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Design Of A Running Robot And The Effects Of Foot Placement In The Transverse Plane

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By Timothy J. Sullivan

Entitled
DESIGN OF A RUNNING ROBOT AND THE EFFECTS OF FOOT PLACEMENT IN THE TRANSVERSE PLANE

For the degree of Master of Science in Mechanical Engineering

Is approved by the final examining committee:

Justin Seipel
Chair
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Approved by Major Professor(s): Justin Seipel

Approved by: Dave Anderson 12/3/2013
Head of the Graduate Program Date
DESIGN OF A RUNNING ROBOT AND THE EFFECTS OF FOOT PLACEMENT IN THE TRANSVERSE PLANE

A Thesis
Submitted to the Faculty
of
Purdue University
by
Timothy Sullivan

In Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

December 2013
Purdue University
West Lafayette, Indiana
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I would like to begin by thanking my family who has always supported me. I was always able to count on you. Thank you for teaching me how to express myself as an artist, and for teaching me a strong work ethic. Finally, thank you for believing in me and encouraging me to succeed in whatever path I chose.

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Finally, I would like to thank all of my brilliant colleagues in the Spira Lab. Without your help and guidance I would probably still be working out some difficult problems.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF TABLES</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vi</td>
</tr>
<tr>
<td>SYMBOLS</td>
<td>ix</td>
</tr>
<tr>
<td>ABBREVIATIONS</td>
<td>xii</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>xiii</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Motivation</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Problem Statement</td>
<td>3</td>
</tr>
<tr>
<td>1.3 Hypotheses</td>
<td>4</td>
</tr>
<tr>
<td>1.4 Thesis Organization</td>
<td>5</td>
</tr>
<tr>
<td>2. BACKGROUND AND LITERATURE REVIEW</td>
<td>6</td>
</tr>
<tr>
<td>2.1 Human Extremity Anatomy and Motion</td>
<td>6</td>
</tr>
<tr>
<td>2.2 Human Running</td>
<td>7</td>
</tr>
<tr>
<td>2.2.1 The Mechanics of Human Running</td>
<td>8</td>
</tr>
<tr>
<td>2.2.2 Amputee Running</td>
<td>13</td>
</tr>
<tr>
<td>2.3 Bipedal Running Models</td>
<td>14</td>
</tr>
<tr>
<td>2.3.1 SLIP</td>
<td>15</td>
</tr>
<tr>
<td>2.3.2 FD-SLIP</td>
<td>15</td>
</tr>
<tr>
<td>2.3.3 TD-SLIP</td>
<td>19</td>
</tr>
<tr>
<td>2.4 Existing Bipedal Robots</td>
<td>19</td>
</tr>
<tr>
<td>3. LEG PLACEMENT STRATEGY FOR A ONE LEGGED RUNNING MODEL</td>
<td>24</td>
</tr>
<tr>
<td>3.1 Methods</td>
<td>24</td>
</tr>
<tr>
<td>3.2 Results</td>
<td>26</td>
</tr>
<tr>
<td>3.3 Discussion</td>
<td>33</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>4. BIPEDAL ROBOT DESIGN</td>
<td>35</td>
</tr>
<tr>
<td>4.1 Bipedal Running Robot Design Objectives</td>
<td>35</td>
</tr>
<tr>
<td>4.2 Discussion of Biological and Robot Reviews</td>
<td>37</td>
</tr>
<tr>
<td>4.3 Design of a Bipedal Running Robot</td>
<td>40</td>
</tr>
<tr>
<td>4.3.1 Mechanical Design</td>
<td>41</td>
</tr>
<tr>
<td>4.3.2 Electrical Design</td>
<td>46</td>
</tr>
<tr>
<td>4.3.3 Spring Leg Design</td>
<td>50</td>
</tr>
<tr>
<td>4.3.4 Controllers</td>
<td>58</td>
</tr>
<tr>
<td>4.3.5 Gait Cycle</td>
<td>63</td>
</tr>
<tr>
<td>5. EFFECTS OF STEP WIDTH ON 3D BIPED LOCOMOTION</td>
<td>69</td>
</tr>
<tr>
<td>5.1 Methods</td>
<td>69</td>
</tr>
<tr>
<td>5.2 Results</td>
<td>79</td>
</tr>
<tr>
<td>6. SUMMARY</td>
<td>97</td>
</tr>
<tr>
<td>7. CONCLUSIONS</td>
<td>99</td>
</tr>
<tr>
<td>8. FUTURE WORK</td>
<td>102</td>
</tr>
<tr>
<td>LIST OF REFERENCES</td>
<td>105</td>
</tr>
</tbody>
</table>
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Bipedal Running Robot Comparison</td>
</tr>
<tr>
<td>3.1</td>
<td>List of Constants and Parameters Used in the Model</td>
</tr>
<tr>
<td>4.1</td>
<td>Bipedal Running Robot Criteria</td>
</tr>
<tr>
<td>4.2</td>
<td>Future Research</td>
</tr>
<tr>
<td>4.3</td>
<td>Bipedal Robot Specifications</td>
</tr>
<tr>
<td>4.4</td>
<td>Final Carbon Fiber Leg Layup Calculations</td>
</tr>
<tr>
<td>4.5</td>
<td>Experimental Pitch Angle and Controller Values</td>
</tr>
<tr>
<td>5.1</td>
<td>Pitch Angle and Controller Gains for associated Step Widths</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>(a) List of Joints, (b) Anatomical Reference Plane of the Human Body</td>
</tr>
<tr>
<td>2.2</td>
<td>Trunk Movements in Human Locomotion.</td>
</tr>
<tr>
<td>2.3</td>
<td>Plantar Flexion</td>
</tr>
<tr>
<td>2.4</td>
<td>Knee Flexion/Extension</td>
</tr>
<tr>
<td>2.5</td>
<td>Ground Reaction Forces for Running</td>
</tr>
<tr>
<td>2.6</td>
<td>Spring Loaded Inverted Pendulum (SLIP) model.</td>
</tr>
<tr>
<td>2.7</td>
<td>Forced Damped SLIP (FD-SLIP) model.</td>
</tr>
<tr>
<td>2.8</td>
<td>FD-SLIP Free Body Diagram.</td>
</tr>
<tr>
<td>3.1</td>
<td>Leg Plot, FD-SLIP and Modified FD-SLIP under Steady State Conditions.</td>
</tr>
<tr>
<td>3.2</td>
<td>ΔE during Stance vs. Time, for FD-SLIP</td>
</tr>
<tr>
<td>3.3</td>
<td>ΔE during Stance vs. Time, for Modified FD-SLIP.</td>
</tr>
<tr>
<td>3.4</td>
<td>FD-SLIP, τ = 2.177Nm</td>
</tr>
<tr>
<td>3.5</td>
<td>FD-SLIP, τ = 2.3Nm</td>
</tr>
<tr>
<td>3.6</td>
<td>Modified FD-SLIP, τ = 1.194Nm</td>
</tr>
<tr>
<td>3.7</td>
<td>FDSLIP with τ =2Nm, V1= 3.7m/s, V2=1.6m/s</td>
</tr>
<tr>
<td>3.8</td>
<td>Modified FDSLIP with τ =2Nm, V1= 3.7m/s, V2=1.6m/s</td>
</tr>
<tr>
<td>3.9</td>
<td>FD-SLIP with τ =4Nm, V1=1m/s, V2=5m/s</td>
</tr>
<tr>
<td>3.10</td>
<td>Modified FD-SLIP with τ =4Nm, V1=1m/s, V2=5m/s</td>
</tr>
<tr>
<td>3.11</td>
<td>Modified FD-SLIP, τ = 4Nm, k_i=.01, k_p=.003</td>
</tr>
<tr>
<td>3.12</td>
<td>Modified FD-SLIP, τ = 4Nm, k_i=.01, k_p=.01</td>
</tr>
<tr>
<td>4.1</td>
<td>Model of Joints Responsible for Bipedal Running</td>
</tr>
<tr>
<td>4.2</td>
<td>(a) Robot Design RHex Configuration (b) Robot Design Human Configuration</td>
</tr>
<tr>
<td>4.3</td>
<td>Average Physical Characteristics of a Four Year Old Girl</td>
</tr>
<tr>
<td>4.4</td>
<td>System Diagram</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>4.5</td>
<td>Final Design Configuration – (a) Front (b) Left and (c) Back Views</td>
</tr>
<tr>
<td>4.6</td>
<td>Final Design Configuration – Running: (a) Right Side (b) Back</td>
</tr>
<tr>
<td>4.7</td>
<td>Carbon Fiber Layup for use with Classical Composite Theory</td>
</tr>
<tr>
<td>4.8</td>
<td>C Spring Side Profile</td>
</tr>
<tr>
<td>4.9</td>
<td>Composite Test Sample Layup for determining Young’s Modulus</td>
</tr>
<tr>
<td>4.10</td>
<td>Final Composite Layup Configuration</td>
</tr>
<tr>
<td>4.11</td>
<td>Resin Infusion Method</td>
</tr>
<tr>
<td>4.12</td>
<td>Resin Infusion of Carbon Fiber Legs</td>
</tr>
<tr>
<td>4.13</td>
<td>Cracks Forming as a result of Fatigue</td>
</tr>
<tr>
<td>4.14</td>
<td>Bipedal Running Control Scheme</td>
</tr>
<tr>
<td>4.15</td>
<td>Gait Cycle Scheme 1</td>
</tr>
<tr>
<td>4.16</td>
<td>Gait Cycle Scheme 2</td>
</tr>
<tr>
<td>4.17</td>
<td>Single Leg Path</td>
</tr>
<tr>
<td>4.18</td>
<td>Double Leg Path</td>
</tr>
<tr>
<td>4.19</td>
<td>Gait Cycle – (a) $t = 0$ (b) $t = t_w/2$ (c) $t = t_f/2 + t_r$</td>
</tr>
<tr>
<td>5.1</td>
<td>Adjustable Step Width and Approximate COM Location</td>
</tr>
<tr>
<td>5.2</td>
<td>Pitch Angle VS Step Width</td>
</tr>
<tr>
<td>5.3</td>
<td>Measurement System</td>
</tr>
<tr>
<td>5.4</td>
<td>Bifilar Pendulum</td>
</tr>
<tr>
<td>5.5</td>
<td>Vicon Markers</td>
</tr>
<tr>
<td>5.6</td>
<td>Data Capture Reference Frame</td>
</tr>
<tr>
<td>5.7</td>
<td>Decomposition of Yaw, Pitch, and Roll</td>
</tr>
<tr>
<td>5.8</td>
<td>Number of Steps for each Trial</td>
</tr>
<tr>
<td>5.9</td>
<td>Average Number of Steps for each Step Width</td>
</tr>
<tr>
<td>5.10</td>
<td>Failure Modes for All Trials</td>
</tr>
<tr>
<td>5.11</td>
<td>Failure Modes for Step Widths of 36.83cm to 44.45cm</td>
</tr>
<tr>
<td>5.12</td>
<td>20 Step Success Rate, Excluding Failure Due to Fixture Constraints</td>
</tr>
<tr>
<td>5.13</td>
<td>Inertia of the Bipedal Robot in Roll, Pitch, and Yaw for all Step Widths</td>
</tr>
<tr>
<td>5.14</td>
<td>44.45cm Step Width Trial 7 Result</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>5.15</td>
<td>44.45cm Step Width Trial 7 Result.</td>
</tr>
<tr>
<td>5.16</td>
<td>44.45cm Step Width Trial 7 Stance Phase.</td>
</tr>
<tr>
<td>5.17</td>
<td>36.83cm Step Width Trial 9 Results.</td>
</tr>
<tr>
<td>5.18</td>
<td>46.99cm Step Width Trial 4 Results.</td>
</tr>
<tr>
<td>5.19</td>
<td>36.83cm Step Width Trial 10 Results.</td>
</tr>
<tr>
<td>5.20</td>
<td>Dimensionless Roll Inertia for all Step Widths</td>
</tr>
<tr>
<td>5.21</td>
<td>36.83cm Step Width Trial 10 Results.</td>
</tr>
<tr>
<td>5.22</td>
<td>46.99cm Step Width Trial 10 Results.</td>
</tr>
<tr>
<td>5.23</td>
<td>36.83cm Step Width Trial 7 Results.</td>
</tr>
<tr>
<td>5.24</td>
<td>36.83cm Step Width Trial 5 Results.</td>
</tr>
</tbody>
</table>
SYMBOLS

β Pitch Angle
F Force
τ Torque
m Mass
ξ Leg Length
g Gravity
k Stiffness
c Dampening
t Time

$V_{LO}$ Velocity at Lift Off
$h_{LO}$ Height at Lift Off
$E_{LO}$ Energy at Lift Off
$E_{ss}$ Steady State Energy at Lift Off
$k_p$ Proportional Gain for Leg Simulation
$k_i$ Integral Gain for Leg Simulation
$d_z$ Carbon Fiber Layer “j” Thickness
$Z_j$ Distance from Middle of Composite to Middle of Layer “j”
$Q_{11}^j$ Young’s Modulus of Elasticity for Layer “j”
r Radius of a Thin Leg
w Leg Width

$D_{ij}$ Flexural Stiffness
$	ilde{\Phi}_{dk}$ Filtered Stance Velocity
$\dot{\Phi}_d$ Desired Stance Angular Velocity
$\tilde{\Phi}_{dk-1}$ Previous Filtered Stance Velocity

$l_{ave}$ Average Leg Length
\( \bar{v} \) Forward Velocity
\( \theta_{dk} \) Desired Pitch Angle
\( v_d \) Desired Forward Velocity
\( k_{vp} \) Speed Controller Proportional Gain
\( \theta_b \) Balance Angle
\( \theta_{sat} \) Saturation Angle
\( \dot{\theta}_d \) Desired Angular Velocity
T Period
\( \ddot{\varphi}_d \) Desired Angular Acceleration
\( k_{\theta p} \) Proportional Gain for Pitch Controller
\( \theta_a \) Actual Pitch Angle of the Robot
\( \theta_d \) Desired Pitch Angle of the Robot
\( \dot{\theta}_a \) Actual Angular Velocity
\( \dot{\theta}_d \) Desired Angular Velocity
\( \theta_t \) Desired Trajectory Angle
\( \dot{\theta}_t \) Desired Trajectory Angular Velocity
\( k_{\theta d} \) Derivative Gain for Pitch Controller
\( k_{\varphi p} \) Motor Controller Proportional Gain
\( \varphi_a \) Actual Leg Position
\( \dot{\varphi}_a \) Actual Leg Angular Velocity
\( \varphi_d \) Desired Leg Position
\( t_s \) Amount of Time Spent in Stance Phase
\( t_f \) Amount of Time Spent in Flight Phase
\( t_c \) Total Cycle Time
\( \dot{\varphi}_{max} \) Max Motor Angular Velocity
\( \dot{\varphi}_f \) Flight Angular Velocity
\( \varphi_f \) Position of Leg in Flight
D Duty Cycle
N Number of Legs
$\hat{I}_{roll}$ Dimensionless Inertia
$I_{roll}$ Robot Inertia
$L_{COM}$ Distance From Swing Arm to COM
$L_W$ Length of Wire
$\alpha_A$ Angular Acceleration about Point “A”
$I_A$ Inertia about Point “A”
d Lateral Distance from COM to Midline of Leg
$M_A$ Moment about Point A
ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>COM</td>
<td>Center of Mass</td>
</tr>
<tr>
<td>SLIP</td>
<td>Spring Loaded Inverted Pendulum</td>
</tr>
<tr>
<td>FD-SLIP</td>
<td>Forced Damped Spring Loaded Inverted Pendulum</td>
</tr>
<tr>
<td>TD-SLIP</td>
<td>Torque Damped Spring Loaded Inverted Pendulum</td>
</tr>
<tr>
<td>DOF</td>
<td>Degrees of Freedom</td>
</tr>
<tr>
<td>ZMP</td>
<td>Zero Moment Point</td>
</tr>
<tr>
<td>HZD</td>
<td>Hybrid Zero Dynamics</td>
</tr>
<tr>
<td>FRP</td>
<td>Fiber Reinforced Plastic</td>
</tr>
<tr>
<td>EMG</td>
<td>Electromyogram</td>
</tr>
<tr>
<td>RHex</td>
<td>Rotary Hexapod</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional Integral Derivative</td>
</tr>
<tr>
<td>LO</td>
<td>Lift Off</td>
</tr>
<tr>
<td>TD</td>
<td>Touch Down</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>UVBH</td>
<td>Ultra Very High Bond</td>
</tr>
<tr>
<td>COP</td>
<td>Center of Pressure</td>
</tr>
<tr>
<td>SPI</td>
<td>Serial Peripheral Interface</td>
</tr>
</tbody>
</table>
ABSTRACT

Sullivan, Timothy MSME, Purdue University, December 2013. Design of a Running Robot and the Effects of Foot Placement in the Transverse Plane. Major Professor: Justin Seipel, School of Mechanical Engineering.

The purpose of this thesis is to make advances in the design of humanoid bipedal running robots. We focus on achieving dynamic running locomotion because it is one metric by which we can measure how far robotic technologies have advanced, in relation to existing benchmarks set by humans and other animals. Designing a running human-inspired robot is challenging because human bodies are exceptionally complex mechanisms to mimic. There are only a few humanoid robots designed specifically for running and the existing robots are either constrained to a plane, do not yet exhibit human-like motion, or are unstable.

One aspect of bipedal running dynamics that could be understood better, and could improve the performance of these robots, is the role of foot placement in the transverse plane, via rotation of the hip, in the sagittal and coronal planes. To achieve this objective, I have developed and studied a running simulation, designed and built a bipedal running robot, and then conducted an experimental study on the effects of step width on overall whole-body locomotion dynamics.

The planar running simulation investigates foot placement in the sagittal plane, by changing the angle of the hip at the beginning of each stance phase. The model effectively mimics a human-like response to a horizontal or vertical velocity disturbance while running. This is achieved by implementing a controller which changes the hip angle at touch down and by using the energy of the system as control feedback. This controller effectively reduces the time required to recover from a perturbation, reduces the overall energy expended recovering from a perturbation, and allows the legged model to function at significantly lower torque values.
The bipedal running robot is designed as a research platform for systematic investigation of key mechanisms and control methods, in order to progressively move towards a more biologically accurate and stable running robot. The result of this design is a simple, lightweight, and powerful research platform which can easily be expanded on in order to systematically study the effects of individual parameters.

The step width study investigates the effects of step width in the coronal plane on a 3D 1DOF per leg bipedal running gait. The results of this study help to confirm biological hypothesis on how stable running is achieved and suggests the next steps in moving towards a more biologically correct 3D running robot. A range of step widths were found for which stable locomotion existed, where stability is empirically assessed by checking if a run surpasses 20 steps. The smallest step width studied exhibited unstable rolling behavior, which confirms previous theory stating that dimensionless inertia, a function of step width and mass moment of inertia, effects roll stability. Similarly, yaw stability was observed to increase with wider step widths. The inability to stabilize roll and yaw for narrow step widths is consistent with biological studies where roll and yaw stability are thought to be mainly achieved by active use of the upper body. The widest step width studied exhibited unstable behavior in pitch. Pitching could be significantly impacted by lateral ground reaction forces, the distance from the hip to the center of mass, and changes in the relative magnitudes of roll, pitch, and yaw inertias. It was found that lateral ground reaction forces increase and the vertical distance from hip to center of mass decreases with increasing step width. Further, the magnitude of yaw inertia gets closer to that of pitch. The convergence of these factors suggest that a presently unidentified coupling in roll, pitch, and yaw occurs that yields the observed behavior for wide step widths.
1. INTRODUCTION

In the past few decades, a large number of advancements have been made concerning the design of humanoid robotics. However, despite these significant advancements, there still remains a large gap in understanding and developing dynamic humanoid locomotion. There are only a handful of running robots in existence today. Most of these robots do not exhibit human like motion, are constrained to a plane, or simply fall down. Furthermore, many scientists have found it difficult to model these systems due to highly nonlinear behavior, and large parameter spaces. This has left a great deal to be discovered in the field of bipedal running robotics. We focus on dynamic locomotion because achieving highly dynamic, running bipedal locomotion is one metric by which we can measure how far robotic technologies have advanced, in relation to existing benchmarks set by humans and other animals.

In order to make advances in the design of humanoid bipedal running robotics, the focus of this thesis is to investigate foot placement in the transverse plane, via hip rotation in the sagittal and coronal planes. This is achieved by designing a planar model to investigate the effects of foot placement in the sagittal plane, and by designing a 3D bipedal running robot in order to investigate foot placement in the coronal plane. In preparation for designing these studies, it is necessary to gain an understanding of human bipedal running, existing mathematical models, and existing bipedal running robots. The robotic platform introduced in this thesis is also designed for continued research, to investigate a wide range of biologically-inspired mechanisms and configurations.

1.1 Motivation

There are a wide range of applications for humanoid robotics including military, devices for assisting the disabled, service industries, and inspiring the design of modern
machinery. Human biology has proven to allow for high mobility over diverse terrain where traditional wheeled vehicles are not capable of travelling. In addition, human running has shown to exhibit similar energetic cost to quadrupeds [35], limited in endurance by muscle type. Further, most innovation is based on the needs and desires of humans, and as a result, most design is either inspired from or is an extension of our bodies. However, nature has evolved in such a way that is difficult to mimic using modern machine design techniques. Humans for instance have highly complex musculoskeletal systems which are capable of adjusting non-linear spring and dampening rates and in some cases act as passive compliant self-stabilizing mechanisms. The basis on how these mechanisms work together to achieve human locomotion is not entirely understood. Currently little is known about how stable roll, pitch, and yaw dynamics of legged locomotion is achieved in humans, or how to achieve this in robots. Further, the need for robustly stable humanoid robots has never been met.

As a result, scientists are working towards understanding which parts of the body contribute the most to stabilizing a bipedal running gait. In some biological studies body parts are restrained and the resulting gait is then analyzed, which sheds some light on the importance of that part to the running motion. However, in some cases this approach is difficult to execute. For example, it would be difficult to restrain movement of the upper body at the waist in the coronal plane, without affecting movement in the sagittal plane. As a result, some mechanisms responsible for stable bipedal running are better explored through simulation and experimentation. Further, existing biological hypothesis can often be supported using this approach.

Since we do not quite yet understand the mechanisms responsible for stable running, building a bipedal running robot for experimentation is challenging. In addition, current technology imposes great restrictions on the design of biologically inspired robots, because this class of robot typically requires fast processing, high power, high strength, and low weight. This results in a delicate balance of available technology that must be optimized for a specific function that is not yet well defined. There are very few humanoid robots designed specifically for running. Most bipedal robots are designed and optimized for walking, and the existing robots designed specifically for running are either
constrained to a plane, do not exhibit human like motion, are slow, or are unstable and fall down.

In order to build a robot based on principles that have not yet been well established, simulations are often used to provide insight on what mechanisms and controllers are important to stable locomotion. On the other hand, modeling nonlinear systems involving complex dynamics and difficult to characterize ground interactions often proves too inaccurate for direct implementation into a robots design. Other difficulties encountered when simulating such complex human functions often revolve around designing a controller and then determining optimal controller values in a vast parameter space. Thus, many simulations are only designed to approximate the conditions exhibited by planar models, which may not necessarily translate to a 3D system.

In order to address this issue, this thesis takes advantage of planar models used to investigate the effects of foot placement in the sagittal plane, because sagittal plane models are more common and well established. Still, the implementation of such a model into a 3D biped robot may require the establishment of additional theories or experiments. Step width models in the coronal plane on the other hand have been studied less. Using theory from an existing and successful bipedal running platform, we were able to design a stable bipedal running platform, enhanced for testing various hypotheses experimentally. This allowed us to begin investigating the effects of foot placement in the coronal plane by simply varying a parameter that already existed in a stable robot and observing the resulting dynamics. This experimental approach served to provide immediate and precise feedback concerning biological hypotheses, current design issues, and future design iterations in an effort to progressively move towards a more biologically correct bipedal running robot.

1.2 Problem Statement

It is not yet fully understood how foot placement affects the stability of bipedal running. On a flat surface, foot placement takes place in the transverse plane, and is mostly
facilitated by movement of the hip in the sagittal and coronal planes during running. In this thesis, the effects of foot placement in the sagittal plane are tested using a planar running model with a biologically inspired controller for leg placement. In order to investigate the effects of foot placement in the coronal plane, a 3D bipedal running robot is designed and constructed, and is used to conduct a step width study. The specific research objectives of this thesis are as follows.

1. Develop a biologically inspired running model that takes advantage of foot placement in the sagittal plane.

2. Design a bipedal running robot for progressively studying the influence of different biologically inspired mechanisms on a bipedal robot running gait.

3. Conduct a study concerning the effects of step width on the gait of the bipedal running robot resulting from objective 2.

1.3 Hypotheses

1. Controlling the leg angle in reference to ground significantly affects our ability to recover from perturbations, and plays a significant role in our ability to transition between different velocities while running.

2. The design of a bipedal running robot for easy manipulation of mechanical configurations, will allow the user to more easily pursue systematic parameter variation studies. Also, different kinds of hypotheses can be explored by replacing part of the system, or by adding additional parts. For the purpose of this thesis, the robot will first be set up to study the effects of step width in the coronal plane.

3. Step width has a significant effect on the stability of bipedal locomotion: 3a) In order to achieve passive stability in roll, A 1 DOF per leg 3D running robot will require a
dimensionless roll inertia less than one, which means a corresponding sufficiently wide step width is needed; 3b) Yaw stability decreases as step width decreases due to a decreased moment in the coronal plane, about the yaw axis, where friction between the leg and the ground is no longer sufficient to inhibit rotation; 3c) Passing beyond an upper bound of step width will cause failure in pitch.

1.4 Thesis Organization

Chapter 1, Introduction, outlines the topic and structure of this thesis.

Chapter 2, Background and Literature Review, begins with a discussion of human anatomy, followed by a review of human running studies that reveal key mechanisms for consideration in bipedal running robot design. Next, a review of existing planar running models is conducted. Finally existing running robots are reviewed.

Chapter 3, Leg Placement Strategy for a One Legged Running Model, introduces a FD-SLIP based running model that focuses on controlling the touch down angle of the leg in response to the current and expected energy state of the system.

Chapter 4, Biped Robot Design, focuses on the design evolution of a bipedal running robot. We begin this chapter by defining the objectives of this platform. Next, a decomposition of the background review for biological studies and existing bipedal robotics is conducted. Finally, the design of a bipedal running robot is conducted, where the focus of each chapter covers the key design components of the base configuration.

Chapter 5, Effects of Step Width on 3D Biped Locomotion, explores the behavior of the bipedal running robot, designed in chapter 4, running with different step widths.

Chapter 6, Summary, concisely states the work conducted in this thesis.

Chapter 7, Conclusions, lists the most important discoveries in this thesis.

Chapter 8, Future Work, discusses improvement that can be made to increase the capabilities of the bipedal running robot, and suggests future research to be conducted in order to move toward a more biologically correct running gait with a smaller step width.

Chapter 9, List of References, cites all sources of information used in the construction of this thesis.
2. BACKGROUND AND LITERATURE REVIEW

Before discussing the running simulation, the running robot design, or the running robot step width study, an overview of anatomy, human running studies, running models, and bipedal running robots, is necessary. This chapter begins with a review of human anatomy, followed by a review of existing human running studies. Next we review the classical SLIP model, along with two variations of this model FD-SLIP and TD-SLIP, which are applicable to the model designed in chapter 3. Finally this chapter concludes with a review of existing running robot platforms. All information covered in this section is important to the design of the simulation as discussed in chapter 3, the bipedal running robot research platform design as discussed in chapter 4, and the step width study as discussed in chapter 5.

2.1 Human Extremity Anatomy and Motion

Understanding the biomechanics of human running is important to the design of bipedal running simulations and robotics. However, before discussing the biomechanics, a brief overview of applicable human anatomy is necessary. The major joints discussed in this thesis are as shown in figure 2.1(a). The movement of body parts can be described using the definitions listed below, and the reference planes as shown in figure 2.1(b).

- **Flexion** bending movement that decreases the angle between the two parts.
- **Extension** bending movement that increases the angle between the two parts.
- **Abduction** a motion that pulls the member away from the midline of the body.
- **Adduction** a motion that pulls the member toward the midline of the body.
- **Medial Rotation** a motion that rotates the member toward the body midline.
- **Lateral Rotation** a motion that rotates the member away from the body midline.
2.2 Human Running

The parts of the body crucial for maintaining stability in a bipedal running robot are not yet entirely known. Biological studies have shown to some extent that all of the joints and associated body parts as shown in figure 2.1a play a role in running. In addition, each part of the body consists of a complex network of bones muscles and tendons. The bones create the frame around which muscles can be used to actuate joints. Some joints are only capable of planar movement, while others, like the hip, are capable of rotation about all axes. In addition, the muscles and tendons work together in order to create variable stiffness and dampening that is both active and passive in form.
In order to make sense of the motions that this complex system produces in the context of running, some studies restrain body parts and the resulting gait is then analyzed [10]. This sheds light on the importance of the restrained appendage to running motion. However, in some cases this approach is difficult to execute. For example, it would be difficult to restrain movement of the upper body at the waist in the coronal plane, without affecting movement in the sagittal plane.

2.2.1 The Mechanics of Human Running

The head and trunk exhibit significant movement during running [14], and represent the majority of the body weight [11]. During running, the head and trunk pitch and bend in the coronal and sagittal planes as shown in figure 2.1(b). The head serves as a frame of reference for vision and thus remains stable, relative to the environment, throughout the running gait in order to preserve vision acuity [40][41]. The upper torso represents 56.34% of the total body mass [11], and the shape is relatively long and flat. This provides a great deal of inertia that can be used to apply torques near the body’s center of mass (COM). Pitching the upper body counteracts the angular momentum of the legs during flight [68].

Hip and pelvis movement in the coronal plane plays the largest role in positioning the upper body, where hip movement mirrors the motion of the pelvis in the coronal plane [24]. Further, actuation of the hip and waist in the coronal plane acts to absorb shock and provide foot clearance, and has been shown to be one of the most important mechanisms for decoupling the lower body motion from upper body motion, allowing balance to be maintained. In the sagittal plane, pelvic movement is minimal and does not increase with speed. On the other hand, the pelvis and trunk tilt forward, increasing as a function of speed. In the transverse plane, pelvic motion is again subtle, but functions as a pivot between the upper and lower body during running. Pelvic movement is conducted via the spine. All motions of the upper torso can be characterized as periodic and sinusoidal as shown in figure 2.2.
Movement of the upper and lower arm segments have a significant effect on energetic cost and lateral balance [10]. One study has shown that running without arm swing increases the metabolic power requirements by 8%. In addition, running without arm swing does not change step width, but increases the step width variability by 9%, again suggesting a decrease in stability [10]. Another study has shown that instead, the arms acted as self-tuning passive mass dampeners which reduced torso and head rotation, while the shoulders and trunk act as an elastic linkage between the pelvis, shoulder griddle, and arms. The result is an arm swing naturally out of phase with our legs during running [37]. Although both of these research articles make compelling arguments, they are supporting somewhat conflicting hypothesis. However, they both agree that arm
swinging has a profound effect on the dynamics of the body during running. Simulations have shown that the torque caused by arm swinging is substantial enough to inhibit yaw rotation in situations where ground friction is sufficient [43].

The foot, ankle, and toes are an integral part of human locomotion. The feet are complex, containing 25.2% of all bones in the human body. They have a wide surface area that spreads out the impact during running. During running, subjects typically lands flat footed, or barely heel strikes. For fast running, or sprinting, the subject is always on his toes [23]. During sprinting, the ankle plays the lead role in shock absorption via plantar flexion as shown in figure 2.3, where the vertical phantom lines represent the stance region. The ankle absorbs energy during the first half of the stance phase, and releases energy during the second half of stance phase, like a spring [44]. In other modes of locomotion, the knee absorbs most of the shock [23,24]. The foot ankle and toes also play a role in projecting the body forward and increasing running velocity [20,21], and become stiffer as a function of running velocity [22].

![Dorsi/Plantarflexion](image)

Figure 2.3: Plantar Flexion, Reproduced from [24].

The knee plays the lead role in ground clearance for all typical biped gaits. However, the role it plays concerning impact absorption and forcing changes, depending
on the gait. It has been shown that knee exhibits flexion and extension, approximately symmetric about mid stance for walking, and running, but almost only extends during the stance phase for sprinting [23][24] as shown in figure 2.4, where the vertical phantom lines define the stance region. For running, energy is absorbed by the knee during the first half of stance phase and then the knee extends during the second half of stance phase to push off. For sprinting, the knee only extends to push off, while the ankle takes a lead role in absorbing energy [24]. The ankle and knee have been shown to do the greatest amount of work during the stance phase of running, but the hip introduces the greatest amount of power input [24].

Figure 2.4: Knee Flexion/Extension, Reproduced from [24].

Foot positioning is done via knee flexion and extension in the sagittal plane, and by hip rotation in the sagittal, coronal and transverse planes. During running the foot tends to be positioned near the midline of the body and the whole body center of mass (COM). This reduces the moment about the COM and effectively directs most of the force in the vertical and forward direction, while lateral forces remain small [10]. This means that less energy is spent pitching the body back and forth in roll. Lateral foot
position can also be characterized by preferred step width, which tends to be around 3.6cm for running [2].

When the step width is less than or greater than the preferred step width, the result is greater step width variability. Step width variability is a result of active control [5]; therefore, greater step width variability suggests less stability. Furthermore greater step width variability results in a higher energetic cost [2]. In walking, the step width increases to about 12cm, step width variability increases, and 3-6% of the net energetic cost is dedicated to active control of lateral balance. When a device is introduced to reduce the need for lateral balance, step width and step width variability decrease. Therefore, lateral balance is achieved during walking in part by using a wider step width and incurring greater energetic cost. Since the step width is near zero during running, it is suggested that there is little need for active control in lateral balance using the legs [2].

Although movement of the upper body is extremely important to running, the movement of the upper body is highly dependent on how the legs interact with the ground. Uniform and repeatable ground reaction forces under steady state conditions are an indication that the upper a lower body segments are working together properly, as any change in the system will result in a slightly different pattern [57]. Other running styles, shoes, and running surfaces can have a small effect on the shape and magnitude of these graphs. Ground reaction forces are shown below in figure 2.5, where the grey region represents typical ground reaction forces for heel to toe running [56].

![Figure 2.5: (a) Vertical “Z” (b) Anterior-Posterior “Y” (c) Medial-Lateral “X” Ground Reaction Forces for Running, Grey Represents a Typical Running Region, Solid Black Represents Constrained Arms, Reproduced from [56].](image-url)
2.2.2 Amputee Running

The feet and ankle clearly play a role in running; however, it has been shown that stable fast running can be achieved without these appendages using modern prosthetics. These prosthetics incorporate a J-shaped carbon fiber leaf spring foot (J-legs) that effectively mimics the ankle by creating controlled dorsiflexion and plantar flexion during the stance phase [8]. Oscar Pistorius, a below knee double amputee (transstibial) athlete, broke the world record at the 2012 Summer Paralympics, running the 200m T44 in 21.30 seconds, using J-Legs [69]. The world record 200m without prosthetic legs is currently held by Usain Bolt at 19.19 seconds [70].

Oscar later competed in the 2012 Summer Olympics 400m, which fueled an international controversy concerning Oscar’s prosthetic legs and whether or not they offer him an unfair advantage. It was found that his metabolic energy expenditure and sprinting endurance was virtually identical, which suggests that the prosthetic legs approximate intact legs [7]. However, it was found that running mechanics were dissimilar at high speeds. For the amputee at top speed, stance phase time increased, the flight phase was reduced, and the average ground reaction forces were reduced. Top speed is generally limited by a person’s ability to reposition the leg in time for the next step. Since Oscars flight phase was enhanced due to lighter legs, while the stance phase was degraded, the average performance was comparable to a non-amputee.

It has also been shown that stable running can be achieved by double above knee amputees (transfemoral). Athletes such as Richard Whitehead, who holds the current world record for the 200m T42 at 24.93 seconds, have proven this [71]. His prosthetic of choice has a straight leg with no knee, because it is more stable, has better response, and the foot placement is more predictable [72]. However, through observation, it is especially clear that for straight leg prosthetics, the running gate is drastically altered. This is because the knee is not available for obstacle avoidance. The hip must abduct, moving the foot laterally to avoid the toe stubbing on the ground. Unfortunately, there is little or no scientific data available on double above knee amputee running. The only related data available considers subjects running with a single transfemoral amputation.
and a prosthetic with a knee. However, one must consider the straight leg configuration carefully because it effectively proves that stable fast running, with a flight phase, can be achieved with legs that consist of nothing more than a carefully designed J-leg actuated at the hip.

2.3 Bipedal Running Models

There are a large number of bipedal running models. Many of these models are specific to a particular robot design or design methodology. Others are generic and highly simplified models intended to be used as a platform for exploring new running models. Further, many of these base models have been combined and manipulated in order to form various hypotheses that are intended for use in designing future bipedal running robots. These models can also be used to confirm hypothesis concerning how we run from a biological perspective. Unfortunately, the transition from model to a physical representation is uncommon. Designing a robot introduces an entirely new set of challenges that may not even be achievable given the simulated approach. In addition, the expectation of a model to succeed in the real world is often left unfulfilled. Yet, these models offer insight on what parameters are important to stable locomotion. Further, a model can become useful once it has been implemented in the design of a robot, at which time data from the model and the robot can be compared, and changes can be made to improve the accuracy of the model, allowing further study without using the robot. In this section a number of popular bipedal running models are reviewed.

The Spring Loaded Inverted Pendulum (SLIP) model was developed to describe center of mass movement patterns observed in animals, using only a springy leg and a point mass. It is a widely accepted and explored model. However, SLIP is energy conserving and thus cannot accurately represent the dynamic processes of non-conserving biological or robotic systems. Still, this model is often used as a foundation for the investigation of improved legged locomotion models. One such model called Torque Damped SLIP (TD-SLIP) utilizes two additional parameters, a time dependent torque and dampening to drastically increase the stability. Also developed recently, Forced-Damped
SLIP (FD-SLIP) increases the stability of SLIP drastically by adding a constant torque and dampening.

2.3.1 SLIP

SLIP, as shown in Figure 2.6, describes the translational dynamics of a point mass on the end of a massless spring, in the sagittal plane [1]. During the stride, the inverted pendulum enters the stance phase with a velocity vector $\mathbf{v}_n$ and angle $\beta$. A liftoff event occurs once the spring has reached equilibrium and the flight phase begins. During the flight phase the leg is reset to angle $\beta$, then the leg touches down and the cycle starts over. This one legged model is energy conserving [4] and is the foundation for many bipedal models. However, without any modifications, it can only recover from small perturbations in the velocity vector direction and is marginally stable with perturbations to velocity magnitude or the energy state of the system [2].

![Figure 2.6: Spring Loaded Inverted Pendulum (SLIP) Model, Reproduced from [62].](image)

2.3.2 FD SLIP

FD-SLIP, as shown in Figure 2.7, is an actuated SLIP model and has proven to be a robust and simple model. It expands on SLIP by adding a constant torque and tuned dampening [2]. During the stride, the inverted pendulum enters the stance phase with a
velocity vector $v_n$, a constant angle $\beta$, and a constant torque is applied. A liftoff event occurs once the leg slips, and the flight phase begins. During the flight phase the leg is reset to angle $\beta$, then the leg touches down and the cycle starts over. The motion of the leg during flight is disregarded, because the leg is considered to be massless. FD-SLIP utilizes damping in the leg, a constant torque at the hip, a constant leg angle at touchdown, a point mass body, and a spring. However, it was found that dampening could be determined using the other parameters, reducing the total number of variables to four. As a result, the model parameters could be fully explored, which makes it a good platform for the investigation of new control systems. Furthermore, the system stabilizes itself with only mechanical feedback [2].

Figure 2.7: Forced Damped SLIP (FD-SLIP) Model, Reproduced from [2].

The free body diagram for FD-SLIP is as shown below in Figure 2.8 where $\tau=$ torque, $m=$ mass, $\xi$ is the leg length, and $\beta$ is the leg angle. $F_\tau$ is the force as a result of the torque, which is always perpendicular to the leg, and $F_\xi$ is the force along the leg through the spring and dampener.
During the flight phase, the equations of motion simply describe ballistic motion as shown by

\[ \sum F_y = 0 \] \hspace{2cm} (2.1)

\[ \sum F_z = m\ddot{z} = -mg \] \hspace{2cm} (2.2)

\[ \ddot{y} = \dot{\dot{y}}_y = 0 \] \hspace{2cm} (2.3)

\[ \ddot{z} = \dot{\dot{z}}_z = -g, \] \hspace{2cm} (2.4)

where the body is a point mass and the leg is considered to be massless. During the stance phase, FD-SLIP differs from SLIP by adding torque and dampening. The addition of torque to the equations of motion is described by
\[ \sum M = \xi F_t - \tau = 0 \quad (2.5) \]

\[ F_t = \frac{\tau}{\xi} \quad (2.6) \]

while the effects of the spring and damper on the force along the leg is described by

\[ \Delta \delta = L_0 - \xi \quad (2.7) \]

\[ F_{spring} = k \Delta \delta \quad (2.8) \]

\[ F_{dampener} = c \Delta \delta \quad (2.9) \]

\[ F_\xi = k(L_0 - \xi) - c \dot{\xi} \quad (2.10) \]

The forces along the leg and perpendicular to the leg are resolved into vectors in the \( y-z \) plane as follows:

\[ \vec{F}_T = F_T(i, j) = F_T \left( \frac{Z}{\xi} - \frac{Y}{\xi} \right) \quad (2.11) \]

\[ \vec{F}_\xi = F_\xi(i, j) = F_\xi \left( \frac{Y}{\xi}, \frac{Z}{\xi} \right). \quad (2.12) \]

Finally, the stance dynamics are governed by

\[ \sum F_y = [k(L_0 - \xi) - c \dot{\xi}] \left( \frac{Y}{\xi} \right) + \frac{\tau Z}{\xi^2} = m \ddot{y} \quad (2.13) \]

\[ \sum F_z = -mg + [k(L_0 - \xi) - c \dot{\xi}] \left( \frac{Z}{\xi} \right) - \frac{\tau Y}{\xi^2} = m \ddot{z} \quad (2.14) \]
\[
\dot{y} = \left[ \frac{k}{m} (L_0 - \xi) - \frac{c}{m} \dot{\xi} \right] (\dot{y}) + \frac{\tau z}{m \xi^2} \tag{2.15}
\]

\[
\ddot{z} = -g + \left[ \frac{k}{m} (L_0 - \xi) - \frac{c}{m} \dot{\xi} \right] (\ddot{z}) - \frac{\tau y}{m \xi^2} \tag{2.16}
\]

### 2.3.3 TD-SLIP

TD-SLIP differs from FD-SLIP in that the torque is not constant, and is instead employed through active control as a function of the change in system energy. This system cannot function without feedback [3]. The model shown in chapter 3 has some similarities to the TD-SLIP model [3], because we also explore a controller that is a function of system energy. On the other hand, the controller itself and what is controlled is different, and these differences are important. The result is a highly simplified model and control system that produces desirable results.

### 2.4 Existing Bipedal Robots

This section details features from some of the best bipedal running robots to date as shown in table 2.1. Interestingly enough, each one of these robots exhibit fundamentally different designs, and the way in which each one achieves running is unique. Understanding the basic principles under which each robot is successful will be important when designing future running robots.

Mark Raibert, a pioneer in legged robotics, built a series of successful biped robots in the leg lab at Carnegie Mellon and MIT from 1981 through 1995. These robots include a planar biped which can travel up to 4.25m/s and later a 3D biped which can travel up to 2.5m/s. Both of these robots used control strategies similar to a previously constructed hopping robot [25]. In order to control the motion of the planar biped, hopping height, body attitude, and forward running speed were used. Hopping height was controlled by considering the resonant bouncing of a spring leg with a mass body, and by using an actuator to introduce thrust. The amount of thrust provided was a function of the
mechanical losses incurred during the hopping cycle. The attitude of the body was controlled by using the angle of the body and angular rate as feedback, and a simple controller applied torque to the body during stance as follows:

\[ \tau = -k_p(\varphi - \varphi_d) - k_v(\dot{\varphi}) \]  

(2.17)

where \( \tau \) is the hip torque, \( k_p \) and \( k_v \) are the gains, \( \varphi \) and \( \varphi_d \) are the actual and desired angle of the body, and \( \dot{\varphi} \) is the angular velocity of the body. Forward running speed was controlled by positioning the foot in order to control the acceleration of the body, using

\[ x_{fh,d} = \frac{\dot{x}T_s}{2} + k_\dot{x}(\dot{x} - \dot{x}_d) \]  

(2.18)

which used estimated forward speed as feedback, where \( x_{fh,d} \) is the forward displacement of the foot, \( \dot{x} \) and \( \dot{x}_d \) are the estimated and desired forward speeds, \( T_s \) is the predicted period for the next step, and \( k_\dot{x} \) is the gain. Hopping robots typically employ point contact type feet. Raibert often used hydraulic actuators because they are easier to control, but tend to be messy and heavy. The consequence is that the hydraulic pump is most often located away from the robot, and hoses must be routed carefully to avoid influence on the robot. Recent robots designed by Boston Dynamics, such as Big Dog, have shown that fully contained hydraulic systems are possible to implement in fully autonomous robots.

Honda also began to develop humanoid robots in the 1980’s, and after many different generations of robots, ASIMO was born two decades later. ASIMO was designed for service, and is constructed in a manner that allows it to execute a wide range of tasks. It has human like articulation in both the upper and lower body, including fully articulated fingers. Actuation is conducted via electric motors and the robot has 34 degrees of freedom (DOF), 3 in the neck, 14 in the arms, 4 in the hands (not counting fingers), 1 in the torso, and 12 in the legs [73]. The control system is based on zero moment point (ZMP). This control method tries to maintain a zero moment between the
ground reaction force and the target inertial force of the walking gait, in the ground plane. The ground reaction force is shifted to match the target inertial force by changing the angle of the feet and shifting the point of contact. When the desired point of contact is outside the area of the foot, the stance phase is accelerated or decelerated in order to maintain balance. Finally, foot placement is used in order to maintain an ideal stride length, due to the change in angle of the upper torso. Although this method has shown to provide a robustly stable bipedal gait, this control scheme suggests that running with point contact feet is not possible, and we know that this is not true because double above knee amputees can run with spring legs.

Built in 2008, Mabel has been tagged as the world’s fastest bipedal running robot. This robot design uses electric actuators, and includes springs in its drive train to increase the agility and robustness of dynamic locomotion [26]. The springs both reduce the impact force at touchdown, act to store energy during the compression phase of stance, and reduce the actuator power requirements. The structure of the robot was designed around adult human proportions, and weighs in at 65kg. The robot is constrained in yaw and roll by using a boom, which is common amongst bipedal running robots. The robot uses a four level Hybrid Zero Dynamics (HZD) controller design, which takes advantage of the compliant mechanisms, and allows for adjustment of the leg stiffness during the stance phase. This robot has 9 DOF, 5 are associated with the robots body links, 2 are associated with the motors and elastic members, and two are associated with horizontal and vertical positions in the sagittal plane. Mabel can run up to 3.06m/s with a flight phase time at approximately 40% of the of cycle time. The running gait appears to closely mimic natural human motion, but is currently limited to single plane motion. A future 3D robot is currently being planned.

Athlete is an elite bipedal running robot in the class of 3D running robots. Human physiology was carefully considered in the design. Pneumatic artificial muscles were used to mimic biological muscles, actuating the hips and knees. Pneumatic air bladders are not good for precise position control, but can control force and torque well [74]. The points at which these muscles connect to the body are consistent with human anatomy. The leg is an elastic blade inspired by the contribution of energy storage and impact
absorption by tendons during running. The leg is similar to that used by amputee runners. The light weight skeletal frame was mostly constructed of polymer parts, nylon joints, and carbon FRP tubes. The running gait was found by directing utilizing EMG data, and then reconstructing the muscle activation patterns for use with the air bladders. These patterns were then used in simulation based optimization. Using the optimized gait, the robot was only able to run 5 steps, but did so using an open loop motor command, and without any planar constraints.

RHex is a hexapod robot designed to simulate cockroach running, and has been used extensively in hexapod research; however, around 2003 it was used to create stable 3D bipedal locomotion with one degree of freedom per leg [4]. The robot is relatively small when compared to other bipedal robots, weighing only 8.4kg and standing approximately .6m tall. The robot comes equipped with 6 brushed motors, which are easy to control. The legs are c springs, similar in structure to an amputee’s leg, but do not have the J shaped curvature that simulates the ankle. RHex is a fully contained system, meaning no off board equipment of any kind is required to run it. This makes this robot the only other self-contained bipedal running robot aside from ASIMO.

Bipedal RHex is passively stable in roll. It was found that the dimensionless inertia could be used to calculate the resistance of translation due to mass distribution [4]. Due to the dimensionless inertia of the robot, and careful leg and motor controller stiffness selection, it was possible for it to become stable in roll without any modifications to the robots structure. It was critical to tune the motor controller so that it acts as a torsional spring in series with the compliant leg spring, and it was found that the most successful gain values for the motor controllers were the values that just began to track position, resulting in low torsional stiffness. This controller is discussed in greater detail in chapter 4.3.4. The pitch controller used to stabilize bipedal RHex in the sagittal plane closely resembles a basic PD controller used to stabilize an inverted pendulum. Of the robots discussed in this chapter, RHex is the only one that does not exhibit a double flight phase. The specifications for the 3D bipedal running robots discussed in this chapter are shown below in table 2.1.
Table 2.1: Bipedal Running Robot Comparisons.

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<tr>
<td>Marc Raibert’s 3-D biped</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>ASIMO (2013)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Bipedal RHEX</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>ATHLETE</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>MABEL</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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</tbody>
</table>

<table>
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<th></th>
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<tbody>
<tr>
<td>Stable Locomotion</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Onboard Computer</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
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<td>Knee</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Onboard power</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
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<tr>
<td>Top Speed</td>
<td>2.5m/s</td>
<td>1.65m/s</td>
<td>1.26m/s</td>
<td>2.42m/s</td>
<td>3.06m/s</td>
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<tr>
<td>Height</td>
<td>1.3m</td>
<td>.645m</td>
<td>1.2m</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Weight</td>
<td>34.11kg</td>
<td>54kg</td>
<td>8.72kg</td>
<td>10kg</td>
<td>65kg</td>
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<tr>
<td>Actuation Method</td>
<td>Hydraulic</td>
<td>Electric</td>
<td>Electric</td>
<td>Pneumatic</td>
<td>Electric</td>
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<tr>
<td>Passive Mechanisms</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Double Flight Phase</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>3D Biped</td>
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<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
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<tr>
<td>Control Method</td>
<td>ZMP</td>
<td>PD</td>
<td>PID</td>
<td>HZD</td>
<td>-</td>
</tr>
<tr>
<td>Main Function</td>
<td>Running</td>
<td>Service</td>
<td>Hexapod Research</td>
<td>Running</td>
<td>Running</td>
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<tr>
<td>Human Form</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
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</tbody>
</table>
3. LEG PLACEMENT STRATEGY FOR A ONE LEGGED RUNNING MODEL

Using FD-SLIP as a base, this section of my thesis explores a foot placement strategy in the sagittal plane, using a simple PI controller. The controller takes advantage of energy symmetry, entering and leaving the stance phase during steady state conditions. The touch down leg angle is adjusted so that the energy dissipation due to dampening, during the stance phase, compensates for any imbalance of energy. This controller approximately doubles the stability region of FD-SLIP when subjected to velocity perturbations at touchdown, enables the model to operate at considerably lower torque values, and drastically reduces the time required to recover from a perturbation, while using less energy. Finally, the leg placement strategy used effectively imitates the natural human response to velocity perturbations while running.

3.1 Methods

We found that with large perturbations, the standard FD-SLIP model took a great deal of time to recover, up to 11.75 seconds (76 strides). The total change in energy of the mass at touch down (TD) and lift off (LO) during the stance phase at steady state conditions is zero. In other words, during steady state conditions, the energy absorbed by the dampener is proportional to the energy provided by the torque [6]. When the system is given a disturbance, there is an imbalance of energy between TD and LO until the system has fully recovered, at which point the energy at TD and LO reaches a steady state value, which is different for each input torque value.

In the standard SLIP model, TD-SLIP, and FD-SLIP, the TD angle \( \beta \), as shown in Figure 2.6, 2.7, and 2.8 is constant. From a biological perspective, this is inaccurate. It has been shown that when humans accelerate, the TD angle \( \beta \) increases. In contrast, when humans decelerate, the TD angle \( \beta \) decreases. When running at a constant velocity, the
TD angle $\beta$ remains constant \[7,8\]. A runner who accelerates or decelerates without rotating the leg or body in reference to ground will fall over \[8\]. Furthermore, if a disturbance is introduced while running at a constant velocity, acceleration or deceleration must occur in order to resume that constant velocity.

Controlling the leg angle in reference to ground requires the use of feedback, and this is consistent with the fact that humans use active control to compensate for disturbances \[5\]. With the addition of leg pitching to the FD-SLIP model, energy dissipation due to dampening can be controlled. In other words, if the mass enters the flight phase with too little energy, $\beta$ can be increased so that the dampener absorbs less energy due to lower resultant forces along the leg. The opposite can also be applied, where if the mass enters the flight phase with too much energy, $\beta$ can be decreased so that the dampener absorbs more energy.

In response to these observations, we developed the PI controller as shown below (3.1) where $E_{L0}$ is the energy at lift off and $E_{SS}$ is the steady state energy, based on the kinetic and potential energy of the mass as shown in equations (3.2) through (3.4). The controller gains are $k_p$ and $k_i$, and the time at LO and TD is $t_n$ and $t_{n-1}$. The velocity vector of the point mass and the height of the leg at LO is the required feedback. This feedback information is used to adjust the angle of the leg at TD in the controller

$$\beta = \beta_0 \left[ 1 - \left\{ \left( E_{L0} - E_{SS} \right) k_p + \left( E_{L0} - E_{SS} \right) (t_n - t_{n-1}) k_i \right\} \right], \quad (3.1)$$

where the energy of the system is defined by

$$E_{L0} = K_{L0} + U_{L0}, \quad (3.2)$$

$$K_{L0} = \frac{1}{2} m V_{L0}^2 \quad (3.3)$$

$$U_{L0} = mgh_{L0}. \quad (3.4)$$
The values listed below are used in the controller for all experiments discussed herein unless otherwise noted.

\[
\beta_0 = 65^\circ \quad k_i = .01 \quad k_p = .005 \quad E_{ss} = 16.7 J
\]

For the purpose of this thesis, we will refer to FD-SLIP with the new controller as “modified FD-SLIP.” We started investigating the effects of the new controller using the fixed set of parameters in the new model as shown below in table 3.1. When using these values, the model experiences no disturbance, starting off at steady state conditions.

Table 3.1: List of Constants and Parameters Used in the Model.

<table>
<thead>
<tr>
<th>Constant/Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>g, gravity</td>
<td>9.81</td>
<td>m/s^2</td>
</tr>
<tr>
<td>m, mass</td>
<td>3</td>
<td>kg</td>
</tr>
<tr>
<td>L_0, Uncompressed leg length</td>
<td>0.3</td>
<td>m</td>
</tr>
<tr>
<td>k, spring constant</td>
<td>1500</td>
<td>N/m</td>
</tr>
<tr>
<td>c, dampening constant</td>
<td>50</td>
<td>Ns/m</td>
</tr>
<tr>
<td>V_0, Initial Velocity</td>
<td>2.4104</td>
<td>m/s</td>
</tr>
<tr>
<td>V_{angle}, Initial Velovicy Angle</td>
<td>-7.09</td>
<td>degrees</td>
</tr>
<tr>
<td>\tau, Constant Torque</td>
<td>3</td>
<td>Nm</td>
</tr>
<tr>
<td>\mu, Ground Friction Coefficient</td>
<td>1.5</td>
<td>N/A</td>
</tr>
</tbody>
</table>

3.2 Results

Under steady-state conditions, FD-SLIP and modified FD-SLIP exhibit the same behavior, where the dimensions of stance phase and flight phase remain constant and periodic as shown below in Figure 3.1. The controller only takes effect when the disturbance is applied. In this Figure, the leg is shown in black, the body is shown in green during the stance phase, and the body is shown in blue during the flight phase.
Figure 3.1: Leg Plot, FD-SLIP and modified FD-SLIP under Steady State Conditions.

For the first experiment, we measured the energy at LO for FD-SLIP, under steady state conditions, as shown in black in Figure 3.2. Next we introduced disturbances as shown in the legend of figure 3.2, where V1 is the imposed vertical velocity in the negative z direction, and V2 is the imposed horizontal velocity in the positive y direction. From this plot, it can be observed that the settling time is large for velocity disturbances that reduce the energy of the system. For large velocity disturbances that increase the energy of the system, the leg assumes oscillatory modes from which it cannot recover. Using modified FD-SLIP, this experiment was reproduced as shown in Figure 3.3. When comparing Figures 3.2 and 3.3, it is clear that the new controller drastically reduces the settling time for all disturbances, and acts to decay oscillatory modes that would otherwise be present.
Figure 3.2: $\Delta E$ during Stance vs. Time, for FD-SLIP.

Figure 3.3: $\Delta E$ during Stance vs. Time, for Modified FD-SLIP.
In the next experiment, we determined the minimum torque for which FD-SLIP and modified FD-SLIP could operate. We found that FD-SLIP could operate at no less than $\tau = 2.177\text{Nm}$, whereas modified FD-SLIP could operate no less than $\tau = 1.194\text{Nm}$. In order to find these values, it was required that we run simulations where the model takes at least 50 strides, because in some cases it took that long to expend the extra energy supplied to the system by the disturbance, and fail.

We plotted the stable region (or basin of attraction) for a wide range of velocity disturbances under the minimum torque as shown in Figure 3.4 for FD-SLIP, and as shown in Figure 3.6 for modified FD-SLIP. Figure 3.4 illustrates that when FD-SLIP operates at the minimum allowable torque, the stable region has holes, and does not solidify until $\tau = 2.3\text{Nm}$, as shown in Figure 3.5. Whereas, Figure 3.6 shows that as soon as the minimum torque is achieved for modified FD-SLIP, a solid stable region appears. This means that modified FD-SLIP can reliably operate at torque values 48% less than FD-SLIP. It can also be observed that the stability region for modified FD-SLIP is far greater for large perturbations. Finally, it should be noted that when the torque is the same for FD-SLIP and modified FD-SLIP, the common stability region is identical.

![Figure 3.4: FD-SLIP, $\tau = 2.177\text{Nm}$](image)

Figure 3.4: FD-SLIP, $\tau = 2.177\text{Nm}$. 
Figure 3.5: FD-SLIP, $\tau = 2.3$Nm.

Figure 3.6: Modified FD-SLIP, $\tau = 1.194$Nm.

Figure 3.7 and 3.8 further illustrate that at a torque of $\tau = 2$Nm, FD-SLIP eventually fails and modified FD-SLIP quickly reaches a periodic steady state condition. It should be noted that the disturbances used to generate this image were chosen carefully, because it often takes several steps for FD-SLIP to fail. When comparing
Figure 3.8 at steady state to figure 3.1, it is clear that the flight phase is less, and the TD angle $\beta$ is greater. This is because as the energy becomes too little to sustain a periodic motion for a set angle $\beta=65^\circ$, the new controller changes $\beta$ accordingly. This trend continues as the torque is decreased until there is almost no flight phase, at which point modified FD-SLIP fails.

Figure 3.7: FDSLIP with $\tau = 2\text{Nm, } V1 = 3.7\text{m/s, } V2 = 1.6\text{m/s}$.

Figure 3.8: Modified FDSLIP with $\tau = 2\text{Nm, } V1 = 3.7\text{m/s, } V2 = 1.6\text{m/s}$.

Next, we explore the new stability region for modified FD-SLIP as previously seen in Figure 3.6. This is achieved by picking velocity perturbations just inside the new stable region, and creating leg plots for FD-SLIP as shown in Figure 3.9 and modified FD-SLIP as shown in Figure 3.10. As shown below, FD-SLIP does in fact fail under these conditions, however, these plots also illustrate that the new stable region is not likely very useful because the perturbations are clearly large and perhaps unrealistic for a biologically inspired model.
In an effort to make the new stability region useful, we conducted an experiment with the controller. When the proportional gain ($k_p$) is decreased the stability region becomes larger, but extends further out, becoming less useful, as shown in Figure 3.11. When $k_p$ is increased the stability region becomes smaller, but approaches a more useful disturbance region, as shown in Figure 3.12. Unfortunately, the original region of stability, common with FD-SLIP, begins to degrade around a gain of .01, which can be seen in the lower left hand corner of Figure 3.12.
Figure 3.11: Modified FD-SLIP, $\tau = 4\text{Nm}$, $k_i=.01$, $k_p=.003$.

Figure 3.12: Modified FD-SLIP, $\tau = 4\text{Nm}$, $k_i=.01$, $k_p=.01$.

3.3 Discussion

Before choosing a PI controller, P, PI, PD, and PID controllers were considered. The P controller does most of the work in terms of decreasing the settling time, reducing the value of torque at which the system can operate, and increasing the region of stability.
It was found that PI and PD controllers have similar effect in terms of further decreasing the torque at which the system can operate; however, it was found that PI and PD controllers had different properties when it came to the stability region and the settling time. The difference in the stability region between PI and PD controllers was concentrated in the less useful disturbance region. As a result, this had little bearing on our choice of controllers. When considering the settling time, PI was better for low torque values and PD was equally better for high torque values. We decided that operating at low torque values was the most valuable result, and therefore a PI controller was used. PID control had the lowest settling time, but acted to degrade the ability of the system to operate at low torque values, and degraded the useful region of stability.

Implementing the PI controller discussed herein requires energy as feedback, which can be derived from the leg angle in reference to the ground, the leg length, and the velocity vector at LO. The leg angle can be found using an encoder at the hip joint. If a boom is used to restrict the leg in yaw and roll, leg length can be found through a combination of the encoder data from the hip, and the angle of the boom. Finally, the velocity vector can be approximated using an IMU located near the hip, on part of the body that does not rotate.
4. BIPEDAL ROBOT DESIGN

Over the past few decades, a large number of advancements have been made concerning the design of biologically inspired robotics. However, despite the significant advancements, there still remains a large gap in the understanding of humanoid bipedal running robotic design. There are only a handful of running robots in existence today. Most of these robots do not exhibit human-like motion, are constrained to a plane, or simply fall down. Furthermore, many scientists have found it difficult to model these systems due to highly nonlinear behavior, and extremely large parameter spaces. Biologically inspired design gives additional constraints that are often difficult or impossible to meet. Using a design methodology based on a highly experimental and progressive research approach, it may be possible to more quickly form hypothesis and intuition, in an effort to move towards the development of robustly stable bipedal running robotics.

The goal of this chapter is to first define objectives for our robotic platform. Once this is firmly established, we proceed to construct a design methodology for developing a bipedal running platform. This is achieved by decomposing the review of biological influences on running, as well as the review of successful bipedal running robots, as seen by the authors of this paper, and forming a hypothesis on what is required for a bipedal running robot to succeed. We then proceed to design and construct a bipedal running research platform.

4.1 Bipedal Running Robot Design Objectives

The immediate design goal is to construct a 3D bipedal running robot capable of investigating the effects of step width. However, designing and building a bipedal running robot is a major undertaking. Thus it is beneficial to consider any other future
research goals during the initial design process. One such goal is to construct a robot capable of transitioning from an existing and stable bipedal running robot design, to a more biologically correct configuration. Further, an ability to manipulate the robots physical configuration will allow us to more easily conduct progressive studies, investigating the influence of different mechanisms on a bipedal running gait. This is not the case for most existing bipedal running robot designs. This progressive approach will allow us to start with a basic and generic design, which we can expand on by adding different degrees of freedom, using motors or passive mechanisms, and refining mechanical and electrical systems as needed.

The list shown in table 4.1 contains additional criteria we chose for our desired bipedal running research platform. By obtaining a platform capable of these tasks, we may be able to conduct years of research using the same platform. In part, many of these requirements are because we wish to take a progressive approach, where we may learn and compare different approaches to stabilizing bipedal robot locomotion. In this same manner, if a particular design modification does not function as expected, it can be replaced, removed, or modified with minimal impact to the system.

Table 4.1: Bipedal Running Robot Criteria.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>The robot must be autonomous.</td>
</tr>
<tr>
<td>2.</td>
<td>The system must be contained, no external power or computation required.</td>
</tr>
<tr>
<td>3.</td>
<td>It must weigh equal to or less than that of an average human of the same height.</td>
</tr>
<tr>
<td>4.</td>
<td>It must have dimensional characteristics that are similar to typical human anatomy.</td>
</tr>
<tr>
<td>5.</td>
<td>It must be capable of equal or greater power output as a human of the same height.</td>
</tr>
<tr>
<td>6.</td>
<td>It must be capable of equal or greater running speed as a human of the same height.</td>
</tr>
<tr>
<td>7.</td>
<td>It must be adaptable to future configurations.</td>
</tr>
<tr>
<td>8.</td>
<td>It must incorporate compliant mechanisms.</td>
</tr>
<tr>
<td>9.</td>
<td>It should allow for progressive learning.</td>
</tr>
<tr>
<td>10.</td>
<td>It must be capable of 3D bipedal running.</td>
</tr>
</tbody>
</table>
4.2 Discussion of Biological and Robot Reviews

Before designing a bipedal running research platform, and in order to move towards a more biologically correct running robot, it is helpful to discuss and compare the mechanisms responsible for running in existing robot platforms, to the biological mechanisms thought possible for human running, as discussed in chapter 2.

ASIMO is capable of body pitching about the hips in the coronal plane, and moving the pelvis in the transverse plane [73]. Athlete is only capable of body pitching via the hips in the sagittal plane [74]. There are currently no bipedal running robots capable of bending about both the hips and the spine in the coronal plane to the knowledge of the authors. Passive and active spines have been studies in greater detail for quadruped robots. Passive spines have been shown to allow for increased velocity, lower energy consumption, and greater stability [30]. Active quadruped spines have also been shown to increase velocity and stability, but with higher energy consumption [31]. It has been shown that quadruped back bending can be modeled as entirely passive [32]. Back bending is exhibited in the fastest quadruped robots in existence today, such as the cheetah robot which can run faster than 28MPH.

Of the robots discussed in this paper, only ASIMO exhibits arm swinging while running. Honda states that increased walking speeds were achieved by rotation of the hips and arm swinging [75,76]. Fully articulated arms may not be necessary. It has been shown that arm swinging can be estimated by using 1 DOF lightly damped pendulums for walking [12].

Most successful walking robots employ relatively flat and unarticulated feet because they increase stability, especially when using control approaches like ZMP, which count on being able to change the point at which ground reaction forces occur. Some robots like ASIMO employ passive mechanisms to simulate the architecture of the feet [73]. For human running, the runner typically lands flat footed, or barely heel strikes [23]. For fast running, or sprinting, the runner is always on his toes. This is indicative of point style feet, used in the majority of the most successful bipedal running robots.
During running and sprinting, the ankle absorbs energy during the first half of the stance phase, and releases energy during the second half of stance phase, like a spring [44].

Asimo, Mabel, and Athlete robots all employ a knee that serves to induce radial forcing and ground clearance. Mark Raibert’s 3D hopping robot retracts the leg for ground clearance and extends to apply a force in order to mimic the purpose of the knee. The RHex running robot uses circumduction by rotating the leg 360 degrees in the sagittal plane, which successfully provides ground clearance and liftoff using the stiffness properties of the leg [4]. RHex is unique in that it is capable of doing this with 1 DOF per leg, actuated at the hip in the sagittal plane. Above knee amputees are capable of running using these same principles, except they use abduction instead of circumduction to provide ground clearance. However, abduction requires a second DOF, and requires movement in both the coronal and sagittal planes.

Based on these observations, the body members which have the greatest influence on stable bipedal running can be greatly simplified into the following. First, the foot, ankle, knee, hip joint and leg segments can be simplified into a single carefully designed spring leg segment actuated at the hip. We know this because above knee amputees can run in this fashion. However, considerably less is known about how stable above knee amputee running is achieved, compared to running with a knee, and so further study must be conducted. Second, the head, neck, and trunk can be consolidated into a single member, flexible at the spine in any direction. Head movement merely plays the role of sight stabilization during running. Finally, the hands and arm segments may simply be represented by single jointed 1 DOF pendulums. This physical representation of these body members and joints in their most basic form is as shown in figure 4.1. The mechanisms used for actuating these joints, as well as applying dampening and stiffness is not yet established.
Figure 4.1: Model of Joints Responsible for Bipedal Running.

Once we can determine the effect that foot placement has on a bipedal robot running gait, we may be able to find ways to improve the stability and biological accuracy by exploring the dynamic effects of the other appendages and joints listed in figure 4.1, on bipedal robot locomotion. While it is important to understand what the arms, legs, and upper body are doing individually, it is what they do as a system that makes fast running a possibility. When humans fast run, they are pushing their bodies to the very limits. In order to achieve this in robots, good control strategies, energetically favorable motions, and the key body parts as discussed in this section must eventually work together.
4.3 Design of a Bipedal Running Robot

We decided to design our base configuration around approximating the original conditions and principals under which bipedal RHx was successful, and being able to manipulate the robot in order to progressively move towards more human like characteristics, and capabilities. We chose to use the principals responsible for stable running in RHx as a baseline for our design, because RHx to bipedal running robotics is like the SLIP model to running simulations: It is perhaps the most basic form of running possible, and the effects of additional parameters on an already stable gait can be more easily investigated.

By considering a list of future research to be conducted with this robot, before beginning the design process, we were able to deduce the most important features to consider for the first design. Further, the design was intentionally left generic and open ended so that it could easily be manipulated in the future. The list below in table 4.2 contains just some of the future research considered.

Table 4.2: Future Research.

<table>
<thead>
<tr>
<th></th>
<th>Future Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Active and passive hip dampening in coronal plane.</td>
</tr>
<tr>
<td>2</td>
<td>Active and passive body pitching in coronal plane.</td>
</tr>
<tr>
<td>3</td>
<td>Active and passive body pitching in transverse plane.</td>
</tr>
<tr>
<td>4</td>
<td>Active and passive arm swinging.</td>
</tr>
<tr>
<td>5</td>
<td>Active and passive body pitching in sagittal plane.</td>
</tr>
<tr>
<td>6</td>
<td>Carbon fiber foot design, leg length, and ankle simulation.</td>
</tr>
<tr>
<td>7</td>
<td>Effects of leg angle via hip rotation in the coronal plane.</td>
</tr>
<tr>
<td>8</td>
<td>Effects of radial forcing.</td>
</tr>
<tr>
<td>9</td>
<td>Nonlinear controller for bipedal running gait.</td>
</tr>
<tr>
<td>10</td>
<td>Ground clearance using a passive knee.</td>
</tr>
</tbody>
</table>
4.3.1 Mechanical Design

Our proposed design as shown below in figure 4.2 allows the user to start with a RHex style platform in order to attempt recreating the original conditions under which bipedal RHex was stable. These conditions include 1DOF at each hip in the sagittal plane, wide hip spacing, and a low COM, relative to human biology, as shown in figure 4.2(a). In this configuration, ground clearance is achieved via circumduction, by rotating the leg 360 degrees in the sagittal plane, as shown in figure 4.2(a), 4.18, and 4.19. The proportions of the frame can be changed easily from that of a RHex style robot as shown in figure 4.2(a), to the size of a 4 year old girl, as shown in figure 4.2(b), and as defined by figure 4.3.

Figure 4.2: (a) Robot Design, RHex Configuration (b) Robot Design, Human Configuration.
Figure 4.3: Average Physical Characteristics of a Four Year Old Girl [65].

In this configuration, achieving ground clearance via circumduction becomes difficult to execute due to a longer leg length, increased leg weight, and an increased moment of inertia. Thus a second DOF per leg was implemented as shown in figure 4.2(b), which allows for movement about the hip in the coronal plane. This DOF can abduct 30°, and can adduct 60°, relative to a vertical leg position. Using this second
DOF, above knee amputee inspired gaits can be explored in order to provide ground clearance via abduction/adduction, and approach a more biologically correct running gait.

Changing the robot from a RHex style configuration to a humanoid configuration is achieved by changing the distance between the hips, the distance between the shoulders, by changing the length of the back, and by changing the vertical location of the shoulders. Changing the distance between the hips is achieved by loosening the screws indicated in figure 5.1, sliding the hips into position, and then tightening the screws. The ability of the hips to change hip width, and still keep the legs perpendicular to the ground is made possible by the second DOF in the hip that allows the leg to rotate in the coronal plane. In order to achieve a step width less than 26.04cm, the leg must be designed as shown in figure 4.2(b) where the leg bends inward to clear the structure of the robot. This “bent” leg design cannot be used for circumduction because it will hit the body. It could be used with an above knee amputee inspired gate on the other hand. An above knee amputee inspired gait would use abduction and adduction to achieve ground clearance instead of circumduction.

The outer limits of hip width, shoulder width, back length, and the vertical location of the shoulders, are only restricted by the strength of the frame material. This is because the frame is made from 7 pieces of 20mm “80/20”, a common structural aluminum. Two members of the frame are responsible for adjusting shoulder width, three are responsible for adjusting body and shoulder height, and two are responsible for hip width. In order to make the transition from the dimensions of the robot shown in figure 4.2(a) to that shown in 4.2(b), new structural members are cut to length and replace existing structural members. Wire and cable lengths are intentionally left long so that a wide range of configurations can be achieved without modifying the electrical system. The inner limits of hip width, back length, and the vertical location of the shoulders is equal to or less than the dimension shown in figure 4.3. The distance between the shoulder joints on the other hand are limited by the current motor length, and have a minimum width of 30cm, almost 10cm greater than the average 4 year old girl. The shoulder width shown in figure 4.3 could be achieved by simply sourcing a shorter motor.
The motors and gearboxes which actuate the hips in the coronal plane are mounted further up the body, away from the hips. This is because the motors and gearboxes are the heaviest components, and the COM would be extremely close to the hips, which is more difficult to balance [64]. This required the use of timing pulleys in order to transmit torque accurately from the motors to the hips. A 1 inch wide AT5 tooth profile was chosen for the timing belts, because it is good for high torque transmission and accurate positioning.

The motors and gearboxes were chosen based on torque and speed requirements established in the following. The torque of the motors was chosen so that the stall torque, after the gearbox, was at least three times the maximum hip torque of a 4 year old girl [77]. Maximum hip torque was used as a baseline because very little information was available concerning the hip torque of a child during running. The speed of the motors was chosen so that the max forward running velocity would be approximately 3m/s, where the average running speed for a 4 year old girl is approximately 2.67m/s [54]. It was also decided that the configuration required for this velocity would include the gait cycle discussed in chapter 4.3.5, a double leg configuration as shown in figure 4.18, and using the leg length of an average 4 year old girl shown in figure 4.3.

Determining the required motor speed, based on this configuration, was achieved by first determining the minimum required angular velocity of the hip during stance

$$\dot{\varphi}_d = \frac{v_{max}}{l_{ave}} \quad (4.1)$$

using the leg length $l_{ave}$ shown in figure 4.3, and the max desired forward velocity $v_{max} = 3\text{m/s}$. This value was then used in equation 4.2 to determine the minimum required flight phase speed

$$\dot{\varphi}_f = \frac{\dot{\varphi}_d \varphi_f D}{(1 - D)\varphi_s} \quad (4.2)$$

Equation 4.2 was derived using equations 4.22 through 4.28, which are based on the gait cycle shown in chapter 4.3.5, where D is the duty cycle at this speed defined by equation
4.23, $\varphi_s$ is the stance region defined by equation 4.22, and $\varphi_f$ is the flight region defined by equation 4.25. For these calculations, the leg was considered massless due to its lightweight construction, and friction due to the gearboxes was neglected. Thus, this speed estimate was expected to be low, and choosing motors that exceeded this value was important.

Once the required speed and torque was determined, torque and speed characteristics of motors, with applicable gear ratios, were compared, and after a series of iterations, the gear ratios and motors were chosen. Other considerations when choosing the motors include maximizing controllability, power density, and efficiency, while minimizing the required distance between the hips in the coronal plane. The gearbox itself was chosen so that the maximum rated torque was equal to the stall torque of the motors. Still, the gearboxes were by far the heaviest components, where the total weight of all four gearboxes was 5.4kg, about 36% of the total weight of the robot.

Since we wish to make the transition from a RHex style robot to a humanoid proportioned robot, we start our experiments with short legs, similar to those used on RHex. This means that we will be restricted to lower running speeds. The leg length used for the purpose of this paper allows for a max running speed of approximately 1.6m/s, when using a double leg configuration. Once again neglecting the dynamics of the leg, this experimental forward velocity scaled up to the target leg length of .49m, shown in figure 4.3 would be 2.86m/s, fairly close to the value approximated using equation 4.2. Preliminary trials also showed that the torque experienced by the motors during running would only allow for short duration running, approximately 10 minutes, before the motor temperature reached about 120°F. This is without a heat sink. However, based on the ground reaction force data measured in chapter 5, more appropriate motor torque values can now be determined.

The leg mounting hubs have a generic hole pattern that can be used to mount a wide range of leg types. Different numbers of legs can be attached to the hub in cases where circumduction is being used and it is desired to reduce the flight time in order to achieve faster running speeds. The number of legs possible with this design is 1, 2, or 4.
In order to match the average weight of a 4 year old girl, light weight and strong aluminum alloys were used to make the frame, motor mounts, and leg mounts. The legs are made from carbon fiber, which weigh only .15kg. In the end our robot weighed 15.2 kg, just under 16kg, the average weight of a 4 year old girl. However, it should be noted that this weight does not include the arms, which have not been used for studies conducted thus far. Instead, the arm mounting brackets have been used as the main supports for lowering the robot down to the treadmill via a rope system. Due to the modular design, components can easily be relocated to another part of the body if a desired configuration demands it. This attribute also allows for easy removal, modification, or addition of parts as required.

4.3.2 Electrical Design

The electronics and power system as shown in figure 4.4 have been designed to accommodate additional actuators. In order to add an additional actuator, another motor driver and controller must be added to the circuit card stack. This is identified in figure 4.4 by the “PCB” label and the green dashed rectangle. The motor controller processor is an Atmega32, programmed via Arduino. The MBED microcontroller runs the main program and sends the desired position to each Arduino based motor controller. The number of actuators is only limited by the number of pins on the on the MBED microcontroller, and the speed in which it can process the movement. As the trajectory planning schemes become more complex, and the number of actuators increase, the processing time naturally increases. The communication speed between the MBED master and the Arduino slave is set at 200Hz using the i²c communication protocol. The communication protocol used between the IMU and the MBED is SPI. The IMU sensor is only providing pitch angle feedback to the robot. The sensor uses an accelerometer, magnometer, and gyro, in combination with advanced filters and disturbance rejecting algorithms to provide low drift Euler angles, as well as a wide range of other information that is not currently being used. The batteries are high discharge lithium polymer (“lipo’s”) that can support all of the electrical needs of this robot in a small
The battery used for powering the motors is capable of supplying 300A continuously at 25.9V. The storage capacity is 5000mAh. The computational system is powered by a smaller 2700 mAh 7.4V battery.

![System Diagram](image)

**Figure 4.4: System Diagram.**

The specifications for this robot are as shown in table 4.3, and the final design configuration is shown in figure 4.5 and is shown running in figure 4.6.
### Table 4.3: Bipedal Robot Specifications.

<table>
<thead>
<tr>
<th>Year</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable Locomotion</td>
<td>Yes</td>
</tr>
<tr>
<td>Onboard Computer</td>
<td>Yes, Micro Controllers</td>
</tr>
<tr>
<td>Knee</td>
<td>No, But Reconfigurable</td>
</tr>
<tr>
<td>Onboard power</td>
<td>Yes</td>
</tr>
<tr>
<td>Top Running Speed</td>
<td>Unknown, (1.2m/s speed tested, 1.6m/s is max speed with current leg length)</td>
</tr>
<tr>
<td>Height</td>
<td>Variable (Configuration Used in the Step Width Study Stands 0.762m Tall)</td>
</tr>
<tr>
<td>Weight</td>
<td>15.2kg (33.5lbs)</td>
</tr>
<tr>
<td>Actuation Method</td>
<td>Electric</td>
</tr>
<tr>
<td>Passive Mechanisms</td>
<td>Yes</td>
</tr>
<tr>
<td>Double Flight Phase</td>
<td>No</td>
</tr>
<tr>
<td>3D Biped</td>
<td>Yes</td>
</tr>
<tr>
<td>Control Method</td>
<td>PD</td>
</tr>
<tr>
<td>Main Function</td>
<td>Running Research</td>
</tr>
<tr>
<td>Human Form</td>
<td>Reconfigurable to Human Form</td>
</tr>
</tbody>
</table>

#### Sensors

| IMU | VectorNav VN-100, 5V, Magnometer, Gyro, and Accellerometer, Output used: Euler Angles |
| Encoder, Hip Circumduction | US Digital, 256 counts per turn, quadrature, incremental, 5V, TTL Logic |
| Encoder, Hip Adduction | US Digital, 256 counts per turn, quadrature, incremental, 5V, TTL Logic |
| Encoder, Arms | Maxon, 256 counts per turn, quadrature, incremental, 5V, TTL Logic |

#### Legs

| Stiffness | 2500 N/m |
| Length | 9 inch diameter spring leg, 10.81 inches from hip center to leg end |

#### Processors

| Master (for main program) | Mbed : 96 MHz ARM Cortex M3 core, 512 KB flash, 64 KB RAM |
| Slave (for motor drivers) | ATmega328, 16MHz, 32KB flash, 2KB RAM |

#### Motors

| Hip Circumduction | Maxon, RE40, Graphite Brushes, 150Watt, 24V, NL Speed 7580RPM, Stall Torque 2280 mNm |
| Hip Adduction | Maxon, RE32, Graphite Brushes, 60Watt, 24V, NL Speed 8810RPM, Stall Torque 1020 mNm |
| Arms | Maxon, RE32, Graphite Brushes, 60Watt, 24V, NL Speed 8810RPM, Stall Torque 1020 mNm |

#### Gearboxes

| Hip Circumduction | Apex Dynamics, ALR series, 25:1, Planitary, 90 deg angle, 54Nm max torque |
| Hip Adduction | Apex Dynamics, AL series, 90:1, Planitary, 54Nm max torque |
| Arms | Maxon, 33:1 Planitary, Max Torque 3.75Nm, 42Nm max torque |

#### Motor Drivers

| For all motors | 5.5-40V, 23A continuous |

#### Batteries

| For drive systems | Thunder Power 5000mAh 7S 25.9V G6 Pro Power 65C |
| For computational systems | Thunder Power 2700mAh 2S 7.4V G6 Pro Power 65C |
Figure 4.5: Final Design Configuration – (a) Front (b) Left (c) Back Views.

Figure 4.6: Final Design Configuration Running - (a) Right Side (b) Back.
4.3.3 Spring Leg Design

The carbon fiber spring legs are the only passive components in the system at this time. Determining the correct stiffness was critical to the stability of the robot. Neil Neville had determined that a leg stiffness of 1640N/m provided stable locomotion for RHex. This leg stiffness value was determined through experimentation on a different system. In order to scale the stiffness for our robot, I used nondimensionalization to match the energetics of RHex. Since mass was the largest parameter change between systems, where RHex weighed 8.4kg (m1) and our robot weighed 15.2kg (m2), we used mass as the scaling property as follows:

\[ m \propto L'^3 \quad \text{(4.3)} \]

\[ k \propto L'^2 \quad \text{(4.4)} \]

\[ \frac{m1}{m2} = \frac{15.2kg}{8.4kg} \quad \text{(4.5)} \]

\[ L' = \left( \frac{m1}{m2} \right)^{1/3} = \left( \frac{15.2kg}{8.4kg} \right)^{1/3} = 1.219 \quad \text{(4.6)} \]

\[ k1 = k2 \cdot L'^2 = 1640 \cdot 1.219^2 = 2437 \text{N/m} \quad \text{(4.7)} \]

where the target stiffness for our robot was determined to be 2437N/m. Using the calculated target stiffness, the legs were designed using composite laminar theory [52] where the bending stiffness of the laminate is characterized by

\[ D_{11} = \sum_{j=1}^{n} \bar{Q}_{11}^j (d_z \ast \bar{Z}_j^2 + \frac{t_z^3}{12}) \quad \text{(4.8)} \]
\[ D_{11} = \frac{EI}{W}. \] (4.9)

Figure 4.7: Carbon Fiber Layup for use with Classical Composite Theory.

I used a c shape leg as shown below in figure 4.8 because it was successfully used with bipedal RHEX, and is an easy shape to manufacture. The stiffness is nonlinear, but it was approximated as linear.

Figure 4.8: C Spring Side Profile.
The first set of legs we designed had carbon fibers aligned with the leg so that the highest strength to weight ratios could be achieved. However, during preliminary trials, it was found that lateral deflections of the leg were a large disturbance source, and would not allow for stable running. In order to minimize lateral deflection, the final leg design incorporates thick layers of carbon fiber biaxial twill oriented at a 45 degree angle, which stiffens the leg laterally or in twist. In addition, these layers would be the furthest out from the center of the composite layup, which makes them influence the behavior of the material significantly more than sub layers. These layers do not offer as much strength or stiffness radially, mainly because the width of the leg does not allow for the fibers to run along the whole length of the leg when they are oriented at 45 degrees. This results in fibers that are in parallel with the epoxy resin. In order to determine the stiffness of a carbon fiber layer with a 45 degree orientation and a leg width of two inches, a sample c-leg was made with the layup as shown in figure 4.9, containing entirely 12k 45 degree oriented 2X2 twill carbon fiber.

![Composite Test Sample Layup for Determining Young’s Modulus.](image)

Using this composite test sample, the radial deflection was measured under half the weight of the robot, and the stiffness was calculated using Hooke’s Law

\[ F = k\delta. \] (4.10)
In order to use this experimentally determined stiffness value for layers oriented at 45 degrees, in a composite containing other orientations, it was necessary to determine the modulus of elasticity. The deflection of a C spring

\[ \delta = \frac{\pi FR^3}{2EI} \]  

and as described by figure 4.8, was derived using Castigliano's Theorem for a thin C spring. Combining equations 4.9, 4.10, and 4.11, we solved for the spring rate \( k \) to get

\[ k = \frac{2wD_{11}}{\pi r^3}. \]  

Since all layers in the test sample are of the same thickness and orientation as shown in figure 4.9, combining equations 4.12 and 4.8 yield the experimental modulus of elasticity

\[ E = \bar{Q}_{11} = \frac{\left( \frac{k\pi r^3}{2w} \right)}{\sum_{j=1}^{n} \left( d_x * Z_j^2 + \frac{4}{12} \right)} \]  

The modulus of elasticity used for the carbon fiber biaxial twill weave, oriented along the leg, was 55.6GPa. The experimentally determined modulus of elasticity for a fabric oriented at 45 degrees and on a 5.08cm wide leg, was 25.9GPa. These values were then used to determine a weave configuration that provided the required stiffness, as shown in figure 4.10.
Using equations 4.8 and 4.12, the stiffness for a 5.08cm wide composite leg with an 11.43cm radius, and the composite layup in figure 4.10, the stiffness was calculated as shown in table 4.4. Once the leg was manufactured, the stiffness was then experimentally measured by measuring the deflection provided by half the weight of the robot, and then using Hooke’s law, equation 4.10. The calculated radial stiffness of the leg was extremely close to both the experimentally determined value, as shown in table 4.4, and the target value. In addition, the lateral deflection was significantly lower using the new legs and did not appear to provide any unwanted perturbations.

Table 4.4: Final Carbon Fiber Leg Layup Calculations.

<table>
<thead>
<tr>
<th>Layer</th>
<th>1,8</th>
<th>2,7</th>
<th>3,6</th>
<th>4,5</th>
</tr>
</thead>
<tbody>
<tr>
<td>filaments per bundle</td>
<td>12K</td>
<td>3k</td>
<td>12k</td>
<td>6K</td>
</tr>
<tr>
<td>Layer Thickness d_z (m)</td>
<td>0.00058</td>
<td>0.00023</td>
<td>0.00058</td>
<td>0.00038</td>
</tr>
<tr>
<td>Distance from center Z (m)</td>
<td>0.00148</td>
<td>0.00108</td>
<td>0.00067</td>
<td>0.00019</td>
</tr>
<tr>
<td>Young’s Modulus Q_{ij} (Pa)</td>
<td>2.59E+10</td>
<td>5.56E+10</td>
<td>2.59E+10</td>
<td>5.56E+10</td>
</tr>
<tr>
<td>Flexural stiffness D_{ij} (EI/W)</td>
<td>33.325</td>
<td>14.972</td>
<td>7.164</td>
<td>1.017</td>
</tr>
<tr>
<td>Total Flexural Stiffness D (EI/W)</td>
<td>112.96</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total thickness (m)</td>
<td>0.00354</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leg width W (m)</td>
<td>0.05080</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radius of C leg R (m)</td>
<td>0.11430</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calculated Stiffness k (N/m)</td>
<td>2446.37</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured Stiffness k_m (N/m)</td>
<td>2487</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In order to manufacture the carbon fiber legs we used the resin infusion method. The setup required for this method is illustrated in figure 4.1. The carbon fiber layup is sandwiched between a mold and an airtight bag. The bag has an inlet for resin to enter the dry fabric, and an outlet for the vacuum. The bagging material is sealed to the mold using sealant tape. There is also an infusion mesh layer that allows air and resin to more easily travel down the layup, and a peel ply layer that allows the infusion mesh and bagging material to be separated from the carbon fiber composite once cured. The hoses are typically clear PVC tubing, and enter the bag sealed by additional sealant tape. The hoses are then attached to spiral wrap with inexpensive T or L plastic compression fittings. The spiral wrap simply allows for even resin distribution.

Before infusion, the bag must be checked for leaks by observing a constant 76.20cmHg vacuum for at least 10 minutes. This is achieved by applying a vacuum to the bag, clamping the line in, and clamping the line out between the pressure dial and the vacuum pump, which allows for monitoring of the pressure. Once the bag has been checked for leaks, the resin is then sucked through the layup. The resin should be mixed thoroughly and degassed before infusion. Degassing is achieved by putting the mixed resin in an air tight chamber under a 76.20cmHg vacuum until all air bubbles rise and pop. Once the layup is saturated, bubbles may form due to the resin boiling. In order to remove the resin vapor, the vacuum end must be clamped off first while resin is throttled in slowly, until the resin vapor turns back into a liquid. Finally the resin end is clamped and the part is left under a vacuum until cured.
Figure 4.11: Resin Infusion Method.
In figure 4.1, the mold is depicted as flat; however, the shape of the mold can change completely while the rest of the setup remains relatively unchanged. This can be seen in figure 4.12, where we used a cylindrical mold to manufacture the legs.

Figure 4.12: Resin Infusion of Carbon Fiber Legs.

The mold itself is simply a 22.86cm diameter stainless steel tube. Resin Infusion is particularly well suited for making carbon fiber springs because it results in a relatively defect free composite, and provides a good carbon fiber to resin ratio. However, it is one of the more difficult methods of carbon fiber manufacturing, and typically requires some trial and error before obtaining good results. After the composite was cured, and demolded, the legs were cut 5.08cm wide, and a rubber shoe sole was attached using UVHB tape. The rubber sole was experimentally chosen so that the friction was high enough to avoid slipping during the stance phase, but was low enough to not influence the dynamics of the robot while entering the flight phase. The legs worked well throughout all parameter tuning and trials as discussed in this thesis, and were only re-soled. However,
figure 4.13 exhibits a stress concentration where cracking is beginning to occur in two out of four legs used. It is occurring on the inside of the leg because carbon fiber composites do not perform as well in compression. This means that we have approached the physical limits of a uniform c shaped carbon fiber leg with this stiffness and width, for a robot of this weight, and with the designed composite layup. All other robotic components show no indication of damage or wear.

![Figure 4.13: Cracks Forming as a result of Fatigue.](image)

### 4.3.4 Controllers

The controller and leg trajectory were modeled after those successfully used in the RHEx bipedal running robot trials. For the purpose of this thesis we will cover the basics for the controller and gait cycles used, for more details see Neil Neville’s thesis [4]. There are three controllers used, one for pitch of the robot, one for speed, and one for controlling the motors. These controllers work together as shown in figure 4.14.
The velocity controller requires an estimation of speed, as shown in equations 4.14, which utilizes a single-pole low pass infinite impulse response filter to estimate speed based on the desired stance velocity. The filtered angular velocity of the leg during stance $\tilde{\phi}_{dk}$ is calculated using

$$\tilde{\phi}_{dk} = \alpha_v \phi_d + (1 - \alpha_v)\tilde{\phi}_{dk-1}$$  \hspace{1cm} (4.14)$$

where $\phi_d$ is the current desired stance velocity, $\tilde{\phi}_{dk-1}$ is the previous filtered stance velocity, and $\alpha_v$ is a filter parameter based on the sampling frequency [4]. The filtered angular velocity is then converted into a forward velocity using

$\bar{v} = \tilde{\phi}_{dk} l_{ave}$  \hspace{1cm} (4.15)$$

where $l_{ave}$ is the average leg length, estimated using the leg length compressed with half of the robot’s weight. The angle at which the robot balances while running is experimentally found and then used as a constant represented by $\theta_b$ as shown in equation
If the speed controller was turned off, and the robot pitched forward, the robot would accelerate in order to correct the pitch, and if the robot pitched backward it would decelerate. If $\theta_b$ was set incorrectly, the robot will continuously accelerate or decelerate in order to try to maintain the angle. This is because it will have a tendency to fall in a single direction due to the asymmetric balance point. The speed controller takes advantage of this fact by changing the desired pitch angle $\theta_{dk}$ according to the estimated forward velocity as follows:

$$\theta_{dk} = k_{vp}(\ddot{v} - v_d) + \theta_b$$  \hspace{1cm} (4.16)

where the desired forward velocity $v_d$ and the proportional gain value $k_{vp}$ are constants.

Due to the nonlinear nature of this robotic running system, the saturation function

$$(\theta_b - \theta_{sat}) < \theta_{dk} < (\theta_b + \theta_{sat})$$  \hspace{1cm} (4.17)

is used to limit the effort from the controller past a threshold value $\theta_{sat}$. If the saturation function is satisfied, the desired pitch angular velocity is calculated using

$$\dot{\theta}_d = \frac{(\theta_{dk} - \theta_{dk-1})}{T}$$  \hspace{1cm} (4.18)

$\theta_{dk}$ and $\dot{\theta}_d$ are then used in the PD pitch controller. If the saturation function is not satisfied, $\theta_{dk}$ is discarded, and the last desired pitch angle and pitch velocity values to satisfy the saturation function are used instead.

The IMU sensor provides pitch angle feedback to the robot. These values are then used to generate $\theta_a$, the actual angle of the robot, and $\dot{\theta}_a$, the actual angular velocity of the robot. These values, along with the desired pitch angle, and pitch rate values are used in the PD controller to generate the desired angular acceleration using

$$\ddot{\theta}_d = k_{\theta_p}(\theta_a - \theta_d) + k_{\theta_d}(\dot{\theta}_a - \dot{\theta}_d).$$  \hspace{1cm} (4.19)
The desired angular acceleration is then integrated and added to the filtered angular velocity of the leg in order to generate the desired stance velocity

\[ \dot{\phi}_d = \ddot{\phi}_d k + \dot{\phi}_d T \]  \hspace{1cm} (4.20)

for use in generating the leg trajectory. The leg trajectory position \( \phi_t \) is calculated using the desired stance angular velocity \( \dot{\phi}_d \) and a clock cycle as discussed in chapter 4.3.5. The trajectory position is then sent to the motor controller where the leg trajectory velocity \( \dot{\phi}_t \) is calculated. Sensor position \( \phi \) and angular velocity \( \dot{\phi} \) are read from the encoders. These values are then used in the PD controller

\[ \tau = k_{\phi p}(\phi - \phi_t) + k_{\phi d}(\dot{\phi} - \dot{\phi}_t) \]  \hspace{1cm} (4.21)

in order to determine the desired motor torque, which is then translated into a PWM signal that actuates the motors.

Due to the difficulty in simulating the dynamics of this robot, the gain values for this controller and this robot must be found experimentally. This is a highly iterative process, but there is a particular order in which determining the gains, proves to be most efficient. It is recommended for a robot of this weight that a crane is constructed for lowering and raising the robot onto a treadmill for parameter tuning. The angle at which the robot is suspended should be adjustable.

The following steps outline a method for experimentally determining the controller gain values: First, the motor controller P gain value \( k_{\phi p} \) should be chosen such that the leg trajectories are just barely tracked. This results in a very low stiffness. With the correct gain values, and the robot hip holding position, you should be able to move the leg back and forth around 20 degrees in either direction without much effort. The D gain provides dampening, and is chosen such that the stiffness of the leg, the motor controller P gain, and the frequency of running do not work together to create input disturbances. This can be determined experimentally.
Angle the pitch of the robot forward around 5 to 10 degrees from the static balance pitch angle using the harness. Set a constant velocity, turn off the pitch and speed controller, and activate the gait cycle. Lower the robot onto the treadmill. If the robot fails in roll or yaw first, try experimenting with the leg controller gains. If the robot fails in pitch first, change the harness pitch angle, opposite the direction that the robot falls. Repeat this until the robot consistently fails in pitch, but not consistently in a single direction. Record the pitch angle. For a given robot configuration and speed, the angle at which the robot wants to balance while running is constant. It has been shown with planar robots that the pitch angle increases as a function of speed [25].

Once a desirable pitch angle is chosen, the P and D values for the pitch controller can be determined. Start with a low value for the proportional gain. With the pitch controller turned on, and the robot hoisted in the air, turn on the gait cycle and change the angle of the robot by a few degrees. An audible difference in running frequency should occur immediately. This controller is fairly aggressive. If not, increase the P gain. Once a suitable gain value is found, lower the robot onto the treadmill. If the robot exhibits unstable oscillations, reduce the gain, otherwise increase it. Find the border of unstable behavior, and then introduce a D gain to smooth out the response. This can be repeated until the gain values produce robustly stable behavior. The pitch angle should be revisited at this point and adjusted so that acceleration or deceleration is minimized. Finally the speed controller P gain value and the saturation values can be adjusted so that the speed remains relatively constant without introducing pitch angles that cause the robot to fail.

All of these gain parameters are dependent on one another, so once initial gain values are found, it will most likely be necessary to go back and tweak the gain values based on observing the output of the system. This requires practice with your robot and an understanding of how a change in gain parameters affects the systems response. The stability of this robot is quite sensitive to the gain parameters, so experimenting with small changes of the gains can result in a large increase of stability. The gain values successfully chosen for the robot configuration as shown in figure 4.5, with a step width of 41.91cm, and a speed of 1.2m/s, are as shown below in table 4.5. The pitch and
velocity controller gains were surprisingly similar to those found for RHex, but scaled up by a factor of 180/π. The pitch P gain was nearly identical, the D gain for our robot was almost four times higher, and the P speed gain was approximately twice as high.

Table 4.5: Experimental Pitch Angle and Controller Values.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Step Width (cm)</td>
<td>41.91</td>
</tr>
<tr>
<td>Pitch Angle (Deg)</td>
<td>68.8</td>
</tr>
<tr>
<td>P Pitch Gain</td>
<td>2000</td>
</tr>
<tr>
<td>D Pitch Gain</td>
<td>80</td>
</tr>
<tr>
<td>P Speed Gain</td>
<td>0.01</td>
</tr>
<tr>
<td>P Leg Tracking Gain</td>
<td>0.135</td>
</tr>
<tr>
<td>D Leg Tracking Gain</td>
<td>0.001152</td>
</tr>
<tr>
<td>Leg Tracking Bandwidth</td>
<td>280</td>
</tr>
</tbody>
</table>

4.3.5 Gait Cycle

The original gait cycle used was based on RHex’s bipedal running gait cycle, as shown in figure 4.15. If velocity saturation occurs during the flight phase, this scheme compensates by changing the ramping profile. During the design process, the motors and gearboxes were chosen so that the top running speed would be similar to a 4 year old girl, with a leg length consistent with 4 year old biology. In order to approximate the conditions under which RHex was successful, we started with a shorter leg length, which resulted in lower running speeds. Although the top running speed, restricted by motor and gearbox limitations, would still be higher than that exhibited by bipedal RHex, after tuning the controllers, it quickly became apparent that the robot would not be capable of running speeds as low as bipedal RHex. The lower bound of running speeds for our robot is around 1.05 m/s, as opposed to RHex’s lowest running speed of .57 m/s. This caused problems when using this scheme, because we were always operating well into the saturation region with a ramping velocity profile, and any loss in time getting to position
because of ramping reduced our already limited speed range. As a result, without increasing the motor size, decreasing the gear ratio, or manufacturing more legs so that a 4 leg configuration could be used to reduce flight time, we had problems with tripping because the foot could not get into position at the beginning of stance phase.

In order to fix this, we considered using gain scheduling in order to assign more aggressive gain values for the flight phase only. However, we found that because the motor controller gains were so low, we could simply use a step velocity profile as shown in figure 4.16, and the resulting gait was still smooth due to the low stiffness and high dampening.

Figure 4.15: Gait Cycle Scheme 1.
This change in velocity profile improved the top running speed without risk of damaging the motors. The stance and flight phases can be characterized as shown in figure 4.17 for a single leg configuration and in 4.18 for a double leg configuration. The robot is also capable of a four leg configuration, but this has not yet been explored. Using the IMU pitch angle, the middle of the stance phase was always forced to be perpendicular to the ground, so that touch down and liftoff always occurred at times when the motion of the leg would have little or no interaction with the ground. For bipedal RHex, an offset was employed instead.
Figure 4.17: Single Leg Path.

Figure 4.18: Double Leg Path.

Figure 4.19: Gait Cycle – (a) $t = 0$ (b) $t = t_s/2$ (c) $t = t_s/2 + t_f$
The entire gait cycle is recalculated every .005s (200Hz), using values provided by the controller. The desired position is estimated using time from the clock cycle, which is reset to zero every time \( t = t_c \). The clock cycle for the right and left hip must always be 180 degrees out of phase in time. Thus, when the right leg time \( t = t_c \), the left leg time \( t = t_c/2 \). This will ensure that the gait frequency is periodic. In order to calculate the leg trajectory you first need the desired stance phase velocity from the controller. The way in which the stance rotation angle and duty cycle are determined is the same as what was used on RHex. In this scheme, inspired by hopping robots and biomechanics studies, the sweep angle

\[
\varphi_s = c_1 + c_2 \dot{\varphi}_d
\]

and the duty cycle

\[
D = c_3 + c_4 \dot{\varphi}_d
\]

are increasing functions of speed. Using the sweep angle \( \varphi_s \), duty cycle \( D \), and the stance speed \( \dot{\varphi}_d \), all of the parameters necessary for generating the gait cycle as shown in figure 4.16 are shown below. The total cycle time

\[
t_c = \frac{\varphi_s}{\dot{\varphi}_d D}
\]

is the time required for the leg to complete one stance phase and one flight phase. The flight angle

\[
\varphi_f = \frac{2\pi}{N} - \varphi_s
\]

is dependent on the number of legs \( N \) that are being used. When more legs are used, smaller flight angles are required, the required flight velocity is lower, and the robot can
run at higher speeds. During one gait cycle, the time spent in the stance phase is calculated using

$$t_s = \frac{\phi_s}{\dot{\phi}_d} \quad (4.26)$$

and the time spent in the flight phase is calculated using

$$t_f = \frac{\phi_s (1 - D)}{\dot{\phi}_d D}. \quad (4.27)$$

Finally, a constant flight speed

$$\dot{\phi}_f = \frac{\phi_f}{t_f} \quad (4.28)$$

is used in the situation where no velocity ramping is present.
5. EFFECTS OF STEP WIDTH ON 3D BIPED LOCOMOTION

The goal of this study is to determine the effects of step width on stable 1DOF per leg bipedal robot locomotion. One of the greatest differences physically, between the gait of a stable 1 DOF per leg bipedal running robot and a human, is step width. Step width is an important characteristic of running, and has been shown in biological studies to have a profound impact on stability and energetic cost. By analyzing the behavior of the robot under a range of step widths, we are able to support biological hypothesis and running stability criteria. Further, this information can be used to characterize the running gait, improve the current design and develop future studies regarding methods for reducing step width, increasing stability, and approaching a more biologically correct running robot configuration.

5.1 Methods

The preferred step width for human running is very small compared to walking. For adult running the step width is around 3.6cm and for walking it is around 12cm [2]. This is in stark contrast to RHex with a step width of 30cm [4]. This wide stance is important to the stability of a 1 DOF per leg bipedal running robot, on the basis that the resistance of translation due to mass distribution can be calculated using the dimensionless inertia

\[ I_{\text{roll}} = \frac{I_{\text{roll}}}{md^2} \]  

(5.1)

where \( I_{\text{roll}} \) is the inertia of the robot in roll, \( m \) is the mass of the robot, and \( d \) is the lateral distance from the COM to the leg [4, 47, 48]. Using this criterion, a dimensionless inertia in roll less than 1 may be passively stable, whereas a dimensionless inertia greater than 1
may require active control. However, for humans, it has been shown that the legs provide
very little active stabilization during running [2], even though step width decreases, and
the dimensionless inertia is far greater than 1. Furthermore, it has been shown that when
the step width is greater than preferred, energetic cost increases and step width variability
increases, which indicates decreased stability [2]. In addition, based on these criteria, an
adult sized 1DOF per leg bipedal running robot would require and even larger step width.
By conducting this study, we look to identify clues that can be used to increase the
stability, the efficiency, and the biological correctness of this robot.

Since the controller for this robot was originally designed around a step width of
41.91cm, this study will use a range of step widths greater than and less than this value,
from 36.83 to 46.99 cm, in 2.54cm increments. This is achieved as shown in figure 5.1,
where the width between the hips can be manually adjusted by loosening the indicated
screws, and sliding the hips into place. After tightening the screws, the hips are then
rotated using the coronal plane DOF, so that the legs remain perpendicular to the ground.
Incremental encoders were used for the construction of this robot, which means that the
position must be reset every time the motor controllers are turned off. In order to get
accurate positioning of the legs at startup, reference marks and tools were used.
We were not sure if the optimal pitch and speed controller gains would change for each step width, so they were experimentally determined, for each step width, prior to conducting the trials, as shown in table 5.1.

Table 5.1: Pitch Angle and Controller Gains for associated Step Widths.

<table>
<thead>
<tr>
<th>Step Width (cm)</th>
<th>36.83 – 44.45</th>
<th>46.99</th>
</tr>
</thead>
<tbody>
<tr>
<td>P Pitch Gain</td>
<td>2000</td>
<td>1500</td>
</tr>
<tr>
<td>D Pitch Gain</td>
<td>80</td>
<td>200</td>
</tr>
<tr>
<td>P Speed Gain</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>
For the step widths of 36.83 through 44.45cm, the original gain values appeared to be the most optimal. Straying from any of these values resulted in decreased stability. There were no stable gain values for the 46.99cm step width on the other hand, so we chose gain values that minimized failure. The main failure mode for the 46.99cm step width was pitch.

Next, the pitch balance angle was experimentally determined for each step width as shown below in figure 5.2.

![Figure 5.2: Pitch Angle VS Step Width.](image)

Determining the angle at which the robot balances is one of the most sensitive parameters. Being off by a degree will most certainly result in lower stability or a change in speed using this control method. These results show a clear trend towards a more vertical posture for smaller step widths. Looking at it from a statics perspective, this trend makes sense. The COM of the robot is in back of the hips when in a vertical standing
position, as shown in figure 5.1. When step width increases the COM moves closer to the bottom of the robot, but otherwise stays the same in other planes. A lower COM in back would mean that in order for the robot to balance it must be pitched forward. In addition, it is clear that the slope is changing in figure 5.2 as a function of step width. This can be accounted for by the way in which the step width is made wider, where the change in height increases as a function of step width, due to the geometry of the leg structure. This is consistent with a human changing step width. Starting with vertical legs, if the legs are made incrementally wider, the height will become increasingly lower for each increment. On the other hand, the position of the COM in a human is dependent on posture, body shape, and size.

For the step width running experiment, 10 runs will be conducted for each step width at a target forward velocity of 1.2 m/s. During each run, data will be collected using the system as shown in figure 5.3. This system includes 6 Vicon 3D motion capture cameras, two high speed cameras, and a Bertek instrumented treadmill. There is no voltage regulator for the battery that is used to power the motors, and it was found that optimal gains were sensitive to voltage, so the voltage for each trial was set between 28 and 29 volts. Voltage was also recorded for each trial, but over a this short voltage range, there was no indication of performance change and thus this information has been omitted.
The inertia of the robot will also play a large role in the stability analysis. As previously discussed, dimensionless inertia criteria will be helpful in evaluating roll stability. Studies have also shown that the intermediate principal axis is unstable [60]. This can be observed by throwing an object in the air that is rotating about the intermediate principal axis, where the rotations will eventually be transferred into rotations about the largest or smallest principal axis. Since certain physical parameter changes may cause the robot to fail, it is helpful to know if the resulting behavior can be attributed to a shift in principal inertial axis.

In order to measure the inertia about each axis, we used a bifilar pendulum as shown in figure 5.4. In order to set up the bifilar pendulum, one must first know the COM of the robot. This can be experimentally determined by balancing the object on a cylindrical rod on a flat level surface. The point at which the object balances represents
the edge of the plane intersecting the CG, and perpendicular to the flat level surface. The strings used to construct the bifilar pendulum, and suspend the object, must be of equal length, equal distance from the COM, and parallel to the axis in question. Once this configuration is achieved, gravity can be calculated by lightly swinging the body in the Z direction as shown in figure 5.4, determining the period of each oscillation, and using

\[ g = \frac{4\pi^2 L_{\text{COM}}}{T^2}. \]  

(5.2)

The length \((L_{\text{COM}})\) is measured from the top of the string to the COM of the object. For each trial we measured the time required for 50 cycles, twice, and averaged them, in order to determine the period \(T\) for each cycle. The calculated value of gravity should be close to 9.81 m/s\(^2\), which helps in determining if the experimental setup is correct. For each setup we calculated gravity within 2%. Our results were always lower than expected, which suggests that other factors such as wind resistance played a roll.

The inertia of each axis was determined by twisting the object a few degrees about the Y axis, the axis of interest, as shown in figure 5.4. Once again, the time to oscillate 50 cycles was measured twice and averaged, in order to determine the period \(T\). This was then used to calculate the inertia of the robot

\[ I = \frac{mgT^2b^2}{4\pi^2L_w}. \]  

(5.3)

where the length used in this calculation is the total length of the string, not the distance to the COM. The results of this experiment are discussed in chapter 5.3.
The procedure for finding the COM and the inertia about each axis can be made difficult by the size and shape of the object. In cases where the object cannot be hung with two equal pieces of string, a hanging tray is implemented, in which case the inertia of the tray can itself be measured and subtracted from the experimental inertia value of the tray with the object on it.
Using the Vicon cameras, we will calculate roll, pitch, yaw, forward velocity, and position of the robot on the treadmill. The data from the Vicon camera system represents trajectories, in 3D space, for each marker located on the back of the robot as shown in figure 5.5. These marker positions are then resolved into yaw, pitch, and roll, using the reference frame as shown below in figure 5.6, and calculated according to the diagram shown in figure 5.7. Position on the treadmill and velocity was estimated using the middle marker and a 2nd order Butterworth filter. The velocity is relative to a fixed frame, so in order to get the total running velocity, it was necessary to add the speed of the treadmill.

Figure 5.5: Vicon Markers.
Figure 5.6: Data Capture Reference Frame.

Figure 5.7: Decomposition of Yaw, Pitch, and Roll.
Using the Bertek instrumented treadmill; we will determine the ground reaction forces in the x, y, and z directions. The Bertek treadmill provides force and moment data about the X, Y, & Z axis, as well as center of pressure (COP) information, relative to the X, and Y axis. However, the treadmill force plates were designed for adult human weights, and the resulting COP data is too noisy. The force and moment data on the other hand can be made quite clean by using a 5th order Butterworth filter. The high speed cameras are aimed at the back and side, so that the source of each disturbance can be documented. Since the robot is supported by ropes before being placed on the treadmill, the data collection for the robot will be cropped, starting when the ropes become visually slack and it is clear that the robot is not being supported.

5.2 Results

Stability of a bipedal running robot is often quantified by the number of steps taken. So to begin, figure 5.8 includes the number of steps achieved for each trial, and grouped by step width. From this graph it is clear that a step width of 44.45cm provides the most stable locomotion. For the RHex trials, the criterion for 100% stable running was marked at 20 steps. Under this criterion, a step width of 44.45cm was 100% stable. The next widest step with of 46.99cm, only 2.54cm wider than the most stable step width, is the least stable.
This is further expressed in figure 5.9, which shows the average number of steps taken for each step width.

Figure 5.8: Number of Steps for each Trial.

Figure 5.9: Average Number of Steps for each Step Width.
However, the failure mode for each run plays an important role in evaluating this information, and the stability of a bipedal robot based on the number of steps. Figure 5.10 lists 7 different types of failure sources, most of which can be attributed to the testing and measurement apparatus used. Disturbances caused by the treadmill include stepping off the treadmill, reaching the limits of the ropes, stepping in between the treadmill tracks, and turning on the treadmill, which effectively trips the robot sideways. Instability failure modes include becoming unstable in pitch, becoming unstable in roll, and “pitching back and then turning”. It is thought that the “pitching back and then turning” failure was caused by the robot crossing over the lower boundary for stable running speeds.

We are unable to consider all potential disturbance sources using this apparatus without running trials that are completely unsupported. The ropes used to lower the robot onto the platform clearly introduce perturbations. The ropes while slack have a tendency to move around, back and forth in an oscillatory fashion while running, and at this point we are unable to determine to what extent the ropes contribute to failure or success. By considering each visually detectible failure mode individually, and excluding all 46.99cm step widths because it is notably unstable, we get figure 5.11, which illustrates the number of trials associated with each failure mode.
Figure 5.10: Failure Modes for All Trials.

Figure 5.11: Failure Modes for Step Widths of 36.83cm to 44.45cm.
From this graph it is clear that for all stable step widths, most failure can be attributed to the treadmill. Out of all 40 trials conducted for 36.83 to 44.45cm step widths, 33 of the failures can be attributed to the treadmill. In fact, if you only consider the trials that exceeded 20 steps or failed due to instability not influenced by the treadmill, and used the 20 step stability criteria [4], you get the percentage of successful trials as shown below in figure 5.12, where all step widths except the smallest, and the largest have a 100% success rate. This implies that the robot may exhibit even greater stability off the treadmill. Further, it suggests that 39.37 and 41.91cm step widths may have had similar pitch stability to the 44.45cm step width, but were less stable in yaw, causing the robot to turn faster and fail earlier due to the treadmill.

Figure 5.12: 20 Step Success Rate, Excluding Failure Due to Test Fixture Constraints.

Testing off the treadmill with a robot of this size and weight, and without any constraints is difficult. Attempting to hold the robot and guide it down a track resulted in too much external influence, and always ended with violent failure. This gives us insight it to what would be required for testing a large running robot on open ground. Starting the
robot off running with the correct initial conditions and very little input disturbance is important. Further, typical bipedal robot designs, including the robot discussed in this paper, are not robust enough to fall on hard ground and survive without some damage.

It may also be possible to increase the stability of the robot by simply changing the way in which the pitch controller is executed. Another source of perturbation includes accumulated error in the speed controller, and drift by the sensor before putting the robot on the treadmill. The robot must be running before setting it on the treadmill. When it is turned on, the controller begins taking effect, and the sensor will slowly begin to drift. In part, the source of this issue stems from a difficulty in adjusting the robots harness to accommodate the exact running angle. The controller is very aggressive, so before the robot can be lowered on the treadmill the controllers begin to make gait adjustments. Once it has been lowered on the treadmill, the state of the controllers is unknown, as there is currently no system set up for collecting this information. It is unknown whether or not this has a substantial effect on the behavior. But because we consistently get stable behavior using this method, it would not be out of line to consider this a minor source of disturbance. In addition, the running gait can typically be partially restrained on the treadmill until it appears to reach some steady state behavior. However, the ability to keep the robot straight during this time period is one of the most difficult tasks during testing, and is entirely dependent on the skill of the person conducting the tests. Minor modifications to the electrical system, and the addition of another slave device intended for recording controller information would shed some light on this problem, and perhaps offer some solutions on how to minimize this disturbance source.

Our lowest stable running speed for the configuration used was approximately 1.05m/s, and our highest speed possible before gait failure was around 1.6m/s. This left us with a fairly small window in which the robot could accelerate and decelerate without entering an unstable speed region. During the trials, the result of these limits were most clearly observed when the robot pitched back to slow down and crossed over the threshold into an unstable region and failed by turning and tripping sideways. This is because our target speed was closer to the lower speed threshold than the upper. This indicates that future studies which address the stable speed regions would be of great
value. This approach may include determining methods for expanding on the stable regions, modifying the motor and gearbox so that the upper limit of stable running speeds can be studied with this length leg, or increasing leg length so that the running velocity increases.

On the other hand, some of the most stable behavior during trials was observed when the robot was pitched forward and accelerating. This behavior was consistent for all step widths. The robot never became unstable when in this particular mode, unless the max speed was exceeded, resulting in gait failure. There are a number of factors that may have played a role in this behavior. These factors include a lower COM relative to the treadmill, increased speed, and a varying gait frequency. It is currently unknown which of these factors contribute to the increased stability. The contribution that varying frequency has to stability may include the inhibition of constructive interference due to the leg stiffness, hip stiffness, and running frequency.

One of the most interesting results is the difference in stability between 44.45 and 46.99cm step widths. As the step width increases, the trials revealed an increase in roll stability for all step widths. Pitch stability also appeared to increase slightly as a function of step width, until the largest step width of 46.99cm, at which time pitch became completely unstable. With a step width of 46.99cm, there were no set of gains capable of stabilizing the robot using the same controller and gait cycle. It has been considered that the source of this instability may be a change in the principal moments of inertia. It has been shown that a rigid body rotating around its intermediate principal axis is unstable [60]. It was thought that perhaps the order of the principal axis were changing at the largest step width, causing failure. However, upon further inspection, it was determined that for all step widths used in this study, the smallest principal axis is yaw, the intermediate axis is pitch, and the largest principal axis is roll as shown in figure 5.13. The order of these principal moments of inertia for our robot coincide with RHex’s. However, pitch and yaw inertia values do appear to be converging as step width becomes wider as shown in figure 5.13. Studies concerning the stability of principal axis focus on aerial summersaults, and do not include the influence of ground reaction forces.
Figure 5.13: Inertia of the Bipedal Robot in Roll, Pitch, and Yaw for all Step Widths.

It was also considered that the pitch instability could be the result of a slightly lower COM, caused by spreading the legs, which is more difficult to balance [64]. However, the COM only changes by approximately 1 cm. This problem presents a good application for simulating the dynamics, where the source of instability for this wide step width might be identified. A comparison between the model and the physical system could lead to the construction of a more precise model. A planar model would likely not suffice for such an analysis, because the nature of this failure may be entirely based on the coupling of all three planes. Thus, a rather involved 3D simulation may need to be designed based on a highly nonlinear system, which has proven to be difficult.

Another way that stability as a result of step width can be explored is by observing the ground reaction forces and position data from each trial, and comparing them to a baseline run. The most consistent and longest run is shown in figure 5.14 and 5.15 has been cropped to 5 seconds in order to show the details for a consistent and
periodic baseline running gait. The red line represents the left leg and the green line represents the right leg.

Figure 5.14: 44.45 cm Step Width Trial 7 Result: (a) Right and Left Leg "X" ground reaction forces (b) Right and Left Leg "Y" ground reaction forces (c) Right and Left Leg "Z" Ground Reaction Forces (d) Position on Treadmill over 5 Seconds.
Comparing the baseline graphs to all 50 trials gives us insight on the influence of step width. When considering the form of these graphs for all trials and step widths, certain characteristics remain constant. For instance, the waveforms exhibited by the ground reaction figures 5.14 a, b, and c, are consistent for all stable running gaits. They may change in magnitude or be distorted as a result of a disturbance or instability, but are otherwise the same. From figure 5.14c, we can observe that there is in fact no double flight phase for steady state conditions. This is not consistent with the definition of running, and thus this robot it actually fast walking. However, this was to be expected as
bipedal RHex exhibited the same behavior and no changes have been made that would introduce a flight phase. However, during unstable behavior, and especially during the parameter tuning phase, occasional modes similar to trotting would occur, and a double flight phase would emerge. This behavior was not easily repeatable; however, this leaves room for experimenting with radial forcing, foot shape, or hip rotation, which may induce flight.

![Figure 5.16: 44.45cm Step Width Trial 7 Stance Phase](image)

The profiles of the measured ground reaction forces, as shown in figure 5.16, are similar in shape to the human ground reaction forces shown in figure 2.5. However, the vertical ground reaction force profile exhibits characteristics more similar to toe running, where the data in figure 2.5 is based on heel to toe running. Further, the peak force occurs early in the stance phase in comparison to biological data. The vertical ground reaction force is the dominant force. The anterior-posterior “Y” ground reaction force data exhibits a similar shape to the biological data, but the magnitude is slightly high. For the biological data, the peak force in the “Y” direction is 15% of the vertical peak force “Z”, and for the experimental data, the peak force in the “Y” direction is 23% of the vertical peak force “Z”. The medial lateral “X” ground reaction force data also exhibits a similar shape to biological data, but the magnitude is very high. For the biological data the peak force in the lateral “X” direction is 6% of the vertical peak force “Z”, and for the
experimental data, the peak force in the lateral “X” direction is 57% of the vertical peak force “Z”. These high lateral forces explain the importance that legs with low lateral deflection have to this particular robot configuration.

Roll, as shown in figure 5.15a, exhibits the least amount of movement, and oscillates only slightly in a sinusoidal fashion. This indicates that roll is the most stable parameter. Pitch and running velocity on the other hand are not periodic; expressing that for this robot the controller is absolutely necessary in order to maintain stability for what would otherwise be a highly unstable axis. Yaw exhibits highly sinusoidal behavior consistently for all step widths. Yaw instability cannot single handedly cause the robot to fall, because an asymmetric yaw oscillation would merely cause turning. Yaw will need to introduce disturbances to pitch and roll. This behavior was most prominent during the smallest step width trials of 36.83cm.

The already large lateral “X” ground reaction force increased as a function of step width while the forces in the Z and Y direction remained relatively constant for all step widths. When comparing the “X” ground reaction forces in figures 5.17 and 5.18, for 36.83 and 46.99cm step widths, there is a clear difference in the magnitude.
With a step width of zero, the lateral forces should also be near zero. By reducing the step width and actively stabilizing the robot in roll using the upper body, it may be possible to approach more human like ground reaction force data. This is directly supported by the biological data as discussed in chapter 2.2.1, where smaller step widths reduce the
moment about the COM and effectively direct most of the force in the vertical and forward direction, while lateral forces remain small. When comparing the roll graphs shown in these figures, the smaller step width has smoother characteristics. Roll stability should become greater as a function of step width, because the inertia increases, the dimensionless inertia decreases, and the required tipping force becomes greater. However, the larger oscillations in roll exhibited by the largest step width could contribute to failure in other planes due to dynamic coupling.

There was only one roll failure observed during this study, and it was for the smallest step width. This run is as shown in figure 5.19. The way in which it failed is interesting because roll exhibits very typical unstable behavior. You can observe how the oscillations form in roll as the first disturbance input, and increase exponentially, affecting other axis as it increases in amplitude. The frequency of the gait, the frequency of the legs, and the body dynamics work together to form constructive interference which builds and causes failure.

This is supported by the dimensionless inertia calculated for each step width as shown in figure 5.20, where the dimensionless inertia value for the smallest step width is greater than 1, suggesting that active stabilization is required.
The ground reaction forces as a result of roll failure are high in the Z direction as shown in figure 5.21. This information will aid in improving the performance of the next leg design. In some cases low stiffness has shown to act as a filter for higher frequency vibration [63]. However, as discussed in the design section of this thesis, the leg strength using the current design is about as low as you can go without breaking. On the other hand, it may be possible to lower the stiffness further by employing a non-uniform leg thickness, thicker in areas of high stress and thinner in areas of low stress. However, this will no doubt result in more difficult to predict stiffness values. The fracture lines exhibited in two of the four legs used in trials are likely the result of a fatigue and high shock, like that shown in figure 5.20. If the fracture lines are a result of high shock, then it may be possible to incorporate dampeners that absorb some of the energy at impact, and allow for a lower stiffness leg design, using the current design methodology.
Figure 5.21: 36.83cm Step Width Trial 10 Results: Right and Left Leg “Z” Ground Reaction Forces.

The stability of pitch is consistent for all step widths from 36.83 to 44.45cm using the same gain values. This makes sense, as from the basic theory (simple models) we expect yaw and roll to be directly affected by step width, but not pitch. A change in step width will increase the distance from the midline of the body and thus increase the moment due to ground reaction forces for both roll and yaw. Pitch on the other hand is mostly affected by the position of the leg normal to the plane in which step width increases, which is defined by a running gait that is consistent for all step widths studied. However, the largest step width fails in pitch. Ground reaction forces in more stable planes, and the dynamic coupling of these planes, may contribute to unstable behavior in plane relatively unaffected by the parameter change. The unstable behavior of pitch for the widest step width is shown in figure 5.22, where roll and yaw are also clearly affected.
Figure 5.22: 46.99cm Step Width Trial 10 Results: (a) Yaw (b) Pitch (c) Roll.

For smaller step widths, yaw has a tendency to turn more as shown in figure 5.23. Keeping the robot straight becomes easier as the step width increases. This is an indication of decreased yaw stability for smaller step widths. This is despite the fact that the magnitude of the yaw oscillations remain relatively constant throughout all step widths. However, it was discussed in chapter 2.2.1 that arm swinging effectively reduces yaw oscillations, and should result in more stable locomotion at smaller step widths where yaw appears to be a disturbance source. This is supported by information released by Honda concerning the effects of arm swinging on robot locomotion.

Figure 5.23: 36.83cm Step Width Trial 7 Results: (a) Yaw (b) Pitch (c) Roll.

Yaw pitch and roll all exhibited robust stability on an individual basis for many trials, but when failure occurs about one axis, it often cascades to all other axis, resulting in failure, as exhibited by figure 5.24. These results express the importance of studying
unconstrained 3D biped dynamics. If pitch yaw and roll dynamics of this robot were individually studied through constrained models, it may not accurately represent the same dynamics exhibited when these three axis are coupled, using a 3D robot.

Figure 5.24: 36.83cm Step Width Trial 5 Results: (a) Yaw (b) Pitch (c) Roll.
6. SUMMARY

The purpose of this thesis is to make advances in the design of humanoid bipedal running robotics. This was primarily achieved by investigating the effects of foot placement in the transverse plane, via movement of the hip in the sagittal and coronal planes. The investigation of foot placement in the sagittal plane was achieved by designing a leg angle controller for a planar running model. The investigation of foot placement in the coronal plane was achieved by designing and constructing a bipedal robot, which was subsequently used to experimentally determine the effects of step width. For all studies conducted in this thesis, a formal biological and robotics review was used to shed light on the features most important to stable bipedal running.

During the biological review it was suggested that roll stability in human running can mostly be attributed to movement of the upper body, which makes smaller and more energetically favorable step widths possible. Pitch stability may also be dependent on some upper body movement in the sagittal plane to counteract the torque of the legs, but due to the way in which the body is propelled: acceleration, deceleration, stiffness, dampening, and leg angle in the sagittal plane play key roles. Many of the studies also suggest that passive compliant mechanisms play an integral role in locomotion, which has already been exploited by most of the bipedal running robots reviewed in this thesis. In fact, this principal has been extended to improve the performance of amputee running prosthetics by incorporating springy legs which employ a leg shape that effectively simulates radial forcing of the ankle. Further, above knee amputees have shown us that stable locomotion can be achieved with no moving joints below the hip. Springy legs, upper body movement, and fully articulated hip joints are all that is required.

The contribution of foot placement, in the sagittal plane, to stable planar locomotion was explored through simulation in chapter 3. The model used FD-SLIP as a base, and a PI controller that changed the leg touch down angle $\beta$, using the energy state
of the system while entering the flight phase, as feedback. This controller takes advantage of a constant dampening coefficient in FD-SLIP by changing the leg touch down angle in order to absorb less energy in cases where more energy input is required to reach steady state and absorb more energy in cases where less energy input is required to reach steady state.

In chapter 4 a bipedal running robot was designed for progressively studying the influence of biologically inspired mechanisms on a bipedal robot running gait. The final design decisions were based on the biological review, the robotics review, criterion that is conducive to autonomous 3D robotics, and an ability to conduct progressive studies. Furthermore, the bipedal running robot research platform presented in this thesis is designed to eventually make the transition from a basic 1DOF bipedal running robot to a more biologically accurate representation of a four year old running child.

Using the bipedal running robot, a study was conducted in order to determine the effects of step width in the coronal plane on running. The motivation for this study was a biological hypothesis that suggests there is little need for active control in lateral balance using the legs, due to a narrow step width and upper body movement. A 1DOF per leg 3D biped robot relies on a wide step width for balance in roll, so understanding the behavior of this gait provides insight for the design and implementation of additional upper body features that will allow us to move towards a more biologically correct running robot with a smaller step width.
7. CONCLUSION

Chapter 3 explores the effect of hip rotation, in the sagittal plane, on running. This is achieved by designing a controller for FD-SLIP, an existing planar running model which utilizes a constant torque and dampening. The controller effectively mimics the motion of a human attempting to adjust speed rapidly, or recover from a perturbation. This controller effectively reduces the time required to recover from a perturbation and reduces the overall energy expended recovering from a perturbation. This controller also allows for increased stability at higher velocities and allows the model to operate at torque values 48% lower than unmodified FD-SLIP.

The bipedal running robot presented in chapter 4 is designed to eventually make the transition from a basic 1DOF bipedal running robot to a more biologically accurate representation of a four year old running child. This includes height, weight, center of gravity, power output of the hips, and selected joint locations. This simple, lightweight, and powerful research platform can easily be expanded on in order to explore running robot parameters progressively. The final light weigh carbon fiber leg design for this robot includes low radial stiffness and high lateral stiffness. Cycling of the legs along with large radial forces in excess of 300N, throughout nearly all of the testing, eventually caused the legs to exhibit some signs of stress.

Chapter 5 explores the effect of step width on a 3D bipedal running robot. First, controller gain values and suitable pitch angles were found for the range of step widths used in the experiment. The pitch angle changes for each step width due to a change in position of the COM, whereas the ideal gain values for the pitch controller were identical for all step widths except for the widest step width, for which no stable gains could be found. The widest and most unstable step width was only 2.54cm wider than the most stable step width. To make matters more interesting, the main failure mode for the widest step width was pitch. It was thought that this could be explained by a change in the order
of the principal moments of inertia, because for ballistic motion, the intermediate axis is unstable. However, it was found that the intermediate principal axis (pitch) and the lower principal axis (yaw) approached one another but did not cross. The inertia values listed do not include ground reaction forces, which may also play a role, and increased as a function of increasing step width. It was also considered that the pitch instability could be a result of a slightly lower COM, caused by spreading the legs, which is more difficult to balance. However, the COM only changes by approximately 1cm.

Due to the size, weight, and robustness of the robot, it was not feasible to conduct initial studies on the ground, so a treadmill was used. The downside of this was that most of the failures can be attributed to the treadmill. If failure due to the treadmill was excluded, all step widths studied, except for the widest and the narrowest, have a 100% success rate under the same criteria used for bipedal RHex.

The ground reaction force profiles during the stance phase are consistent for all stable step widths, and show a striking resemblance to the ground reaction force profiles of toe running. However, when considering the magnitude of these forces, the lateral forces exhibited by the biped robot were much too high when compared to biological data. For the biological data, the peak force in the lateral direction is 6% of the vertical peak force, and for the experimental data, the peak force in the lateral direction is 57% of the vertical peak force. These high lateral forces explain the importance that legs with low lateral deflection have to this particular robot design. Further, this result is directly supported by the biological data, where smaller step widths reduce the moment about the COM and effectively direct most of the force in the vertical and forward direction, while lateral forces remain small. However, the smallest step width did not exhibit 100% stable behavior. It was shown that the smallest step width had a dimensionless inertia greater than 1, making passive stability more difficult to execute. Further yaw instability for the smallest step often results in turning. This behavior is consistent with information from the biological and robotics review which suggests that arm swinging is required at higher speeds and smaller step widths where friction is no longer sufficient to overcome yaw oscillations.
The current running gait does not exhibit a double flight phase during steady state conditions. This is not consistent with the definition of running, and thus this robot is actually fast walking. However, this was to be expected as bipedal RHex exhibited the same behavior and no changes have been made that would introduce a flight phase. However, during unstable behavior, and especially during the parameter tuning phase, occasional modes similar to trotting would occur, and double flight phases were observed.
8. FUTURE WORK

When designing an experimental robot, a number of assumptions must often be made. During the design of the robot discussed in chapter 4, it was unknown what kinds of forces and torques the motors and gearboxes would experience and if the mechanisms responsible for stable locomotion in RHex would scale up to larger and heavier robot. Further, weight was a major factor in the selection of the motors and gearboxes, because they are by far the heaviest components. Although the final design worked, some small changes to the design may increase its capabilities substantially.

First, the motors and gearboxes for actuating the hips of this robot in the sagittal plane were chosen based on the leg length, running speed, and hip torque of a four year old girl. However, in order to approximate the conditions under which bipedal RHex was stable, shorter legs were used. This meant that the top running speed was reduced. Further, during preliminary trials it was also found that this robot was not stable for lower running speeds. This severely limited our running speed range from 1.05 to 1.6 m/s when using a circumduction gait. Preliminary experiments with an above knee amputee inspired gait was also explored. This gait uses abduction/adduction instead of circumduction in order to provide ground clearance, which is consistent with above knee amputee running. However, these experiments revealed that the current sagittal plane hip motors were incapable of reaching the desired position in time at TD, because the hip has to change direction twice during flight in the sagittal plane. Thus future design modifications for the robot may include another set of gearboxes with a higher gear ratio or faster motors, so that higher running speeds can be achieved with a short leg, and adduction/abduction based gaits can be implemented. The low gain values required for stable running barely track position of the gait cycle. This delicate balance of control and low stiffness suggests that passive mechanisms in series with the sagittal plane hip
motors could help improve the performance of this robot by reducing the loads experienced by the motors and conserving energy when changing direction.

The motors and gearboxes that actuate the second DOF at the hip in the coronal plane on the other hand appear to be capable of introducing ground clearance via abduction/adduction in the coronal plane for an above knee amputee inspired gait. Though formal studies using this degree of freedom have not yet been formally explored. Due to the high gear ratio of the gearboxes that are responsible for movement in the coronal plane, the gearboxes are not easily back driven. This means that they are great for holding position, but offer little if lower stiffness properties are desired.

Most of the failure modes experienced during the step width study discussed in chapter 5 were due to the treadmill. Due to the size, weight, and robustness of the robot, it was not feasible to conduct initial studies on the ground. This suggests that it is important to design robots for falling, so that off treadmill runs can be conducted, in which case stability can be more accurately assessed. Other failure modes, not due to the treadmill, suggest that 3D coupling between roll pitch and yaw planes play an important role in analyzing the stability of bipedal robot running locomotion. This expresses the importance of investigating 3D bipedal robotics, where it would be impossible for a planar biped to exhibit many of the observed failure modes.

Low stiffness of the legs and the sagittal plane hip motor controllers has shown to be crucial for stable locomotion with the robot design presented in chapter 4. The legs used in the design exhibited signs of stress after all trials were complete. In order to further reduce the stiffness of the legs, future design considerations may include dampeners to absorb large shocks, and a non-uniform composite layer thickness along the length of leg, thicker in areas of higher stress concentration. Dampening may also aid in disturbance rejection, and could be used to take advantage of the model designed in chapter 3.

Small step widths also exhibited yaw instability during the study conducted in chapter 5. Biological studies suggest that arm swinging plays a large role in stable running. Simulations have shown that the torque caused by arm swinging is substantial enough to inhibit yaw rotation in situations where ground friction is sufficient. It has also
been reported by Honda that arm swinging and upper body movement was necessary for faster running speeds. Further, it has been suggested that arm swinging can be approximated using simple pendulums. Thus, experiments with passive and active arm swinging would be of great value to understanding yaw stability and working towards achieving smaller step widths.

Biological studies also suggest that the upper body plays a lead role in the stability of human running, and allows for humans to run with a small step width. Pitching the upper body counteracts the angular momentum of the legs during flight. Further, hip and pelvis movement in the coronal plane plays the largest role in positioning the upper body, acts to absorb shock, provides foot clearance, and has been shown to be one of the most important mechanisms for decoupling the lower body motion from upper body motion, allowing balance to be maintained. Results from the experiment shown in chapter 5 further support the need for upper body movement in order to achieve smaller step widths. Thus, future modifications to the robot should include mechanisms for investigating the effects of upper body pitching.

Finally, the bipedal robot discussed in chapter 5 does not exhibit a double flight phase, which is not consistent with human running. Mechanisms that may induce a flight phase include a knee or linear actuator to extend the leg during the stance phase and introduce radial forcing, a J shaped leg designed to simulate forcing of the ankle, and upper body pitching.
LIST OF REFERENCES
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