in the system is crucial. As a team it is important that the final system will withstand the proper physiologic loads. This is to test the strength and speed of the device.

10.2. Initial Loading Calculations:
Before any type of actuator is bought, or linkage system is created, a series of analysis will take place to choose what type of actuators and linkage system is necessary to support the animal. Once the initial calculation are completed, actuators will be bought and linkages will be created.
10.3. Load Testing:
Once the actuators are bought, the team will test to see if they can handle the necessary loads with a proper safety factor in place. Recordings of the load and speed will be recorded and run through statistical analysis to ensure the exoskeleton will work and remain safe. Results (expected): If the correct calculations are completed then the proper actuators will be bought. Therefore, it would be expected that the exoskeleton could withstand all physiologic loads. However, if there is a failure, it will be important to look at all of the calculations and search to make the proper correction to the system.

11. Testing of Actuators
11.1. The exoskeleton will require two actuators for each leg, one for bringing the femur forward and one for pulling the metatarsis and tibia upward for leg clearance in the swing phase and then extending the leg back down for impact. This is to test the speed and strength of the device.

11.2. Comparison of Available Actuators
A comprehensive motor analysis is currently occurring before actuators are chosen. A cheap linear actuator and stepper motor have been acquired and initial testing involves understanding how the motors react to loads. It is important that the motor associated with flexing and extending the lower leg can handle the impact of the paw contacting the ground when making a step without affecting the motors capability to continue its motion. Results: Preliminary testing indicates a linear actuator will handle the flexion and extension of the lower bones of the hind leg while a stepper motor with feedback will provide the force needed to actuate the femur forward.

11.3. Testing of Final Actuators
After the final, more precise and expensive actuators have been purchased, they will undergo testing on the final linkage system. A load cell will be attached in between the links connecting to each of the actuators to determine the loads the motor is undergoing and ensure that the motor can handle all associated forces and torques. Additionally, high speed video analysis will be utilized to determine the speeds at which the actuators move the system. Results (expected): The linear actuator may run slower than desired, so steps are being taken with respect to the linkage design so that the actuator travel is minimal. With respect to loading however, it is expected that the actuators will be able to handle forces recorded from the load cells.

12. Testing of Kinematics
12.1. It is important that the produced exoskeleton acts in a biomechanically correct manner and does not allow the canine’s legs to move to unnatural positions or at unnatural speeds that could risk the safety of the animal. Therefore, motion analysis testing must be performed before placing the device on a dog so that the safety of the dog is ensured. This is to test the interdependency and accuracy of dog movement for the device.

12.2. Preliminary Research
A thorough literature review was performed to determine what joint angles/velocities the device must follow in order to create a biomechanically accurate device. Results: Figure below exemplifies one of the three joints that were researched, the knee.
12.3. Testing of Joint Angles on Prototype and Final Design
For both the prototype and final device, high speed video analysis will be utilized to determine the joint angles and speeds of the dog leg as it is actuated by the device. Since the device is only providing motion in 2D, a professional gait lab is unnecessary and a simple high speed video will be recorded using a rented camera from the Colorado State Engineering Services group. This video will then be easily analyzed for different time points on a computer using a free image analysis software such as ImageJ.

Results (expected): The kinematics of the prototyped design will not be extremely accurate due to the cheaper materials and actuators, but will demonstrate the general motion needed and highlight any issues that need to be considered for the final design. It is expected that the final design will accurately portray the biomechanically accurate joint angles and speeds within 15%.

13. Testing of the Linkage System
A linkage system will transmit motion from the actuator to the brace, which can then move the leg in a predefined motion. This linkage system will be able to handle maximum loads that will be applied from the actuator, and properly supply these loads to the braces and therefore dog legs. This test is for the safety, simplicity, strength, and accuracy of the device.

13.1. Initial Dynamics Calculations
A dynamics analysis will be performed to create a linkage system that is able to follow a predefined pattern to properly actuate the joint angles. Once initial concepts for the linkage system are created, basic cardboard “links” will be cut to scale and pinned together to check if the desired motion is achieved. The program Linkages™ requires input link lengths, forces, and joints, and then provides coupler curves and motion paths. Following the cardboard test, this software will be utilized to determine if the proposed linkage system accurately produces desired kinematics. If it does not produce the desired motion, a new concept will be developed and run through the same above cycle.

Results (expected): The desired motion will be achieved within 15% of the desired leg kinematics. This percentage will be used because of the large variability in biomechanics from one dog to the next, even if the same breed.

13.2. Test for Loading of Links
A robust material must be utilized for fabricating the linkage system. After loading calculations have been performed (found in the “Loading” Section), a material that meets loading requirements will be used for the links. This will require determining the material’s elastic modulus, hardness, tensile strength, and compressive strength. This material will most likely either be a light metal such as aluminum or a high density plastic. Once a material has been
chosen, a test link will be fabricated to undergo a uniaxial tensile testing to ensure that the material will withstand the associated loads before an entire linkage system is fabricated. Results (expected): The material will perform as expected and will be able to handle the loads of the exoskeleton device. Mechanical properties of materials have been well studied so it is expected that, with sufficient research, a proper material will be chosen.

13.3. Testing for Final Linkage Design

After a linkage system has been designed for dynamics and loading, it will be fabricated and assembled. Actuators will be attached to the final dog model and the previously recorded healthy dog data will be input into the actuators to check the overall ability of the linkage system to handle loads and perform the desired motion. Results (expected) The actuators will be able to handle the loads and move the model leg forward. When the leg makes contact with the ground at impact, the linkage system will remain sturdy and not buckle or result in any unexpected pauses or issues.
Appendix F: IACUC and RICRO Training

In order to handle a live animal, all handling persons were responsible for completing IACUC and RICRO training through CSU. Every team member has completed this training and attached is our certifications.
Appendix G: Canine Anatomy

SKELETON OF A DOG

- skull
- cervical vertebrae
- thoracic vertebrae
- lumbar vertebrae
- sacrum
- caudal vertebrae
- orbit
- lower maxillary
- scapula
- rib
- humerus
- radius
- ulna
- carpus
- metacarpus
- phalange
- pelvis
- femur
- fibula
- tibia
- tarsus
- metatarsus
- phalange
**Appendix H: Failure Modes and Effects Analysis (FMEA)**

Attached is the FMEA chart that was created for the risk analysis portion of this report. Assumptions: Only one failure mode can best present at a time, all inputs are at nominal values, nominal power is available.

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Leg Speed</td>
<td>Mechanical Actuator Speed &gt;17/sec</td>
<td>Low actuator speed (for both knee and ankle actuators)</td>
<td>Moving system unable to keep up with sensor inputs, dog is unable to walk forward at any appreciable speed</td>
<td>4</td>
<td>High loads are applied to actuator</td>
<td>6</td>
<td>Attachment points strategically placed for best mechanical advantage</td>
<td>Actuator feedback along with sensors on back leg including gyroscope and pressure sensors</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Code isn’t efficient enough or there is a bug</td>
<td>6</td>
<td>Streamline code and numerous trials</td>
<td>6</td>
<td>Pressure sensors and actuator feedback will not be their expected values</td>
<td>9</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Low current</td>
<td>5</td>
<td>Mathematical analysis of datasheet for each of the components</td>
<td>5</td>
<td>Use of a voltage meter during testing</td>
<td>7</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Low voltage</td>
<td>2</td>
<td>Mathematical analysis of datasheet for each of the components</td>
<td>2</td>
<td>Use of a current meter during the testing phase</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Leg movement</td>
<td>Physiological Angles (within 5 degrees) achieved throughout gait cycle</td>
<td>Linear actuators extend too far outward</td>
<td>Overextension of knee and/or ankle</td>
<td>7</td>
<td>Error in code</td>
<td>2</td>
<td>Trials and debugging</td>
<td>Pressure sensors within brace will be extreme and gyroscope values will be abnormal causing an emergency shut off</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Brace shifts causing actuators to be misaligned</td>
<td>4</td>
<td>Rigid attachment points combined with a well-fitting brace</td>
<td>4</td>
<td>Pressure sensors within brace</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Code doesn’t extend the actuator far enough</td>
<td>3</td>
<td>Through trails and debugging</td>
<td>4</td>
<td>Gyroscope values will tell the system to continue to extend actuators till values align</td>
<td>6</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Brace shifts causing actuators to be misaligned</td>
<td>4</td>
<td>Rigid attachment points combined with a well-fitting brace</td>
<td>4</td>
<td>Pressure sensors within brace</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Overextension of knee and/or ankle</td>
<td>10</td>
<td>Actuators feedback stops working</td>
<td>0</td>
<td>Debugging code, Model testing</td>
<td>Over extended gyroscope angles will activate automatic shut off</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Feedback mechanisms on any of these actuators stops working</td>
<td>4</td>
<td>Debugging code, Model testing</td>
<td>3</td>
<td>Over extended gyroscope angles and extreme pressures will activate automatic shut off</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Initiation of Walk</td>
<td>Front leg movement initiates back leg movement</td>
<td>Back leg does not move forward after front leg movement</td>
<td>Dog unable to walk</td>
<td>6</td>
<td>Gyroscope accelerometer misalignment</td>
<td>3</td>
<td>Working with OrthoPet’s front paw strap that has previously been used to prevent this</td>
<td>Erratic gyro values will be interpreted by code and stop the device</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Small front leg movement unable to be sensed by gyroscope</td>
<td>2</td>
<td>Dog will be walked on a leash with constant forward movement</td>
<td>2</td>
<td>Pressure sensors within brace and feedback from actuators</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Code way too slow</td>
<td>6</td>
<td>Code will be streamlined</td>
<td>4</td>
<td>Pressure sensors and gyroscope values will not align with expected values and go into a shutting down state</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Actuator power source drained</td>
<td>9</td>
<td>Two rechargeable batteries</td>
<td>9</td>
<td>Understanding time batteries have for each component and having next set charged and ready</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Termination of Walk</td>
<td>Absence of front leg movement prevents back leg from moving</td>
<td>Back leg moves forward when it should not</td>
<td>Dog essentially runs into itself</td>
<td>10</td>
<td>Gyroscope accelerometer incorrectly senses front leg movement</td>
<td>4</td>
<td>Working with OrthoPet’s front paw strap that has previously been used to secure rigid positioning of gyro. Also ensuring electrical circuit is securely housed and code is accurate</td>
<td>Pressure sensors and feedback from actuators. Thorough checking of hardware, constant testing of code</td>
<td>2</td>
</tr>
</tbody>
</table>
Appendix I: Sensor System Code

Arduino: code

//include libraries
#include <MPU6050_9Axis_MotionApps41.h>
#include <MPU6050.h>
#include <math.h>
#include "I2Cdev.h"
#include <Wire.h>
#include <Kalman.h>
#define RESTRICT_PITCH

// these provide us with processed angles
Kalman kalmanX1;
Kalman kalmanY1;
Kalman kalmanX2;
Kalman kalmanY2;

// voltages for the sensors on the Left side
float voltageL1 = 0.0;
float voltageL2 = 0.0;
float voltageL3 = 0.0;
float voltageL4 = 0.0;
float voltageL5 = 0.0;
float voltageL6 = 0.0;
float voltageL7 = 0.0;

// voltages for the sensors on the Right side
float voltageR1 = 0.0;
float voltageR2 = 0.0;
float voltageR3 = 0.0;
float voltageR4 = 0.0;
float voltageR5 = 0.0;
float voltageR6 = 0.0;
float voltageR7 = 0.0;

//sensor inputs for the Left and Right sides
int sensorsL1 = 0;
int sensorsL2 = 0;
int sensorsL3 = 0;
int sensorsL4 = 0;
int sensorsL5 = 0;
int sensorsL6 = 0;
int sensorsL7 = 0;
int sensorsR1 = 0;
int sensorsR2 = 0;
int sensorsR3 = 0;
int sensorsR4 = 0;
int sensorsR5 = 0;
int sensorsR6 = 0;
int sensorsR7 = 0;

int count = 0;

double accX1, accY1, accZ1, accX2, accZ2;
double gyroX1, gyroY1, gyroZ1, gyroX2, gyroY2, gyroZ2;
int16_t tempRaw;

double gyroX1angle, gyroY1angle, gyroX2angle, gyroY2angle; // Angle calculate using the gyro only
double compAngleX1, compAngleY1, compAngleX2, compAngleY2; // Calculated angle using a complementary filter
double kalAngleX1, kalAngleY1, kalAngleX2, kalAngleY2; // Calculated angle using a Kalman filter
uint32_t timer;
int16_t ax1, ay1, az1, ax2, ay2, az2, gx1, gy1, gz1, gx2, gy2, gz2;

// make the gyros
MPU6050 gyro1(0x68);
MPU6050 gyro2(0x69);

void setup() {
    // pinMode(2, OUTPUT); //s0
    // pinMode(3, OUTPUT); //s1
    // pinMode(4, OUTPUT); //s2
    // pinMode(5, OUTPUT); //s3
    Wire.begin();
    Serial.begin(115200);
    gyro1.initialize();
    gyro2.initialize();
    // put your setup code here, to run once:
    delay(100);
    // this grabs the initial raw values from the gyros
    gyro1.getAcceleration(&ax1, &ay1, &az1);
    gyro1.getRotation(&gx1, &gy1, &gz1);
    accX1 = ax1;
    accY1 = ay1;
    accZ1 = az1;
    gyroX1 = gx1;
    gyroY1 = gy1;
    gyroZ1 = gz1;
    gyro2.getAcceleration(&ax2, &ay2, &az2);
    gyro2.getRotation(&gx2, &gy2, &gz2);
    accX2 = (double)ax2;
    accY2 = (double)ay2;
    accZ2 = (double)az2;
    gyroX2 = gx2;
    gyroY2 = gy2;
    gyroZ2 = gz2;

    // this starts the processing of the data
    double roll1 = atan2(accY1, accZ1) * RAD_TO_DEG;
    double pitch1 = atan(-accX1 / sqrt(accY1 * accY1 + accZ1 * accZ1)) * RAD_TO_DEG;
    double roll2 = atan2(accY2, accZ2) * RAD_TO_DEG;
    double pitch2 = atan(-accX2 / sqrt(accY2 * accY2 + accZ2 * accZ2)) * RAD_TO_DEG;

    kalmanX1.setAngle(roll1);
    kalmanY1.setAngle(pitch1);
    kalmanX2.setAngle(roll2);
    kalmanY2.setAngle(pitch2);
    gyroX1angle = roll1;
    gyroY1angle = pitch1;
    compAngleX1 = roll1;
    compAngleY1 = pitch1;
    gyroX2angle = roll2;
    gyroY2angle = pitch2;
    compAngleX2 = roll2;
    compAngleY2 = pitch2;
    timer = micros();
}

void loop() {
    // put your main code here, to run repeatedly:
}
// repeat of the set up code
gyro1.getAcceleration(&ax1, &ay1, &az1);
gyro1.getRotation(&gx1, &gy1, &gz1);
accX1 = ax1;
accZ1 = az1;
accY1 = ay1;
gyroX1 = gx1;
gyroY1 = gy1;
gyroZ1 = gz1;

gyro2.getAcceleration(&ax2, &ay2, &az2);
gyro2.getRotation(&gx2, &gy2, &gz2);
accX2 = ax2;
accZ2 = az2;
accY2 = ay2;
gyroX2 = gx2;
gyroY2 = gy2;
gyroZ2 = gz2;

double dt = (double)(micros() - timer)/1000000;
timer = micros();

double roll1 = atan2(accY1, accZ1) * RAD_TO_DEG;
double pitch1 = atan(-accX1 / sqrt(accY1 * accY1 + accZ1 * accZ1)) * RAD_TO_DEG;

double roll2 = atan2(accY2, accZ2) * RAD_TO_DEG;
double pitch2 = atan(-accX2 / sqrt(accY2 * accY2 + accZ2 * accZ2)) * RAD_TO_DEG;

double gyroX1rate = gyroX1 / 131.0; // Convert to deg/s
double gyroY1rate = gyroY1 / 131.0; // Convert to deg/s
double gyroX2rate = gyroX2 / 131.0; // Convert to deg/s
double gyroY2rate = gyroY2 / 131.0; // Convert to deg/s

if((roll1 < -90 && kalAngleX1 > 90) || (roll1 > 90 && kalAngleX1 < -90)){
kalmanX1.setAngle(roll1);
compAngleX1 = roll1;
gyroX1angle = roll1;
} else{
kalAngleX1 = kalmanX1.getAngle(roll1, gyroX1rate, dt);
}

if(abs(kalAngleX1) > 90)
gyroY1rate = -gyroY1rate;
kalAngleY1 = kalmanY1.getAngle(pitch1, gyroY1rate, dt);

if((roll2 < -90 && kalAngleX2 > 90) || (roll2 > 90 && kalAngleX2 < -90)){
kalmanX2.setAngle(roll2);
compAngleX2 = roll2;
kalAngleX2 = roll2;
gyroX2angle = roll2;
} else{
kalAngleX2 = kalmanX2.getAngle(roll2, gyroX2rate, dt);
}

if(abs(kalAngleX2) > 90)
gyroY2rate = -gyroY2rate;
kalAngleY2 = kalmanY2.getAngle(pitch2, gyroY2rate, dt);

gyroX1angle += gyroX1rate * dt; // Calculate gyro angle without any filter
gyroY1angle += gyroY1rate * dt;
gyroX2angle += gyroX2rate * dt; // Calculate gyro angle without any filter
gyroY2angle += gyroY2rate * dt;

compAngleX1 = 0.93 * (compAngleX1 + gyroX1rate * dt) + 0.07 * roll1; // Calculate the angle using a Complimentary filter
compAngleY1 = 0.93 * (compAngleY1 + gyroY1rate * dt) + 0.07 * pitch1;
compAngleX2 = 0.93 * (compAngleX2 + gyroX2rate * dt) + 0.07 * roll2; // Calculate the angle using a Complimentary filter
compAngleY2 = 0.93 * (compAngleY2 + gyroY2rate * dt) + 0.07 * pitch2;

if (gyroX1angle < -180 || gyroX1angle > 180)
gyroX1angle = kalAngleX1;
if (gyroY1angle < -180 || gyroY1angle > 180)
gyroY1angle = kalAngleY1;
if (gyroX2angle < -180 || gyroX2angle > 180)
gyroX2angle = kalAngleX2;
if (gyroY2angle < -180 || gyroY2angle > 180)
gyroY2angle = kalAngleY2;

for(count = 0; count <= 13; count ++){

// Grabbing pressure sensor data inputs and convert them to voltages.

if(count == 0){
sensorsL1 = analogRead(A0); //change number for pin
voltageL1 = sensorsL1 * (5.0 / 1023.0);
}
if(count == 1){
sensorsL2 = analogRead(A1); //change number for pin
voltageL2 = sensorsL2 * (5.0 / 1023.0);
}
if(count == 2){
sensorsL3 = analogRead(A2); //change number for pin
voltageL3 = sensorsL3 * (5.0 / 1023.0);
}
if(count == 3){
sensorsL4 = analogRead(A3); //change number for pin
voltageL4 = sensorsL4 * (5.0 / 1023.0);
}
if(count == 4){
sensorsL5 = analogRead(A4); //change number for pin
voltageL5 = sensorsL5 * (5.0 / 1023.0);
}
if(count == 5){
sensorsL6 = analogRead(A5); //change number for pin
voltageL6 = sensorsL6 * (5.0 / 1023.0);
}
if(count == 6){
sensorsL7 = analogRead(A6); //change number for pin
voltageL7 = sensorsL7 * (5.0 / 1023.0);
}
if(count == 7){
sensorsR1 = analogRead(A7); //change number for pin
voltageR1 = sensorsR1 * (5.0 / 1023.0);
}
if(count == 8){
sensorsR2 = analogRead(A8); //change number for pin
voltageR2 = sensorsR2 * (5.0 / 1023.0);
}
if(count == 9){
sensorsR3 = analogRead(A9); //change number for pin
voltageR3 = sensorsR3 * (5.0 / 1023.0);
}
if(count == 10){
}
```c
sensorsR4 = analogRead(A10); //change number for pin
toVoltageR4 = sensorsR4 * (5.0 / 1023.0);
}
}
if(count == 11){
sensorsR5 = analogRead(A11); //change number for pin
toVoltageR5 = sensorsR5 * (5.0 / 1023.0);
}
}
if(count == 12){
sensorsR6 = analogRead(A12); //change number for pin
toVoltageR6 = sensorsR6 * (5.0 / 1023.0);
}
}
if(count == 13){
sensorsR7 = analogRead(A13); //change number for pin
toVoltageR7 = sensorsR7 * (5.0 / 1023.0);
}
}
// Send the all of the gyro data and sensor data to the serial port
// first set print
Serial.print(roll1); Serial.print(\t);
Serial.print(gyroX1angle); Serial.print(\t);
Serial.print(compAngleX1); Serial.print(\t);
Serial.print(kalAngleX1); Serial.print(\t);
Serial.print(\t);
Serial.print(pitch1); Serial.print(\t);
Serial.print(gyroY1angle); Serial.print(\t);
Serial.print(compAngleY1); Serial.print(\t);
Serial.print(kalAngleY1); Serial.print(\t);
Serial.print(\t);
// second set print
Serial.print(roll2); Serial.print(\t);
Serial.print(gyroX2angle); Serial.print(\t);
Serial.print(compAngleX2); Serial.print(\t);
Serial.print(kalAngleX2); Serial.print(\t);
Serial.print(\t);
Serial.print(pitch2); Serial.print(\t);
Serial.print(gyroY2angle); Serial.print(\t);
Serial.print(compAngleY2); Serial.print(\t);
Serial.print(kalAngleY2); Serial.print(\t);
Serial.print(\t);
// pressure sensor print
Serial.print(voltageL1); Serial.print(\t);
Serial.print(voltageL2); Serial.print(\t);
Serial.print(voltageL3); Serial.print(\t);
Serial.print(voltageL4); Serial.print(\t);
Serial.print(voltageL5); Serial.print(\t);
Serial.print(voltageL6); Serial.print(\t);
Serial.print(voltageL7); Serial.print(\t);
Serial.print(\t);
Serial.print(voltageR1); Serial.print(\t);
Serial.print(voltageR2); Serial.print(\t);
Serial.print(voltageR3); Serial.print(\t);
Serial.print(voltageR4); Serial.print(\t);
Serial.print(voltageR5); Serial.print(\t);
Serial.print(voltageR6); Serial.print(\t);
Serial.print(voltageR7); Serial.print(\t);
98
```
Processing 3 Code:

Graphing Function:

// imports to read data from arduino and write to a file
import java.io.FileWriter;
import processing.serial.*;

// variable declarations
Serial serial;
PrintWriter output;
PrintWriter dump;
String stringGyroX1, stringGyroY1, stringGyroX2, stringGyroY2;
String stringAccX1, stringAccY1, stringAccX2, stringAccY2;
String stringCompX1, stringCompY1, stringCompX2, stringCompY2;
String stringKalmanX1, stringKalmanY1, stringKalmanX2, stringKalmanY2;
String stringL1, stringL2, stringL3, stringL4, stringL5, stringL6, stringL7;
String stringR1, stringR2, stringR3, stringR4, stringR5, stringR6, stringR7;

// Creating dementions for the graph display
final int width = 800;
final int height = 600;

// Creating lines that are drawn on the graph
float[] gyroX1 = new float[width];
float[] gyroY1 = new float[width];
float[] gyroX2 = new float[width];
float[] gyroY2 = new float[width];
float[] accX1 = new float[width];
float[] accY1 = new float[width];
float[] accX2 = new float[width];
float[] accY2 = new float[width];
float[] compX1 = new float[width];
float[] compY1 = new float[width];
float[] compX2 = new float[width];
float[] compY2 = new float[width];
float[] kalmanX1 = new float[width];
float[] kalmanY1 = new float[width];
float[] kalmanX2 = new float[width];
float[] kalmanY2 = new float[width];
float[] sensorL1 = new float[width];
float[] sensorL2 = new float[width];
float[] sensorL3 = new float[width];
float[] sensorL4 = new float[width];
float[] sensorL5 = new float[width];
float[] sensorL6 = new float[width];
float[] sensorL7 = new float[width];
float[] sensorR1 = new float[width];
float[] sensorR2 = new float[width];
float[] sensorR3 = new float[width];
float[] sensorR4 = new float[width];
float[] sensorR5 = new float[width];
floating[] sensorR6 = new float[width];
floating[] sensorR7 = new float[width];

boolean drawValues = false;

// creates graph
void setup() {
  println(Serial.list()); // Use this to print connected serial devices
  serial = new Serial(this, "COM5", 115200); // Set this to your serial port obtained using the line above
  serial.bufferUntil('
'); // Buffer until line feed

  for (int i = 0; i < width; i++) { // center all variables
    gyroX1[i] = height/2;
    gyroY1[i] = height/2;
    gyroX2[i] = height/2;
    gyroY2[i] = height/2;

    accX1[i] = height/2;
    accY1[i] = height/2;
    accX2[i] = height/2;
    accY2[i] = height/2;

    compX1[i] = height/2;
    compY1[i] = height/2;
    compX2[i] = height/2;
    compY2[i] = height/2;

    kalmanX1[i] = height/2;
    kalmanY1[i] = height/2;
    kalmanX2[i] = height/2;
    kalmanY2[i] = height/2;

    sensorL1[i] = height/2;
    sensorL2[i] = height/2;
    sensorL3[i] = height/2;
    sensorL4[i] = height/2;
    sensorL5[i] = height/2;
    sensorL6[i] = height/2;
    sensorL7[i] = height/2;

    sensorR1[i] = height/2;
    sensorR2[i] = height/2;
    sensorR3[i] = height/2;
    sensorR4[i] = height/2;
    sensorR5[i] = height/2;
    sensorR6[i] = height/2;
    sensorR7[i] = height/2;

    // creates an easy to read file and a data dump file
    // Change the string name between " " to create new files
    // Otherwise it will overwrite that file
    output = createWriter("FULLTESTSTOP2output1.txt");
    dump = createWriter("FULLTESTSTOP2datadump1.txt");
  }

  drawGraph(); // Draw graph at startup
}

void draw() {
  /* Draw Graph */
  if (drawValues) {
    drawValues = false;
    drawGraph();
  }
}
void drawGraph() {
    background(255); // White
    for (int i = 0; i < width; i++) {
        stroke(200); // Grey
        line(i*10, 0, i*10, height);
        line(0, i*10, width, i*10);
    }
    stroke(0); // Black
    for (int i = 1; i <= 3; i++)
        line(0, height/4*i, width, height/4*i); // Draw line, indicating -90 deg, 0 deg and 90 deg
    convert();
    drawAxisX();
    drawAxisY();
}

// This reads all the values the arduino sends over
void serialEvent (Serial serial) {
    // Get the ASCII strings:
    stringAccX1 = serial.readStringUntil('t');
    stringGyroX1 = serial.readStringUntil('t');
    stringCompX1 = serial.readStringUntil('t');
    stringKalmanX1 = serial.readStringUntil('t');
    serial.readStringUntil('t'); // Ignore extra tab
    stringAccY1 = serial.readStringUntil('t');
    stringGyroY1 = serial.readStringUntil('t');
    stringCompY1 = serial.readStringUntil('t');
    stringKalmanY1 = serial.readStringUntil('t');
    serial.readStringUntil('t'); // Ignore extra tab
    stringAccX2 = serial.readStringUntil('t');
    stringGyroX2 = serial.readStringUntil('t');
    stringCompX2 = serial.readStringUntil('t');
    stringKalmanX2 = serial.readStringUntil('t');
    serial.readStringUntil('t'); // Ignore extra tab
    stringAccY2 = serial.readStringUntil('t');
    stringGyroY2 = serial.readStringUntil('t');
    stringCompY2 = serial.readStringUntil('t');
    stringKalmanY2 = serial.readStringUntil('t');
    serial.readStringUntil('t'); // Ignore extra tab
    stringL1 = serial.readStringUntil('t');
    stringL2 = serial.readStringUntil('t');
    stringL3 = serial.readStringUntil('t');
    stringL4 = serial.readStringUntil('t');
    stringL5 = serial.readStringUntil('t');
    stringL6 = serial.readStringUntil('t');
    stringL7 = serial.readStringUntil('t');
    serial.readStringUntil('t'); // Ignore extra tab
    stringR1 = serial.readStringUntil('t');
    stringR2 = serial.readStringUntil('t');
    stringR3 = serial.readStringUntil('t');
    stringR4 = serial.readStringUntil('t');
    stringR5 = serial.readStringUntil('t');
    stringR6 = serial.readStringUntil('t');
}
stringR7 = serial.readStringUntil('t');
serial.readStringUntil('t'); // Ignore extra tab
serial.clear(); // Clear buffer
drawValues = true; // Draw the graph

printAxis(); // prints all values in program terminal and writes to the files
} // This prints all the data within the program terminal
void printAxis() {
print(stringGyroX1);
print(stringAccX1);
print(stringCompX1);
print(stringKalmanX1);
print('t');
print(stringGyroY1);
print(stringAccY1);
print(stringCompY1);
print(stringKalmanY1);
println();
println();
print(stringGyroX2);
print(stringAccX2);
print(stringCompX2);
print(stringKalmanX2);
print('t');
print(stringGyroY2);
print(stringAccY2);
print(stringCompY2);
print(stringKalmanY2);
println();
println();
print(stringL1);
print(stringL2);
print(stringL3);
print(stringL4);
print(stringL5);
print(stringL6);
print(stringL7);
println();
println();
print(stringR1);
print(stringR2);
print(stringR3);
print(stringR4);
print(stringR5);
print(stringR6);
print(stringR7);
String temp1;
String temp2;
String temp3;
String temp4;
String temp5;
String temp6;
// Creates strings of the data and writes them to the files
Convert Axis Function:

//convert all axis
final int minAngle = -180;
final int maxAngle = 180;

void convert() {
  /* Convert the gyro x-axis */
  if (stringGyroX1 != null) {
    stringGyroX1 = trim(stringGyroX1); // Trim off any whitespace
    gyroX1[gyroX1.length - 1] = map(float(stringGyroX1), minAngle, maxAngle, 0, height); // Convert to a float and map to the screen height, then save in buffer
  }
  if (stringGyroX2 != null) {
    stringGyroX2 = trim(stringGyroX2); // Trim off any whitespace
    gyroX2[gyroX2.length - 1] = map(float(stringGyroX2), minAngle, maxAngle, 0, height); // Convert to a float and map to the screen height, then save in buffer
  }
  /* Convert the gyro y-axis */
  if (stringGyroY1 != null) {
    stringGyroY1 = trim(stringGyroY1); // Trim off any whitespace
    gyroY1[gyroY1.length - 1] = map(float(stringGyroY1), minAngle, maxAngle, 0, height); // Convert to a float and map to the screen height, then save in buffer
  }
  if (stringGyroY2 != null) {
    stringGyroY2 = trim(stringGyroY2); // Trim off any whitespace
    gyroY2[gyroY2.length - 1] = map(float(stringGyroY2), minAngle, maxAngle, 0, height); // Convert to a float and map to the screen height, then save in buffer
  }
  /* Convert the complementary filter x-axis */
  if (stringCompX1 != null) {
    stringCompX1 = trim(stringCompX1); // Trim off any whitespace
    compX1[compX1.length - 1] = map(float(stringCompX1), minAngle, maxAngle, 0, height); // Convert to a float and map to the screen height, then save in buffer
  }
  if (stringCompX2 != null) {
    stringCompX2 = trim(stringCompX1); // Trim off any whitespace
    compX2[compX2.length - 1] = map(float(stringCompX2), minAngle, maxAngle, 0, height); // Convert to a float and map to the screen height, then save in buffer
  }
  ""
/* Convert the complementary filter x-axis */
if (stringCompX1 != null) {
    stringCompX1 = trim(stringCompX1); // Trim off any whitespace
    compX1[compX1.length - 1] = map(float(stringCompX1), minAngle, maxAngle, 0, height); // Convert to a float and map to the screen height, then save in buffer
}
if (stringCompX2 != null) {
    stringCompX2 = trim(stringCompX2); // Trim off any whitespace
    compX2[compX2.length - 1] = map(float(stringCompX2), minAngle, maxAngle, 0, height); // Convert to a float and map to the screen height, then save in buffer
}

/* Convert the kalman filter x-axis */
if (stringKalmanX1 != null) {
    stringKalmanX1 = trim(stringKalmanX1); // Trim off any whitespace
    kalmanX1[kalmanX1.length - 1] = map(float(stringKalmanX1), minAngle, maxAngle, 0, height); // Convert to a float and map to the screen height, then save in buffer
}
if (stringKalmanX2 != null) {
    stringKalmanX2 = trim(stringKalmanX2); // Trim off any whitespace
    kalmanX2[kalmanX2.length - 1] = map(float(stringKalmanX2), minAngle, maxAngle, 0, height); // Convert to a float and map to the screen height, then save in buffer
}

/* Convert the kalman filter y-axis */
if (stringKalmanY1 != null) {
    stringKalmanY1 = trim(stringKalmanY1); // Trim off any whitespace
    kalmanY1[kalmanY1.length - 1] = map(float(stringKalmanY1), minAngle, maxAngle, 0, height); // Convert to a float and map to the screen height, then save in buffer
}
if (stringKalmanY2 != null) {
    stringKalmanY2 = trim(stringKalmanY2); // Trim off any whitespace
    kalmanY2[kalmanY2.length - 1] = map(float(stringKalmanY2), minAngle, maxAngle, 0, height); // Convert to a float and map to the screen height, then save in buffer
}

void drawAxisX() {

    /* Draw gyro1 x-axis */
    noFill();
    stroke(255, 255, 0); // Yellow
    // Redraw everything
    beginShape();
    vertex(0, gyroX1[0]);
    for (int i = 1; i < gyroX1.length; i++) {
        if ((gyroX1[i] < height/4 && gyroX1[i-1] > height/4*3) || (gyroX1[i] > height/4*3 && gyroX1[i-1] < height/4)) {
            endShape();
            beginShape();
        }
        vertex(i, gyroX1[i]);
    }
    endShape();

    // Put all data one array back
    for (int i = 1; i < gyroX1.length; i++)
        gyroX1[i-1] = gyroX1[i];

    /* Draw gyro2 x-axis */
    noFill();
    stroke(150, 150, 0); // dark yellow
    // Redraw everything
    beginShape();
    vertex(0, gyroX2[0]);

    Draw Axis Function:
for (int i = 1; i < gyroX2.length; i++) {
    if ((gyroX2[i] < height/4 &
        & gyroX2[i-1] > height/4*3) || (gyroX2[i] > height/4*3 &
        & gyroX2[i-1] < height/4)) {
        endShape();
        beginShape();
        vertex(i, gyroX2[i]);
    }
}
endShape();

// Put all data one array back
for (int i = 1; i < gyroX1.length;i++)
    gyroX1[i-1] = gyroX1[i];

/* Draw accelerometer1 x-axis */
noFill();
stroke(0, 255, 0); // Green
// Redraw everything
beginShape();
vertex(0, accX1[0]);
for (int i = 1; i < accX1.length; i++) {
    if ((accX1[i] < height/4 &
        & accX1[i-1] > height/4*3) || (accX1[i] > height/4*3 &
        & accX1[i-1] < height/4)) {
        endShape();
        beginShape();
        vertex(i, accX1[i]);
    }
}
endShape();

// Put all data one array back
for (int i = 1; i < accX1.length;i++)
    accX1[i-1] = accX1[i];

/* Draw accelerometer2 x-axis */
noFill();
stroke(0, 100, 0); // dark green
// Redraw everything
beginShape();
vertex(0, accX2[0]);
for (int i = 1; i < accX2.length; i++) {
    if ((accX2[i] < height/4 &
        & accX2[i-1] > height/4*3) || (accX2[i] > height/4*3 &
        & accX2[i-1] < height/4)) {
        endShape();
        beginShape();
        vertex(i, accX2[i]);
    }
}
endShape();

// Put all data one array back
for (int i = 1; i < accX2.length;i++)
    accX2[i-1] = accX2[i];

/* Draw complementary1 filter x-axis */
noFill();
stroke(0, 0, 255); // Blue
// Redraw everything
beginShape();
vertex(0, compX1[0]);
for (int i = 1; i < compX1.length; i++) {
    if ((compX1[i] < height/4 &
        & compX1[i-1] > height/4*3) || (compX1[i] > height/4*3 &
        & compX1[i-1] < height/4)) {
        endShape();
        beginShape();
        vertex(i, compX1[i]);
    }
}
endShape();

// Put all data one array back
for (int i = 1; i < compX1.length; i++)
    compX1[i-1] = compX1[i];

/* Draw complementary2 filter x-axis */
noFill();
stroke(0, 0, 100); // dark Blue
// Redraw everything
beginShape();
vertex(0, compX2[0]);
for (int i = 1; i < compX2.length; i++) {
    if ((compX2[i] < height/4 && compX2[i - 1] > height/4*3) || (compX2[i] > height/4*3 && compX2[i - 1] < height/4)) {
        endShape();
        beginShape();
    }
    vertex(i, compX2[i]);
}
endShape();

// Put all data one array back
for (int i = 1; i < compX2.length; i++)
    compX2[i-1] = compX2[i];

/* Draw kalman1 filter x-axis */
noFill();
stroke(255, 0, 0);// Red
// Redraw everything
beginShape();
vertex(0, kalmanX1[0]);
for (int i = 1; i < kalmanX1.length; i++) {
    if ((kalmanX1[i] < height/4 && kalmanX1[i - 1] > height/4*3) || (kalmanX1[i] > height/4*3 && kalmanX1[i - 1] < height/4)) {
        endShape();
        beginShape();
    }
    vertex(i, kalmanX1[i]);
}
endShape();

// Put all data one array back
for (int i = 1; i < kalmanX1.length; i++)
    kalmanX1[i-1] = kalmanX1[i];

/* Draw kalman2 filter x-axis */
noFill();
stroke(150, 0, 0);// dark Red
// Redraw everything
beginShape();
vertex(0, kalmanX2[0]);
for (int i = 1; i < kalmanX2.length; i++) {
    if ((kalmanX2[i] < height/4 && kalmanX2[i - 1] > height/4*3) || (kalmanX2[i] > height/4*3 && kalmanX2[i - 1] < height/4)) {
        endShape();
        beginShape();
    }
    vertex(i, kalmanX2[i]);
}
endShape();

// Put all data one array back
for (int i = 1; i < kalmanX2.length; i++)
    kalmanX2[i-1] = kalmanX2[i];

void drawAxisY() {
    /* Draw gyro1 y-axis */
    noFill();
stroke(255, 0, 255); // Purble
    // Redraw everything
    beginShape();
    vertex(0, gyroY1[0]);
}
for (int i = 1; i < gyroY1.length; i++) {
    if ((gyroY1[i] < height/4 && gyroY1[i - 1] > height/4*3) || (gyroY1[i] > height/4*3 && gyroY1[i - 1] < height/4)) {
        endShape();
        beginShape();
    }
    vertex(i, gyroY1[i]);
}
endShape();

// Put all data one array back
for (int i = 1; i < gyroY1.length; i++)
    gyroY1[i - 1] = gyroY1[i];

/* Draw gyro2 y-axis */
noFill();
stroke(150, 0, 150); // dark Purble
// Redraw everythng
beginShape();
vertex(0, gyroY2[0]);
for (int i = 1; i < gyroY2.length; i++) {
    if ((gyroY2[i] < height/4 && gyroY2[i - 1] > height/4*3) || (gyroY2[i] > height/4*3 && gyroY2[i - 1] < height/4)) {
        endShape();
        beginShape();
    }
    vertex(i, gyroY2[i]);
}
endShape();

// Put all data one array back
for (int i = 1; i < gyroY2.length; i++)
    gyroY2[i - 1] = gyroY2[i];

/* Draw acceleromter y-axis */
noFill();
stroke(0, 255, 255); // Light blue
// Redraw everything
beginShape();
vertex(0, accY1[0]);
for (int i = 1; i < accY1.length; i++) {
    if ((accY1[i] < height/4 && accY1[i - 1] > height/4*3) || (accY1[i] > height/4*3 && accY1[i - 1] < height/4)) {
        endShape();
        beginShape();
    }
    vertex(i, accY1[i]);
}
endShape();

// Put all data one array back
for (int i = 1; i < accY1.length; i++)
    accY1[i - 1] = accY1[i];

/* Draw acceleromter y-axis */
noFill();
stroke(0, 100, 100); // Light blue
// Redraw everythng
beginShape();
vertex(0, accY2[0]);
for (int i = 1; i < accY2.length; i++) {
    if ((accY2[i] < height/4 && accY2[i - 1] > height/4*3) || (accY2[i] > height/4*3 && accY2[i - 1] < height/4)) {
        endShape();
        beginShape();
    }
    vertex(i, accY2[i]);
}
endShape();

// Put all data one array back
for (int i = 1; i < accY2.length; i++
accY2[i-1] = accY2[i];

/* Draw complementary1 filter y-axis */
noFill();
stroke(255, 100, 0); // Lawn Green
// Redraw everything
beginShape();
vertex(0, compY1[0]);
for (int i = 1; i < compY1.length; i++) {
  if ((compY1[i] < height/4 && compY1[i - 1] > height/4*3) || (compY1[i] > height/4*3 && compY1[i - 1] < height/4)) {
    endShape();
    beginShape();
  }
  vertex(i, compY1[i]);
}
endShape();

// Put all data one array back
for (int i = 1; i < compY1.length; i++)
  compY1[i-1] = compY1[i];

/* Draw complementary2 filter y-axis */
noFill();
stroke(150, 50, 0); // dark orange
// Redraw everything
beginShape();
vertex(0, compY2[0]);
for (int i = 1; i < compY2.length; i++) {
  if ((compY2[i] < height/4 && compY2[i - 1] > height/4*3) || (compY2[i] > height/4*3 && compY2[i - 1] < height/4)) {
    endShape();
    beginShape();
  }
  vertex(i, compY2[i]);
}
endShape();

// Put all data one array back
for (int i = 1; i < compY2.length; i++)
  compY2[i-1] = compY2[i];

/* Draw kalman1 filter y-axis */
noFill();
stroke(0, 0, 0); // Black
// Redraw everything
beginShape();
vertex(0, kalmanY1[0]);
for (int i = 1; i < kalmanY1.length; i++) {
  if ((kalmanY1[i] < height/4 && & kalmanY1[i - 1] > height/4*3) || (kalmanY1[i] > height/4*3 && & kalmanY1[i - 1] < height/4)) {
    endShape();
    beginShape();
  }
  vertex(i, kalmanY1[i]);
}
endShape();

// Put all data one array back
for (int i = 1; i < kalmanY1.length; i++)
  kalmanY1[i-1] = kalmanY1[i];

/* Draw kalman filter y-axis */
noFill();
stroke(100, 100, 100); // Black
// Redraw everything
beginShape();
vertex(0, kalmanY2[0]);
for (int i = 1; i < kalmanY2.length; i++) {
  if ((kalmanY2[i] < height/4 && & kalmanY2[i - 1] > height/4*3) || (kalmanY2[i] > height/4*3 && & kalmanY2[i - 1] < height/4)) {
    endShape();
  }
  vertex(i, kalmanY2[i]);
}
endShape();
beginShape();
    vertex(i, kalmanY2[i]);
endShape();

// Put all data one array back
for (int i = 1; i<kalmanY2.length;i++)
    kalmanY2[i-1] = kalmanY2[i];
Appendix J: Actuation System Code:

**Arduino Code:**

```c
#include <Servo.h>
#include <Stepper.h>
Servo myServoLT;  // create servo object to control a servo
Servo myServoLB;
Servo myServoRT;
Servo myServoRB;

const int stepsPerRevolution = 3200;
// twelve servo objects can be created on most boards
Stepper myStepperR(stepsPerRevolution, 8,9);
Stepper myStepperL(stepsPerRevolution, 10,11);
char i;
String readS;
long posR = 0;
long posL = 0;
void setup() {
  // put your setup code here, to run once:
  Serial.begin(115200);
  myServoRT.attach(2);  // attaches the servo on pin 9 to the servo object
  myServoRB.attach(3);
  myStepperL.setSpeed(30);  //left leg
  myServoLT.attach(4);
  myServoLB.attach(5);
  myStepperR.setSpeed(30);
  myServoLT.write(106);
  myServoLB.write(106);
  myServoRT.write(115);
  myServoRB.write(115);
}

void loop() {

  // ///////////stepper test/////////////////
  while(Serial.available()){
    i = Serial.read();
    readS += i;
    delay(15);
  }

  if(readS.length() > 0){
    if(readS == "f"){

      myServoLT.write(135);
      myServoLB.write(135);
      for(int i = 0; i < 48; i++)
      myStepperL.step(50);

    }
    for(int i = 0; i <= 2; i++){

      myServoLT.write(70);
      myServoLB.write(70);
      for(int i = 0; i < 48; i++)
      myStepperL.step(-50);

      //
    }

  }
```

```
for(int i = 0; i < 48; i++){
    myStepperL.step(-50);
}

myservoLT.write(110);
myservoLB.write(110);
for(int i = 0; i < 48; i++){
    myStepperL.step(50);
    if(i == 22){
        myservoLT.write(115);
        myservoLB.write(115);
    }
}

myservoLT.write(135);
myservoLB.write(135);
for(int i = 0; i < 48; i++){
    myStepperL.step(50);
}

// USE THIS SECTION!!!!

// Takes first step
if(readS == "b"){
    myservoRT.write(140);
    myservoRB.write(140);
    myservoLT.write(70);
    myservoLB.write(70);
    for(int i = 0; i < 48; i++){
        myStepperL.step(-50);
        myStepperR.step(-55);
    }
    // Goes Through walking motion
    for(int i = 0; i <= 4; i++){
        myservoRT.write(80);
        myservoRB.write(80);
        myservoLT.write(115);
        myservoLB.write(115);
        for(int i = 0; i < 48; i++){
            myStepperL.step(50);
            myStepperR.step(55);
            if(i == 24){
                myservoLT.write(110);
                myservoLB.write(110);
            }
        }
    }
    //
    myservoLT.write(135);
    myservoLB.write(135);
    for(int i = 0; i < 48; i++){
        myStepperL.step(50);
        myStepperR.step(50);
    }
    //
    myservoRT.write(120);
    myservoRB.write(120);
    myservoLT.write(80);
    myservoLB.write(80);
    for(int i = 0; i < 48; i++){
        myStepperL.step(-50);
        myStepperR.step(-50);
    }
}
if(i == 22){
    myservoRT.write(115);
    myservoRB.write(115);
}

//
myservoRT.write(140);
myservoRB.write(140);
for(int i = 0; i < 48; i++){
    myStepperL.step(-50);
    myStepperR.step(55);
}

// adjusts the final step
myservoRT.write(110);
myservoRB.write(110);
myservoLT.write(110);
myservoLB.write(110);
for(int i = 0; i < 48; i++){
    myStepperL.step(50);
    myStepperR.step(55);
}
}

readS = "";

---

**Processing 3 Code:**

```java
import processing.serial.*;
Serial serial;
serial = new Serial(this, "COM4", 115200); // change com port here
// Change string between " " to the file name that needs to be read.
// Use data dump files
String Data[] = loadStrings("test.txt"); // Grabs individual lines in file and stores them in an array
for(int i = 0; i < Data.length; i++){ // send the data one string at a time for all of the array.
    serial.write(Data[i]);
}
```
Appendix K: Hardware Schematic Diagrams

Attached on the following pages are the AutoCAD Files of the hardware wiring for the system.
Appendix L: Submitted and Approved Animal Testing Protocol

Attached on the following pages is the approved protocol that was submitted to IACUC.
Protocol Title: Development of a Canine Orthotronic Mobility System to assist impaired pets with walking
Protocol Type: IACUC
Date Submitted: 02/09/2016
Approval Period: 02/17/2016-01/27/2019
Important Note: This Print View may not reflect all comments and contingencies for approval. Please check the comments section of the online protocol.

** ** Amendment ** **

PROTOCOL AMENDMENT

After providing a response to the "Purpose for Amendment" question below, please make changes to the information in the appropriate protocol sections, updating the protocol to reflect the changes you are requesting. You can do this by clicking the appropriate section/link on the left side menu.

Once approved by the IACUC this Amendment becomes the official protocol, so it should accurately reflect all animal manipulations that have been completed already and any changes moving forward. Therefore, do not delete sections that have been performed or will continue to be performed, as the resulting protocol should reflect what has/will happen.

When you have completed this you will need to do the Certifications section again, and then use the "submit protocol" button in the left-hand column to submit for IACUC review.

Please contact an IACUC Coordinator if you have any questions about amendments.

Purpose for Amendment

Please briefly describe the changes to be made and provide a justification for the proposed amendment in the box below. Please then update the protocol itself to include the changes.

Expand study population to include client-owned healthy dogs as well (currently approved for Faculty/Staff/Student dogs).

List of Sections (and questions) that have been changed/modified. (List of changed sections will be automatically updated after they are changed.)

** ** Personnel Information ** **

COLORADO STATE UNIVERSITY INSTITUTIONAL ANIMAL CARE AND USE COMMITTEE
ANIMAL USE APPLICATION

IACUC approval of this completed form is necessary prior to animals being obtained, housed or manipulated for research, testing or teaching purposes; performed at CSU or by CSU at other locations.

When you have completed all applicable sections of the protocol, you must also complete the certifications section and then click "Submit Form" link on the left-hand column.

All individuals listed on the protocol must have certified completion of the online CSU Animal Care and Use Training. Additionally, a "Training Record" should be uploaded in the Attachments section for the PI, Co-PI, and each person who will handle animals as a part of this study. Also, all individuals working with animals
must be enrolled in the CSU Occupational Health and Safety Program (OHSP) via annual submission of a Risk Assessment Form to the OHSP.

Please contact an IACUC Coordinator if you have any questions.

Principal Investigator*

<table>
<thead>
<tr>
<th>Name</th>
<th>Title</th>
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<tbody>
<tr>
<td>Packer, Rebecca</td>
<td>Associate Professor</td>
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<table>
<thead>
<tr>
<th>Email</th>
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<tbody>
<tr>
<td><a href="mailto:Rebecca.Packer@colostate.edu">Rebecca.Packer@colostate.edu</a></td>
<td>rapacker</td>
<td>(970) 297-4543</td>
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<tbody>
<tr>
<td>1678 Clinical Sciences</td>
<td>1678</td>
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Will PI work with animals as part of this project?  Y

Co-Principal Investigator

<table>
<thead>
<tr>
<th>Name</th>
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<tbody>
<tr>
<td>Lambrechts, Nic</td>
<td></td>
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<tr>
<td><a href="mailto:Nic.Lambrechts@colostate.edu">Nic.Lambrechts@colostate.edu</a></td>
<td>nelamb</td>
<td>(970) 297-4304</td>
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Will Co-PI work with animals as part of this project?  Y

Department Head

<table>
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<tr>
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<th>Degree</th>
<th>Title</th>
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<tbody>
<tr>
<td>Jensen, Wayne</td>
<td></td>
<td>Professor</td>
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<table>
<thead>
<tr>
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<tbody>
<tr>
<td><a href="mailto:Wayne.Jensen@colostate.edu">Wayne.Jensen@colostate.edu</a></td>
<td>(970) 297-4284</td>
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Will the Department Head work with animals as a part of this project?  N

If this person will work with animals as a part of this protocol, upload a "Training Record" for this individual under the "Attachments" section of this protocol.

Administrative Contact

<table>
<thead>
<tr>
<th>Name</th>
<th>Title</th>
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<tbody>
<tr>
<td>Hastings, Candice</td>
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<tr>
<td><a href="mailto:Candice.Hastings@colostate.edu">Candice.Hastings@colostate.edu</a></td>
<td></td>
<td>(970) 297-4251</td>
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</table>
**Will Administrative Contact work with animals as part of this project?**

**N**

**Other Submitter**

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<th>Name</th>
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<tr>
<td>Jayasumana, Anura</td>
<td></td>
<td><a href="mailto:Anura.Jayasumana@colostate.edu">Anura.Jayasumana@colostate.edu</a></td>
<td>(970) 491-7855</td>
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<tbody>
<tr>
<td>1373 Elec &amp; Comp Engnr</td>
<td></td>
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**Other Personnel**

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<tbody>
<tr>
<td>Bryant, Jacob</td>
<td>Student</td>
<td><a href="mailto:Jacob.Bryant@rams.colostate.edu">Jacob.Bryant@rams.colostate.edu</a></td>
<td>(720) 474-4239</td>
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<tr>
<td>Harada, Katelyn</td>
<td>Student</td>
<td><a href="mailto:Katelyn.Harada@rams.colostate.edu">Katelyn.Harada@rams.colostate.edu</a></td>
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<td>King, Haley</td>
<td>Student</td>
<td><a href="mailto:Haley.King@rams.colostate.edu">Haley.King@rams.colostate.edu</a></td>
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<tbody>
<tr>
<td>Valades, Jeremy</td>
<td>Student</td>
<td><a href="mailto:Jeremy.Valades@rams.colostate.edu">Jeremy.Valades@rams.colostate.edu</a></td>
<td></td>
</tr>
</tbody>
</table>
**Species**

*Species to be Used*

- **Common Name**: Dog
- **Scientific Name**: Canis familiaris
- **Animal Sex**: Male or Female
- **Age Range**: 1 - 15 Year(s)
- **Weight Range**: 20 - 70 kg(s)
- **Strain/Breed/Subline**: Any strain
- **Housing Location**: VTH, Engineering Building, and Oval
- **Room Number**: Various
- **Maximum number of animals for three year project period**: 5

**USDA Pain Category (Choose all that will apply)**
- Pain Category B
- **X** Pain Category C (5)
- Pain Category D
- Pain Category E

---

*Will this person be working with animals as a part of this project? Y*
Pain Categories

Category B: Animals bred, conditioned or maintained for use in teaching, testing, or research, but not yet used for such purposes.

Category C: Animal use subjects them to no more than momentary or slight pain or distress and they do not receive pain-relieving drugs. Example: euthanasia prior to tissue collection; observation under normal conditions; positive rewards; routine injections (not Freund's adjuvant); tattooing; blood sampling.

Category D: Animal use subjects them to procedures where pain or distress is appropriately relieved with anesthetics, analgesics and/or tranquilizer drugs or other methods for relieving pain or distress which would otherwise be more than slight or momentary. Example: Needle biopsy non-survival or survival surgeries, terminal cardiac blood collection under terminal anesthesia; exposure of blood vessels for catheter implantation; induced infections or antibody production. PROCEDURES AT PAIN D REQUIRE VETERINARY CONSULTATION WITH THE UNIVERSITY VETERINARIAN OR DESIGNEE.

Category E: Animal use in which they must be subjected to unrelieved pain or distress for scientific reasons. Examples: toxicological or microbial testing or infectious disease research that requires continuation until severe clinical symptoms are evident or death occurs; application of noxious stimuli from which the animal cannot escape; prolonged restraint; use of paralyzing drugs for restraint of conscious animal; infliction of burns or trauma. PAIN E PROCEDURES REQUIRE CONSULTATION WITH THE UNIVERSITY VETERINARIAN OR DESIGNEE, AND MUST BE SCIENTIFICALLY JUSTIFIED IN THE PROTOCOL.

Source of Animals

Please indicate the source of the animals that will be used in the protocol. Be as specific as possible:
Outside Vendor (indicate whether purchased through LAR or by the investigator/department);
Transferred from another approved protocol (indicate protocol number);
Free-ranging Wildlife;
Faculty/Staff/Student-Owned;
Client-Owned;
Other (please explain).

NOTE: If this is a study using Client Owned animals, you must provide a copy of the Informed Owner Consent Form along with approval from VMC Director in the Attachments section.

* * * Are You Using? * * *

Please indicate if you propose to use any of the following so the IACUC may better assess your protocol.

1. Will you be using live animals for teaching? N
   What are the goals of the course(s) and who is the intended audience(s)?
   Please describe the preparation the students will have prior to handling live animals (e.g. lecture, demonstrations, anatomical model use, videos)

2. Will you be using euthanized animals for teaching purposes? N
   What will be the source of the animals (LAR or Vendor) and what is the disposal plan?
   What are the goals of the course(s) and who is the intended audience(s)?

3. Will you be collaborating with another institution(s)? N

Institution(s)
4. Will you be using biohazardous agents?

   a) Recombinant DNA (rDNA), human fluids or human tissues  N
   b) Infectious Agents?  N
      If you indicated "Yes" to 4a. or b. above, please provide IBC protocol "PARF" number, or indicate "Submitted" or "Submission Pending," as appropriate.
   c) Will this protocol involve the generation of new transgenic or knockout lines using rDNA?  N
   d) If using an infectious agent or toxin, is it on the USDA or CDC Select Agent List (see Select Agents for the two lists of agents)?  N

5. Will studies be performed under Good Laboratory, Good Clinical, or Good Manufacturing Practices (GLP/GCP/GMP)? Such studies are regulated by the Food and Drug Administration (FDA) or the Environmental Protection Agency (EPA). Please contact the CSU Quality Assurance Manager for additional review and approval of GLP/GCP/GMP documentation.
   If yes, please provide the name of the individual who will be the Study Monitor, and briefly describe how the project involves GLP/GCP/GMP or preliminary product testing.

6. Will you be using controlled drugs?
   Will controlled drugs (including HCG and Ketamine) be used?  N
      If yes, list whose CSU "drug cabinet" will be accessed.

7. Will carcinogenic or chemical substances that are hazardous to humans or animals be used?
   Toxic Agent(s)  N

8. Will you be using radiological agents
   Isotope(s)  N

9. Will this be a field study (i.e. conducted on free-living wild animals in their natural habitat)? In addition to IACUC approval, the investigator is responsible for obtaining all necessary federal/state or other government permits for wildlife studies.
   Field Study or Wildlife Study  N

** Funding Sources **

Funding Checklist

Funding - Grants/Contracts

Funding - Other
This protocol is funded (in whole or in part) with funding from an agency in the U.S. Department of Defense (DoD)? This includes direct grant/contract funding or subcontract work that is flow-through of funding from DoD.

If DoD funding is involved, the PI will be responsible for obtaining approval from the DoD Animal Care and Use Research Office (ACURO) for all new protocols and amendments to existing protocols prior to initiation of the work/change to the protocol.

Check here if this project is self-funded (No aspect of this work will have charges to a sponsored project, departmental account, other CSU-related account associated with it.)

NOTE: Applicable Federal Grant Application, including competing renewals must be attached. Applicable investigator's brochure and sponsor's protocol must be attached for all industry sponsored clinical trials. You will be prompted for these in the Attachments section.

Has this protocol received other internal reviews (check all that apply):

<table>
<thead>
<tr>
<th>Reviewed for CRC Funding</th>
<th>Yes</th>
<th>No</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reviewed by VTH/Clinical Sciences Clinical Research Review Board:</td>
<td>Yes</td>
<td>No</td>
<td>X</td>
</tr>
</tbody>
</table>

I assure that the activities described with in this document submitted for IACUC review are consistent with those described in any related grant, contract, or subcontract that has been submitted or awarded.

* * * Rationale * * *

1. PROJECT INFORMATION

a) Protocol title

Development of a Canine Orthotronic Mobility System to assist impaired pets with walking

b) Application type

Note: If you are editing a previously approved protocol for an Amendment or Continuing Review, please leave the answer to the questions under b. below as they were in the originally approved protocol.

This project is a: (check only one)
X New project
4th year renewal (please enter number of protocol that you are renewing below)

If this is a 4th year renewal, please indicate the number of the protocol it is renewing.

2. LAY SUMMARY

a) What is the overall goal or purpose of this animal use?
Provide a brief description which would convey to a lay audience the purpose for the proposed use of animals. Use language understandable to a layperson. Avoid overly technical terms and define acronyms. The readability should be similar to a newspaper article. For example, the goal of a study could be expressed as follows: “Disease XYZ is a serious threat to the health of…. This project will seek to test the efficacy of treatment ABC.” Or, “This project seeks to understand the cellular mechanisms that influence X through in vitro analysis utilizing tissues harvested from the proposed species Y.”

Note: A section from your grant application using highly technical terms is not acceptable.

Many pets suffer from partial paralysis, and are unable to walk unassisted, as the primary quality of life limiting factor. The overall goal of this prototyped project is to develop technology for an electronically controlled active exoskeleton that assists hind limb movement in partially paralyzed canines. The exoskeleton will sense existing but suppressed movement from the canine and then activate motors embedded in the orthoses, to provide additional joint movement and stability. This project is primarily aimed at supplying physical therapy for disabled canines (as a adjunct or supplement to canine wheelchairs or sling walking); and in fact may be preferred over these modalities as it emulates and reprograms normal gait and posture. It could also contribute to human exoskeleton development. Animals are required for this as using a model only permits development of the prototype shape/conformation, but not functional use, as thoracic limb movement is required as a component of the sensory input. Living dogs are required as the prototype model.

b) What will the impact of the use of live animals in this project be for human OR animal health, the advancement of knowledge, or the good of society?
Regulations and ethical standards require that procedures involving the use of animals in research or teaching be designed and performed with due consideration of their relevance to human or animal health, the advancement of knowledge or the good of society. Provide a brief description which would convey to a lay audience the impact the proposed research will have for one or more of the above considerations. For example, “1 million people are estimated to contract disease XYZ each year. The proposed project will further the cause of developing effective treatments for the disease.” Or “The cellular mechanisms X have previously been studied, but no studies have looked at aspect C of this mechanism. This study will advance the scientific understanding of X by exploring aspect C.”

Note: Projects are not required to have application for human health to receive IACUC approval.

See above (a) as well. The CSU VTH admits approximately 5-10 canine patients per week that have difficulty walking unassisted due to neurological impairment (e.g., disc herniations, strokes, etc). In these patients the primary quality of life limitation is the inability to walk unassisted and maintain independence. An orthotic that mechanically assists with normal walking in these patients will greatly improve their quality of life. This device will have applications to human exoskeleton projects as well, in the sensing technology as well as the automated movement.

3. JUSTIFICATION FOR USE OF ANIMALS

For parts a. and b. below, please answer "Yes" or "No" for each question.
There should be a Yes/No answer in all questions a)i. through a)vii. and b)i. through b)v.

a) Living animals are required for this project because:
(You should select either Y or N for each query.)

   i) Y Complexity of the processes studied cannot be duplicated-modeled using in vitro models
ii) Y Not enough information known about processes being studied to design non-living models

iii) Y Pre-clinical studies in living animals are necessary prior to human testing

iv) N This study requires tissue harvested from animals prior to in vitro testing

v) N Currently this is the best method to accomplish the required teaching

vi) N Populations are being studied in natural or semi-natural environments

vii) N Animal behavior is being studied

viii) Other (please specify):

b) This species has been selected because:
(You should select either Y or N for each query.)

i) Y Anatomy, physiology, behavior or agent susceptibility of species uniquely suited to the study

ii) N Lowest phylogenetic species providing adequate size, tissue, or anatomy for proposed study

iii) Y This species provides a particularly good model for the human or other animal disease or process

iv) N Previous studies which form the background for this project used this species

v) Y The objective of this study is to provide information about the target species

vi) Other (please specify):

4. JUSTIFICATION FOR NUMBER OF ANIMALS TO BE USED

The IACUC requires justification of proposed animal use numbers. A power calculation, confidence interval width, or an explanation why a power calculation is not feasible for this project should be provided. Complete one or more of the following (as appropriate) to justify the number of animals you will use (you may refer to Russ Lenth’s U. Iowa stats website for statistical calculations). For experimental designs with multiple groups/treatments, it is suggested that a table of animal numbers per group be provided in the Attachments section. In addition make sure the animal numbers justified here agree with those mentioned in other sections of the application.

Answer N/A for any question (a-i) that is not applicable. There should be an answer or N/A in all boxes a-i.

a) This is an exploratory or pilot study. Describe how the proposed number of animals needed was determined. Note: A total of more than 12 animals indicates to the IACUC that the project may not
A maximum of 5 dogs will be used for this pilot study, to develop a prototype orthotic system. Dogs must be willing to wear the brace and walk on leash calmly and in a straight line along the gait analysis mat. The number of 5 dogs allows us to have at least 3 useable data sets for normal canine movement and testing/development. Some dogs do not walk calmly on the walkway for gait analysis recording, and thus are not good candidates and may need to be excluded. For this reason we have a buffer in case we need to exclude up to 2 of the dogs initially selected for the study.

b) The group size was determined using a statistical package. Specify the statistical package used, effect size(s), estimate of variation used, and power level expected. (If multiple response variables are to be measured, the power calculation should be based on the most critical measures. When the objective is not to test but to estimate differences between mean or proportions, sample size may be justified based on confidence interval width criteria.):

| N/A |

| N/A |

c) This is a teaching protocol. Specify student-to-animal ratio, and explain how that was determined. There should be a clear correlation between the teaching objective and the number of animals per student:

| N/A |

| N/A |

d) This study involves tissue or cells harvested from animals for in vitro studies. Explain the number of animals requested for the amount of tissue needed to obtain a specified level of precision desired, or if an experiment involving the tissue samples will be conducted as part of this protocol, provide power calculations as described in b above. Clearly show the relationship between the number of animals requested and the number needed for the in vitro work:

| N/A |

| N/A |

e) This study involves breeding animals for later use in research, testing, or teaching. List the number of breeding males and females to be used/number of offspring produced each year, and describe how the animals are expected to be allocated to the subsequent experiment(s). If only a portion of the offspring will be usable in experiments, please indicate the number and reason for this:

| N/A |

| N/A |

f) This is a study of feral or wild animals where animals will be captured and released attempting to maximize sample size within logistical constraints. Describe and suggest a level of precision necessary to obtain useful information and the sample size required to obtain this precision:

| N/A |

| N/A |

g) This is an observational, non-manipulative study in which animals will only be observed and animal numbers cannot be predicted. The animals will not be captured nor will their behavior be manipulated:

| N/A |

| N/A |

h) Sample size is government driven or agency mandated. Provide appropriate references documenting this requirement (e.g. product safety testing as mandated by FDA regulations):

| N/A |

| N/A |

i) Other. Please describe in detail:

| N/A |

| N/A |
** *** Procedures *** **

** Procedure Type:** Other

** Procedure Title:** Walking assessment of healthy dog with mechanical orthotic brace

** Species:** Canis familiaris (VTH, Engineering Building, and Oval)

** Pain/Distress Category:** C

** Approximate number of animals to be used in this procedure:** 5

All D and E studies require date of consultation with the University Veterinarian; or, the name of other vet who was consulted:

** Use Location (Campus)** VTH, Engineering Bldg, Oval

** Building Name:** Various

** Room Number:** Various

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** *** Procedure Description *** **

** Procedure Description.** Provide a brief description of how the procedure will be conducted. For blood/fluid collections include the route(s) of collection, volume, and frequency. For drug/compound dosing include route(s) of administration, volume, and frequency. For inoculations, include agent/vaccine information, route(s) of administration, volume, frequency, and dose. For procedures requiring administration of anesthesia, analgesia, provide the doses/route of administration; and for procedures requiring aseptic preparation, briefly describe animal, surgeon, and instrument preparation. Please DO NOT simply cut-and-paste from laboratory SOPs with superfluous or overly general information in them.

The prototyped exoskeleton system will be composed of two separate orthotic braces. The first brace will contain motors, and possess the ability to move the exoskeleton. This brace will be place on a model of a dog that the team has fabricated with the help of Orthopets. The second brace system will contain a sensor array consisting of seven pressure sensors and three gyroscopes per hind leg. This brace will be placed on a healthy dog in order to record the pressure and gyroscope readings of a normal dog. This data will then be sent to the second brace system that is attached to a model (most likely foam) dog. This second brace system will move forward, through motors, based on the input from the healthy dog signals.

This brace system will extend from the femur to the paw. The brace consists of three sections. There is a section attached to the femur, one attached to the tibia, and one attached to the tarsus. Each piece will be equipped with the appropriate pressure sensors and gyroscopes depending on what is being measured for that section. The most important pressure sensors will be place on the bottom of the paw, and they will be used to evaluate the stage of the gait cycle the animal is in. The number and location of the pressure sensors and gyroscopes is subject to change due to the results of initially working with a dog. The risks to the dogs of using these sensors is extremely minimal, and will not increase or decrease with varying number.

There will be five testing sessions for this project. For each session, each dog will need 10 recordable trials each while walking at two different speeds (slow walk, normal walk). The dog will be leash-guided by a trained person and between each trial the dog will undergo a resting period of at least two minutes. Each dog will walk for approximately 30 feet for each trial (up to 100 feet), and for each trial the data will be read into the microcontroller.

Please list any clinical effects or changes from normal health and behavior which may occur as a result of this procedure. This should include both short and longer-term effects of the procedure, as
This will be a completely passive process - the dog will not have any motors attached to it, therefore the motors will not move the limbs of the dog in any way. The brace containing the sensors will be attached to the dog, and it will contain secured wires, and a small voltage source (5V) connecting all of the circuitry together.

The animals will not be exposed to any of this current, as it is contained within the brace. There will be no risk to the dog from this voltage (and even were there to be a malfunction, 5 volts is too small of a voltage to do any harm to the dog). Due to the design of the mechanical system, there will be no pinch points, if encountered an easy fix can be implemented so that the canine does not get hurt. The only other potential risk to the dog could be if the dog becomes stressed during the experiment. If any signs of stress are observed (e.g., anxiety, persistent vocalizing), the experiment will be immediately stopped, the brace sensor system will be removed, and we will return to data collecting at a later time. If a dog appears anxious or stressed on the repeated occasions, a new dog will be enrolled as a replacement.

Describe post procedure monitoring that will be performed. This should clearly indicate the frequency of monitoring, who will conduct it, and address the short- and longer-term complications that may result from the procedure.

N/A

What criteria will be used to determine if animals exhibiting clinical or behavioral changes should be given rescue analgesia, other clinical treatments, or euthanasia. Please include any scoring system that will be used to determine when humane intervention will be triggered in the Attachments section or provide the scoring criteria below, as applicable.

N/A

*** Surgeon Details ***

Surgeon Details

*** Anesthetic Regimen ***

Anesthetic Regimen

Note: Documentation of training is not required if you are using VMC or LAR services

Anesthetists

Parameters monitored during surgery:

Anesthetic Agents

Paralytic Agents

Other premedications not already listed above

-----------------------------------------------------------------------------------------------
Perioperative Care

Pre-emptive agents (analgesics given prior to procedure)

Intra-operative analgesics (local blocks; intracavity blocks).

Describe what parameters will be monitored during anesthesia/surgery to assure proper anesthesia.

Antibiotics or Anti-Microbials

Post Operative Monitoring

Analgesic Agents

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Parameters Monitored

Note: Include any pain scale or scoring system as an attachment in attachments section.

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* * * Other Drugs Utilized * * *

Other Drugs Utilized

Other Drugs Agents

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**Surgery Info**

Specific room number where surgery is performed:

Surgery Type:

**ALSO NOTE:** The Guide defines major surgery as one that penetrates and exposes a body cavity or produces substantial impairment of physical or physiological functions, and the USDA defines a major operative procedure as any surgical intervention that penetrates and exposes a body cavity or any procedure that produces permanent impairment of physical or physiological functions.

Will this project include Multiple Major Survival Surgery (MMSS)?

**PLEASE NOTE:** If multiple major survival procedures are to be performed, you will be asked for specific justification in Project Overview section of this form.

Number of animals per year:

---

**Physical Exam**

**Procedure Type:** Physical Exam

**Procedure Title:** Orthopedic and neurologic examination

**Species:** Canis familiaris (VTH, Engineering Building, and Oval)

**Pain/Distress Category:** C

Approximate number of animals to be used in this procedure: 5

All D and E studies require date of consultation with the University Veterinarian; or, the name of other vet who was consulted:

Use Location (Campus)

**Building Name:** Various

**Room Number:** Various

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**Procedure Description**

Procedure Description. Provide a brief description of how the procedure will be conducted. For blood/fluid collections include the route(s) of collection, volume, and frequency. For drug/compound dosing include route(s) of administration, volume, and frequency. For inoculations, include agent/vaccine information, route(s) of administration, volume, frequency, and dose. For procedures requiring administration of anesthesia, analgesia, provide the doses/route of administration; and for procedures requiring aseptic preparation, briefly describe animal, surgeon, and instrument preparation. Please DO NOT simply cut-and-paste from laboratory SOPs with superfluous or overly general information in them.

Each dog will have an orthopaedic and neurological examination by a DVM to ensure there are no
clinical gait abnormalities or orthopaedic or neurological abnormalities that would affect normal gait and preclude evaluation/data collection for the study. Dogs will be observed for normal behavior, and owners will be questioned as to their dogs’ recent and past behavior. Dogs will be walked while gait is observed. Dogs will be palpated for pain or abnormalities in the joints, muscles, bones and tested for reflexes, cranial nerves, and proprioception. So for neuro we do things like flip the paw upside down and they should correct it quickly. We test the knee reflex and a few others like they do in humans. We tickle the face in various places and look for them to blink, twitch, respond.

Please list any clinical effects or changes from normal health and behavior which may occur as a result of this procedure. This should include both short and longer-term effects of the procedure, as applicable.

Dogs may experience slight elevation in stress briefly, in response to a few of the tests. If a dog appears very nervous or stressed, it likely will not make a good candidate for the rest of the project anyway and the exam will be discontinued. No clinical effects are expected.

Describe post procedure monitoring that will be performed. This should clearly indicate the frequency of monitoring, who will conduct it, and address the short- and longer-term complications that may result from the procedure.

N/A

What criteria will be used to determine if animals exhibiting clinical or behavioral changes should be given rescue analgesia, other clinical treatments, or euthanasia. Please include any scoring system that will be used to determine when humane intervention will be triggered in the Attachments section or provide the scoring criteria below, as applicable.

N/A

-----------------------------------------------------------------------------------------------

* * * Anesthetic Regimen * * *

Anesthetic Regimen

Note: Documentation of training is not required if you are using VMC or LAR services

Anesthetists

Parameters monitored during surgery:

Anesthetic Agents

Paralytic Agents

Other premedications not already listed above

-----------------------------------------------------------------------------------------------

* * * Other Drugs Utilized * * *

Other Drugs Utilized

Other Drugs Agents

-----------------------------------------------------------------------------------------------

Other
Procedure Type: Other
Procedure Title: Gait analysis
Species: Canis familiaris (VTH, Engineering Building, and Oval)
Pain/Distress Category: C

Approximate number of animals to be used in this procedure: 5

All D and E studies require date of consultation with the University Veterinarian; or, the name of other vet who was consulted:

Use Location (Campus) VMC Campus
Building Name: VTH
Room Number: B114A

*** Procedure Description ***

Procedure Description. Provide a brief description of how the procedure will be conducted. For blood/fluid collections include the route(s) of collection, volume, and frequency. For drug/compound dosing include route(s) of administration, volume, and frequency. For inoculations, include agent/vaccine information, route(s) of administration, volume, frequency, and dose. For procedures requiring administration of anesthesia, analgesia, provide the doses/route of administration; and for procedures requiring aseptic preparation, briefly describe animal, surgeon, and instrument preparation. Please DO NOT simply cut-and-paste from laboratory SOPs with superfluous or overly general information in them.

Each dog may also be recorded on the instrumented gait analysis (IGA) lab at the VTH. If occurs, they would be walked over a 10-foot long pressure-sensitive walkway up to 20 times (average of 10 trials per dog). Each pass will take approximately 5 seconds to complete. The pressure-sensitive walkway is housed in the Colorado State University canine gait analysis laboratory. The primary outcome measure will be the collection of kinetic and temporospatial variables obtained by objective IGA. Variables recorded will include gait cycle duration, stance and swing phase duration, stride length, stride velocity, stride acceleration, peak vertical force, % weight distribution and vertical impulse. These data may be collected without and with the brace in place, to ensure that the brace itself does not alter the dog's normal gait. Dogs will be housed in the VTH wards/runs as with any outpatient.

Please list any clinical effects or changes from normal health and behavior which may occur as a result of this procedure. This should include both short and longer-term effects of the procedure, as applicable.

This will be a completely passive process - the dog will not have any motors attached to it, therefore the motors will not move the limbs of the dog in any way. The brace containing the sensors will be attached to the dog, and it will contain secured wires, and a small voltage source (5V) connecting all of the circuitry together.

The animals will not be exposed to any of this current, as it is contained within the brace. There will be no risk to the dog from this voltage (and even were there to be a malfunction, 5 volts is too small of a voltage to do any harm to the dog). Due to the design of the mechanical system, there will be no pinch points, if encountered an easy fix can be implemented so that the canine does not get hurt. The only other potential risk to the dog could be if the dog becomes stressed during the experiment. If any signs of stress are observed (e.g., anxiety, persistent vocalizing), the experiment will be immediately stopped, the brace sensor system will be removed, and we will return to data collecting at a later time. If a dog appears anxious or stressed on the repeated occasions, a new dog will be enrolled as a replacement.

Describe post procedure monitoring that will be performed. This should clearly indicate the frequency of monitoring, who will conduct it, and address the short- and longer-term complications that may result from the procedure.

N/A

What criteria will be used to determine if animals exhibiting clinical or behavioral changes should be
given rescue analgesia, other clinical treatments, or euthanasia. Please include any scoring system that
will be used to determine when humane intervention will be triggered in the Attachments section or
provide the scoring criteria below, as applicable.

| N/A |

* * * Surgeon Details * * *

Surgeon Details

* * * Anesthetic Regimen * * *

Anesthetic Regimen

Note: Documentation of training is not required if you are using VMC or LAR services

Anesthetists

Parameters monitored during surgery:

Anesthetic Agents

Paralytic Agents

Other premedications not already listed above
**Perioperative Care**

Pre-emptive agents (analgesics given prior to procedure)

Intra-operative analgesics (local blocks; intracavity blocks).

Describe what parameters will be monitored during anesthesia/surgery to assure proper anesthesia.

Antibiotics or Anti-Microbials

Post Operative Monitoring

Analgesic Agents

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**Other Drugs Utilized**

Other Drugs Utilized

Other Drugs Agents
**Surgery Info**

Specific room number where surgery is performed: [ ]

Surgery Type: [ ]

**ALSO NOTE:** The Guide defines major surgery as one that penetrates and exposes a body cavity or produces substantial impairment of physical or physiological functions, and the USDA defines a major operative procedure as any surgical intervention that penetrates and exposes a body cavity or any procedure that produces permanent impairment of physical or physiological functions.

Will this project include Multiple Major Survival Surgery (MMSS)?

PLEASE NOTE: If multiple major survival procedures are to be performed, you will be asked for specific justification in Project Overview section of this form.

Number of animals per year:

--------------------------------------------------------------------------------------------

Other

Procedure Type: Other

Procedure Title: Walking assessment of healthy dog with mechanical orthotic brace

Species: Canis familiaris (VTH, Engineering Building, and Oval) Pain/Distress Category: C

Approximate number of animals to be used in this procedure: 1

All D and E studies require date of consultation with the University Veterinarian; or, the name of other vet who was consulted:

--------------------------------------------------------------------------------------------

Use Location (Campus) University Plaza Building Name: Various

Room Number: Various

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**Procedure Description**

Procedure Description. Provide a brief description of how the procedure will be conducted. For blood/fluid collections include the route(s) of collection, volume, and frequency. For drug/compound dosing include route(s) of administration, volume, and frequency. For inoculations, include agent/vaccine information, route(s) of administration, volume, frequency, and dose. For procedures requiring administration of anesthesia, analgesia, provide the doses/route of administration; and for procedures requiring aseptic preparation, briefly describe animal, surgeon, and instrument preparation. Please DO NOT simply cut-and-paste from laboratory SOPs with superfluous or overly general information in them.

The students involved in this project may be eligible to display this work at Engineering Days, requiring a demonstration dog to show the signaling between the live dog and model dog braces. This will be
performed exactly as the previous trials, and the dog used will have been selected because it was happy to wear the brace and walk in the previous trials.

The dog will walk in the brace no more than the number of times it has did on previous trial days, to demonstrate the function of the prototype. Water will be provided at all times the dog is not actively walking for the demonstration.

Please list any clinical effects or changes from normal health and behavior which may occur as a result of this procedure. This should include both short and longer-term effects of the procedure, as applicable.

Similar to the original trials, low risk of side-effects. Since this will presumably take place outside, the team will take temperature into consideration, and monitor panting or other signs the dog is getting hot. In that case, the brace will be removed, and the dog will be moved to the shade, or the dog will be taken home by the owner.

Describe post procedure monitoring that will be performed. This should clearly indicate the frequency of monitoring, who will conduct it, and address the short- and longer-term complications that may result from the procedure.

Personnel handling the dog will be monitoring and interacting with the dog constantly while the dog is wearing the brace. If the brace is no longer needed, the dog will be released to owner. No short- or long-term complications are expected.

What criteria will be used to determine if animals exhibiting clinical or behavioral changes should be given rescue analgesia, other clinical treatments, or euthanasia. Please include any scoring system that will be used to determine when humane intervention will be triggered in the Attachments section or provide the scoring criteria below, as applicable.

N/A

* * * Surgeon Details * * *

Surgeon Details

* * * Anesthetic Regimen * * *

Anesthetic Regimen

Note: Documentation of training is not required if you are using VMC or LAR services

Anesthetists

Parameters monitored during surgery:

Anesthetic Agents

Paralytic Agents

Other premedications not already listed above
**Perioperative Care**

**Pre-emptive agents** (analgesics given prior to procedure)

**Intra-operative analgesics** (local blocks; intracavity blocks).

Describe what parameters will be monitored during anesthesia/surgery to assure proper anesthesia.

**Antibiotics or Anti-Microbials**

**Post Operative Monitoring**

**Analgesic Agents**

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*** * * Other Drugs Utilized* * ***

**Other Drugs Utilized**

**Other Drugs Agents**
**Surgery Info**

Specific room number where surgery is performed: 
Surgery Type: 

**ALSO NOTE:** The Guide defines major surgery as one that penetrates and exposes a body cavity or produces substantial impairment of physical or physiological functions, and the USDA defines a major operative procedure as any surgical intervention that penetrates and exposes a body cavity or any procedure that produces permanent impairment of physical or physiological functions.

Will this project include Multiple Major Survival Surgery (MMSS)?

**PLEASE NOTE:** If multiple major survival procedures are to be performed, you will be asked for specific justification in Project Overview section of this form.

Number of animals per year:

-----------------------------------------------------------------------------------------------

**Alternative Search**

**Alternatives Search**

Federal regulations require that the fewest number of live animals necessary are used for research, testing, or teaching, and that investigators document that they have given all due consideration to reducing or eliminating the use of potentially painful or distressful procedures (Pain Category D or E). The USDA considers automated literature searches the most effective and efficient method for demonstrating compliance with the above requirements.

For ALL projects, regardless of pain categorization, please conduct a literature search utilizing terms that would allow you to demonstrate that the proposed research or other animal use is not unnecessarily duplicative of previously documented work. Please enter the appropriate Search Data (click the "Add" button) and answer Question 1 below.

If the proposed project involves procedures at Pain Categories D and/or E, documentation of a literature search which demonstrates that the fewest number of the lowest order of animals will be used to obtain valid results, and alternatives to EACH potentially painful/distressful procedure proposed have been sought. Therefore please enter the appropriate Search Data and answer Questions 2 & 3 below. See USDA Policies #11 and 12).

For assistance with alternatives searches, please consult the CSU Libraries IACUC Alternatives Search Help page, see the Alternatives to Painful or Distressful Procedures document (prepared by the University Veterinarian), or contact an IACUC Coordinator.

Click the "Add" button below to enter information pertinent to your search(es). Please then address question 1 and, as appropriate to the procedures to be conducted, address, questions 2-3.

**Search Data**
Search Terms

Please provide the Keywords and the Boolean terms such as AND, OR used to relate keywords (e.g. term#1 [AND] term#2) for searches for each of the three components of the Alternatives Search indicated above:

Dog AND orthotic

Databases Searched (you must search at least 2 databases):

- Agricola Data Base
- ALTBIB - Bibliography on Alternatives to Animal Testing
- SCIRUS
- AnimAlt-ZEBET
- ATLA (FRAME--Alternatives to Laboratory Animal Testing)
- BioOne (access from CSU Libraries website)
- BIOSIS (Note: CSU Libraries does not subscribe to this database)
- CAB Abstracts (access from CSU Libraries website)
- Medline / PubMed
- Lab Animal
- Lab. Animals Journal
- HSVMA Alternatives in Education Database
- Medline / PubMed
- NORINA
- TOXLINE
- Web of Science (access from CSU Libraries Website)
- Other, please specify:

1. N Did the search reveal that your project is duplicative of previously documented work?
   a) Please provide the number of hits and an overview of the results.
   No, there was no duplication

   b) If "Yes," please provide a list of the relevant citations and a discussion of how you determined that it is necessary to conduct the project anyway.

2. N Did the search reveal any possible reductions or replacements that would allow the use of fewer animals or animals of a lower order?
   a) Please provide the number of hits and an overview of the results.
   No, this is novel work and already a pilot study with low sample numbers required

   b) If "Yes," please provide a list of the relevant citations and a discussion of how you determined that it is necessary to conduct the project as proposed.

3. N Did the search reveal any possible refinements that would allow the use of alternative procedures to those that will potentially cause pain and/or distress for the animals (Protocols utilizing procedures at pain category D and/or E)?
   a) Please provide the number of hits and an overview of the results.
   Pubmed 15 hits, CAB Abstract 17 hits. All hits only mention use of orthotics as rigid non-mobile support structures but not mechanisms for assistance during active walking. The current device will not cause pain or distress, but simply requires application in live dogs to
refine the sensory/mechanical system and shape/conformation of the brace.

b) If "Yes," please provide a list of the relevant citations and a discussion of how you determined that it is necessary to conduct the project as proposed.

Teaching Protocols
1. If this is a teaching protocol, please specify why there are no alternatives to using live animals.

   N/A

Protocols Involving Unrelieved Pain or Distress
1. For Pain Category E procedures, explain why drugs or other ameliorative treatments cannot be used to fully alleviate pain/distress. Please provide citations to the relevant literature.

Other Means of Determining Non-Duplication and Alternatives
The Animal Welfare Act allows other means of determining whether your project is duplicative AND whether it can be refined to decrease the animal number or order, AND to determine if alternatives to a potentially painful/distressful procedure can be used. For example, under some circumstances, colloquia, subject expert consultants, or other sources may provide relevant and up-to-date information regarding alternatives. When other sources are the primary means of considering alternatives, sufficient documentation, such as the consultant's name and qualifications and the date and content of the consult should be provided. If you used an alternative search strategy, provide information on the strategy, methods, sources, and relevant findings.

   N/A - this is novel work and not duplication of prior work. There are no alternatives to using live animals who can move normally, from which to develop the mechanism for simulating normal gait in paralyzed dogs. Phase I of the project already involves only a foam dog model, but Phase II requires a living and moving dog.

* * * Project Overview * * *

Project Overview

Provide a clear and concise sequential description of the procedures the animals will undergo. The description should include information on the experimental groups and the study endpoints. It should allow the reader to see the timing and relationship of all procedures that will be conducted with the animals. For lengthy or complex experiments with many groups and/or procedures, a table or flowchart showing the experimental manipulations by group should also be uploaded into the Attachments section. A response here is required.

Five healthy dogs will serve to provide data for a gait-enhancement system prototype. Data from the live dog wearing a sensory brace will be transmitted to a motorized brace on a model dog, and cause the motorized brace to move the model. The purpose of this study is ultimately to design a movement-assisting exoskeleton for dogs with movement restrictions, with possible translation to human subjects eventually.

Dogs in the trails will first undergo an examination for fitness for the study. Once enrolled, they will be fitted with the sensory brace and perform a series of walking trials. During each session, each dog will need 10 recordable trials each while walking at two different speeds (slow walk, normal walk) with a two minute rest between each trial.
minute rest between each trial.

To test the difference between the dog's normal gait and the gait with the brace on, each dog may also be recorded on the instrumented gait analysis (IGA) lab. For those recordings, the dogs would be walked over a 10-foot long pressure-sensitive walkway up to 20 times (average of 10 trials per dog). Each pass will take approximately 5 seconds to complete. These data may be collected without and with the brace in place to show whether there is a difference.

At various points we may videotape the trials in order to have a video demonstration available, for engineering competitions and the like. If, at a later time, we feel the video is not sufficient as a standalone demo for the engineering competition, we will submit an amendment and discuss the options further with the IACUC.

Before and after each session the dog will remain with its owner.

Multiple Major Survival Surgery (MMSS) Description:

Describe why it is necessary to perform multiple major surgical procedures on the same animal.

----------------------------------------------------------------------

*** Husbandry ***

Animal Care/Husbandry

Emergency Contact Information

List all individuals/phone numbers that are to be notified by veterinary staff or others in the event of an emergency:

Dr. Rebecca Packer 765-714-1227 or 970-219-3380
Dr. Nicolaas Lambrechts 970-692-4486

Will Lab Animal Resources provide the daily care  N

If "No," specify who will provide the daily care:

N/A - Animals will never be housed here for daily care. They will be at home with their owners (staff/faculty/students) when data collection is not actively being acquired. During instrumented gait analysis at the VTH, dogs will be in the VTH wards or runs as with any outpatient.

If "No," justify why LAR will not be providing animal care:

N/A

What veterinarian will provide medical care to animals?  Other

If "Other" specify who:

In the event that medical care is required related to the study activities, Drs Packer and Lambrechts are available for assessment and recommendations, and LAR will be notified of any such events. Medical needs that develop unrelated to the project will be addressed by the pet's general veterinarian as would normally occur.

Contact information:

Dr. Rebecca Packer 765-714-1227 or 970-219-3380
Dr. Nicolaas Lambrechts 970-692-4486

If "Other" justify why LAR will not be providing medical care:
Animals will only be on campus during the times specified, and otherwise will be living with their owners (faculty/staff/students). Also, procedures simply involve walking while wearing a brace. No medical care is anticipated; however, Drs. Packer and Lambrechts will remain available to the team and will inform LAR of any events.

**Location of medical records (indicate building/room or other applicable information):**

VTH Electronic Medical Record System (for gait analysis and any medical care needs related to the project); Research records will be kept in the Engineering Building, regarding general study activities.

Special Husbandry or Care

List any special or unusual requirements for care of the animals and who will provide this care (e.g. special diet, altered light cycle, variation from standard enrichment, etc.):

N/A

Non-standard Experimental Requirements (Procedures requiring Exemptions from the Guide).

Social Housing

If you are using a social species there are mandatory housing requirements. CSU considers social housing to include compatible housing with conspecifics, as well as housing in the same secondary containment with visual, auditory, olfactory or tactile contact with conspecifics. See the "Policy on Social Management of Animals" on the IACUC Policies and Guidelines Page.

Please indicate which of the following is true:

1. Animals will be provided with social housing (unless an animal has individual incompatibility or vet care concerns, or due to cohort attrition).
2. Animals will not be housed at CSU. **X**
3. Animals will be housed singly because that is appropriate for this species (including hamsters, rabbits, male mice, tom cats, and livestock in stalls).
4. Animals will be housed singly because such housing is necessary for research, testing or teaching goals.

If you will be housing animals singly for research, testing or teaching purposes (#4 above), you must provide a written justification which indicates the experimental constraints that make the housing necessary:

Food or Fluid restriction (other than up to 12 hours prior to surgery/general anesthesia) **X** None

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<th>Fluid Restriction</th>
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**Description**

Restraint of Conscious Animals (other than momentary restraint for routine procedures, e.g. blood collections, injections, and such) **X** None

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**Restraint of Conscious Animals**
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**Description**

**Non-standard housing requirements**

- **X** None

---

**Disposition of Animals**

Please provide the information requested below regarding what will happen to animals at study end. (Check all that apply)

- Animals will be adopted (Note, PI is required to follow the IACUC “Policy on Animal Adoptions” which is located on the page IACUC Policies and Guidelines Page.
- Sold at auction (hoof stock only)
- Released into home territory (wildlife studies)
  - **X** Returned to client
  - Transferred to other studies (please specify below)

Animals will be euthanized  (Please add method below)

If using CO2 as the method of euthanasia for mice and rats, please be aware that the IACUC requires use of the “Directions for CO2 Euthanasia of Rodents” (available on the IACUC Policies and Guidelines Page) unless the protocol provides scientific justification why that procedure cannot be used.

**Euthanasia Method**

Please briefly describe what will happen with the animals at the conclusion of the study in the text box below:

- Returned to client (faculty/staff/student)

---

**Attachments**

PLEASE ATTACH ANY RELEVANT DOCUMENTS, INCLUDING:

- Grant applications to any PHS agency, NSF, and USDA related to this activity
- Training Records for all personnel on this protocol
Any scientific literature or articles relevant to the review of this project.  
Please upload training records for the PI, Co-PI, and all individuals who will be working with animals as a part of this protocol. Click here to obtain the template for the Training Record.

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* * * Guidelines * * *

Guidelines

The CSU IACUC Policies and Guidelines page can assist you and your staff in the protocol development and animal study process.

* * * Certifications * * *

I understand that changes in the approved protocol must be submitted in writing to the IACUC as a protocol amendment and approved by the IACUC prior to implementation. Such changes include, but are not limited to: species, animal numbers, animal-related procedures, animal restraint, food/water deprivation, euthanasia, PI, research staff, and the like. Minor changes can be reviewed by the IACUC via the designated member review process throughout the month; significant changes (e.g. a large increase in animal numbers, adding an invasive procedure) usually require a new protocol be submitted for review by the IACUC at its next regularly scheduled meeting.

Please contact an IACUC Coordinator if you have any questions about preparing new protocol applications, amendment requests, or continuing reviews.

Certification Test

By submitting this protocol to the CSU Institutional Animal Care and Use Committee (IACUC), the Principal Investigator certifies the following:

1) I assure that myself and all students, staff, and faculty on this project are familiar with the Animal Welfare Act (AWA) and AWA Regulations and the Public Health Service (PHS) Policy on Humane Care and Use of Laboratory Animals, the Guide for the Care and Use of Laboratory Animals, and the Guide for the Care and Use of Agricultural Animals in Research and Teaching, as applicable, and all recognize their responsibility in strictly adhering to approved protocols.

2) I assure that all individuals listed on this project are qualified through education and/or training to conduct procedures involving animals under this proposal and have taken the online CSU Animal Care and Use Training, which includes information on the regulatory responsibilities of the institution, the IACUC, and investigators, as well as the concepts of research or testing methods that limit the use of animals or minimize distress, and the methods for reporting animal welfare concerns. Additionally, as applicable to their work with animals, all individuals on the protocol have received training in the biology, handling, and care of the species to be used; aseptic surgical methods and techniques; and the proper use of anesthetics, analgesics, and tranquilizers.

3) I assure that all procedures will be conducted in accordance with all applicable Colorado State University IACUC policies as well as Occupational and Biosafety requirements, including those pertaining to the use of personal protective equipment.
4) I assure that all individuals working on this proposed protocol are participating in the Occupational Health and Safety Program (OHSP).

5) I assure that ANY change in the care and use of animals involved in this protocol will be promptly forwarded to the IACUC for review. Such changes will not be implemented until approval is obtained from the IACUC. Animals will not be transferred between investigators without prior approval.

6) I assure that I have reviewed the pertinent scientific literature and the sources and/or databases and have found no valid alternative to any procedures described herein which may cause more than momentary or slight pain, distress, or generalized discomfort to animals, whether it is relieved or not.

7) I assure that every effort has been made to minimize the number of animals used and reduce the amount of pain, distress, and/or discomfort these animals must experience.

8) I assure that the activities described in this document submitted for IACUC review are consistent with those described in any related grant, contract, or subcontract that has been submitted or awarded.

9) I assure that the information contained in this application for animal use is accurate to the best of my knowledge.

10) I understand that this application and/or my animal use privileges may be revoked by the IACUC if I violate any of the aforementioned assurance statements.

X The Principal Investigator has read and agrees to abide by the above assurances

* * * Event History * * *

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