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Dynamic viscoelastic model of the Hydro Muscle and the control of a multi-fiber Hydro Muscle actuated bionic ankle

by

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Declaration of Authorship

I, Chinmay Harmalkar, declare that this thesis titled, 'Dynamic viscoelastic model of the Hydro Muscle and the control of a multi-fiber Hydro Muscle actuated bionic ankle' and the work presented in it are my own. I confirm that:

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Abstract

The Hydro Muscle is a soft linear actuator which utilizes hydraulic pressure and elastic properties of its core for actuation. The Hydro Muscle has been recruited to actuate bio-inspired robot systems using a classic set point tracking feedback control system. A more efficient method is to develop a model-based control system which uses a dynamic model of the Hydro Muscle. The dynamic behavior of the Hydro Muscle which describes the relation between the forces exerted to the resultant motion can be studied with the help of a dynamic viscoelastic model. A dynamic viscoelastic model defines the force exerted by the Hydro Muscle as a function of the hydraulic pressure, the tensile expansion of the Hydro Muscle and the rate of its tensile expansion. Multivariable linear regression is employed to generate a model to relate fluid pressure, tensile expansion, and the rate of tensile expansion to the force exerted by the Hydro Muscle. The developed model can be utilized to implement a model-based control algorithm for the force control of individual joints. This model based control design could be extended to systems involving multiple Hydro Muscles to allow for a modular control system. The design and test of multi-fiber Hydro Muscle actuated biologically inspired ankle is considered to study control strategies for multi-fiber system. A set-point tracking control algorithm with a proportional differential controller is used to minimize the tracking error. Modular force variation with sequential recruitment of Hydro Muscle is studied.

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Chapter 1

Introduction

1.1 Hydro Muscle

The Hydro Muscle is a soft actuator[1] powered by hydraulics or pneumatics to achieve the desired actuation. The core of the Hydro Muscle structure is a latex tube. It is covered by a non expansive sheathing which restricts the radial expansion of the Hydro Muscle while allowing it to expand axially. The expansion of the Hydro Muscle is due to a combination of elastic nature of the core and the fluid pressure. The relaxation is due to the elastic properties of the core as seen in figure 1.1.

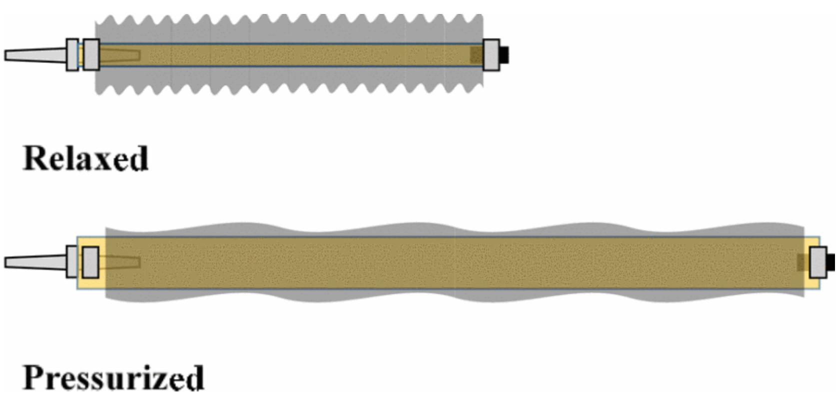

FIGURE 1.1: Hydro Muscle sketch when pressurized and relaxed

1.2 Viscoelasticity

Viscoelasticity is a property of materials which exhibit both elasticity and viscosity. Elasticity is the property of a material to return back to its original shape after being deformed. Viscosity is the property of a material to provide resistance to the shear or tensile force experienced during its deformation. Viscoelasticity is characterized by noticeable changes in the stress-strain characteristics of a material during the loading phase and during the relaxation phase. This is shown in figure 1.2. Hydro Muscle is categorized as a viscoelastic solid[2]. The modeling of the Hydro Muscle would help to correlate the force exerted by the Hydro Muscle to the hydraulic pressure, the elongation and rate of elongation.

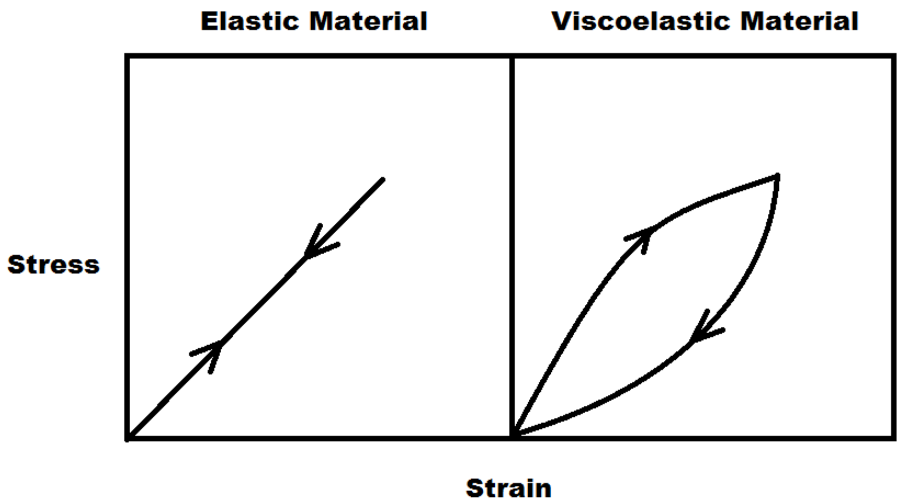

FIGURE 1.2: Stress vs Strain plot of elastic and viscoelastic materials

1.3 Motivation

The robotic systems involving Hydro Muscles have been controlled using control strategies which involve tracking error from a set point and applying a Proportional Derivative(PD) control system[2] to reduce this error. These control strategies, though effective, do not take into consideration the physical properties of the system for the design of the control algorithm. A more elegant and accurate method to design a control strategy would require the solution to the inverse dynamics of the Hydro Muscle. This motivates the development of a viscoelastic model of the Hydro Muscle which would allow for an improved understanding of the dynamics of a Hydro Muscle when it is subjected to fluid pressure. Such a model can be extended to determine the dynamics of systems involving multiple Hydro Muscles actuating a single joint(see Appendix A).

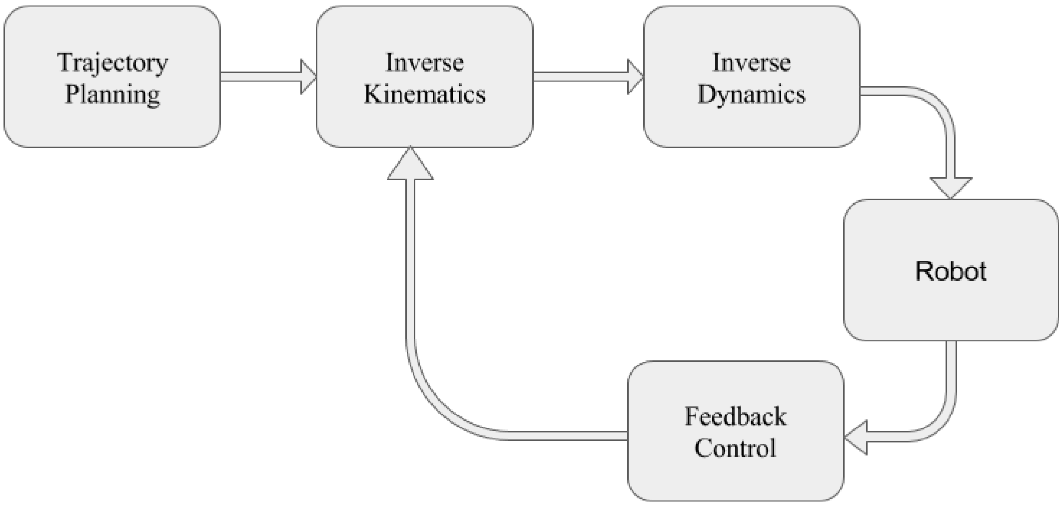

Figure 1.3: Feed-forward Control system using inverse dynamic model for control

Position and force control strategies implemented for the Hydro Muscle would utilize this dynamic model to solve the inverse dynamics. The solution would yield the input required to manipulate the Hydro Muscle to reach its desired goal state. Figure 1.3 illustrates a generic feed-forward system utilizing the dynamic model of the robot and feedback from its current state to send the required signals to reach its goal.

1.4 Model-Based Control

Model-Based Control involves the use of a mathematical model of a system to accurately estimate the control parameters to drive the system to a desired state. The process of model-based design goes through the order of modeling, synthesizing a controller, simulation and testing and finally, deployment. This method helps define driving and driven parameters[3]. The driven parameters are controlled using active control elements in the system e.g. in a system that has a motor as its actuator, the active control elements, motor speed and motor torque are controlled using source voltage and current. The driven parameters are affected by the values taken by the driving parameters e.g. position, velocity of the end effector.

The Hydro Muscle being a viscoelastic element, dynamic mechanical analysis should be used to obtain the structural model. This model would accurately describe the extension and relaxation of the Hydro Muscle. In addition to the physical properties of the Hydro Muscle, the properties of the experimental assembly should be taken into consideration when developing the model. These properties include friction between mobile surfaces including pulleys, the viscosity of the hydraulic fluid, and the friction between the sheathing and the latex core of the Hydro Muscle. Individually, these effects can be compensated by a robust controller, but the additive effect may lead to large errors in viscoelastic modeling.

An effective method is to model this cumulative friction [4] and negate its impact on the process of developing the viscoelastic model. The resultant viscoelastic model would explain the force of the Hydro Muscle as function of its elongation, rate of elongation, and the hydraulic pressure in the system. It may be used to design inverse dynamic control strategies for the Hydro Muscle.

1.5 Overview

Here, the development of a viscoelastic model for the Hydro Muscle which takes into consideration the effect of dynamic forces is described. This model may be utilized to execute a model-based control system for a robotic knee joint. Chapter 2 illustrates the derivation of a purely mathematical dynamic model based on the analytical physical equations governing the actuation of the Hydro Muscle. Chapter 3 covers the viscoelastic models previously used to represent the behavior of the Hydro Muscle. It introduces the concept of dynamic loading and the need to deviate from traditional creep and stress relaxation tests. In chapter 4, the development of the dynamic viscoelastic model for the Hydro Muscle is summarized. The validation of the model on a robotic system is the subject of chapter 5. Chapter 6 depicts the design and test of a biologically inspired multi-fiber Hydro Muscle actuated ankle. Chapter 7 gives a brief conclusion and proposes future consideration for the development of an absolute model.

Chapter 2

Mathematical Model

The mathematical model is an analytical model of the Hydro Muscle. This model takes into consideration only the primary physical forces which are responsible for the elongation and relaxation of the Hydro Muscle. This model does not examine the viscoelastic nature of the Hydro Muscle.

The Hydro Muscle uses the hydraulic force of the fluid for its tensile expansion. The core of the Hydro Muscle stores energy during its expansion in the form of elastic potential energy. The evacuation of the hydraulic fluid from an elongated Hydro Muscle leads to the instant release of energy stored in the elastic core. The core retracts to its original state with this energy at a faster rate than its expansion. This retraction is the primary source of actuation in robotic systems recruiting a Hydro Muscle.

As described earlier, the extension of the Hydro Muscle is the combination of the stiffness of the core resisting the hydraulic pressure and storing energy in the process. The physical equation which describes the expansion of the Hydro Muscle is as follows -

$$ma = (P - P_{atm})A - kx \tag{2.1}$$

Here, m represents the mass of water in the Hydro Muscle, a is the acceleration of the mass of water entering the Hydro Muscle, P is the gauge pressure of the water before entering the Hydro Muscle, P_{atm} is the atmospheric pressure, A is the cross-sectional area of the Hydro Muscle, k is the stiffness co-efficient of the Hydro Muscle core, and x is the axial tensile elongation of the Hydro Muscle along its length.

The contraction involves the release of the elastic potential energy stored in the Hydro Muscle core. The physical equation depicting the retraction of the Hydro Muscle is as follows -

$$kx = ma \tag{2.2}$$

Here, m represents the mass of water inside the Hydro Muscle, a depicts the acceleration of the mass of water as it exits the Hydro Muscle.

2.1 Model Parameters and Description

The state of the Hydro Muscle is specified by the hydraulic pressure, acceleration, velocity, and the elongation at the mobile end of the muscle. The dynamics are modeled for the contraction of a single Hydro Muscle, initially extended to a known length and then allowed to contract by releasing the pressure in the muscle.

An experiment is simulated to develop the mathematical model. The figure 2.1 depict the simulated experimental setup. A Hydro Muscle of known dimensions is fixed to a testbed at one end. A known mass is suspended from the free end of the Hydro Muscle. At this point, the Hydro Muscle is elongated using a known hydraulic pressure. The experiment begins when the fluid in the Hydro Muscle is allowed to evacuate through a simulated valve, which results in its relaxation. The

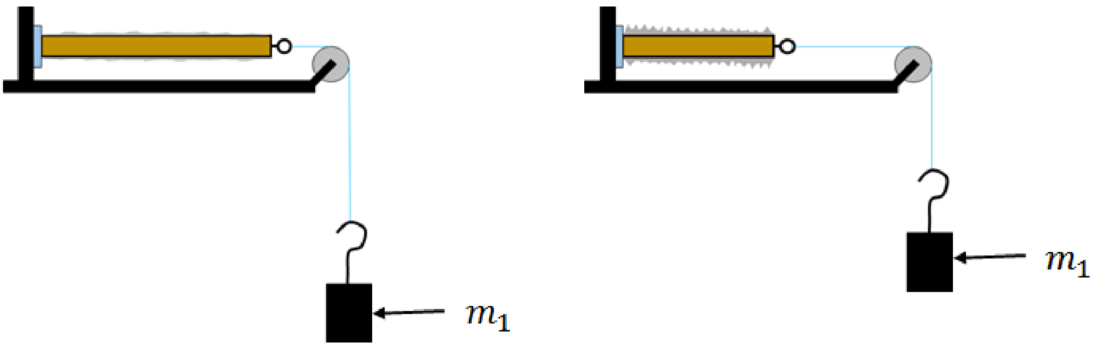

FIGURE 2.1: Initial state of the experiment(left) and final state of the experiment(right)

experiment terminates when the Hydro Muscle reaches equilibrium. The mass suspended from the free end of the Hydro Muscle is $10kg$ ($22lbs$). The relaxed length of the Hydro Muscle is $0.165m$ ($6.5in$). The stiffness coefficient k=5,885N/m ($33.6lbf/in$) of the hollow latex core of the Hydro Muscle is experimentally obtained. The inner diameter of the latex core is $2.54cm$ ($1in$) and outer diameter is $0.0381m$ ($1.5in$). The maximum radial expansion of the Hydro Muscle is equal to the inner diameter of the sheathing which is measured to be 0.0559 m (2.2 in). This makes the cross section area of the muscle to be $0.0014m^2$ ($85.4in^3$). The inner diameter of the valve is $0.02m$ ($0.8in$). This makes the cross sectional area of the valve to be $3.017 * 10^{-4}$ m^2 ($18.4in^2$). The stopping condition for the model is considered to be the point at which the muscle reaches its relaxed length. The model assumes water to be a non-viscous, incompressible fluid, and the Hydro Muscle does not have a damping factor. The simulation is conducted for two different arrangements, one in which the valve is completely opened instantaneously, the second in which the area of the valve is increased at 1% per millisecond.

The experimental setup changes equations 2.1 and 2.2 respectively as follows -

$$(m + m_1)a = m_1 g + (P - P_{atm})A - kx \tag{2.3}$$

$$(m + m_1)a = kx - m_1 g \tag{2.4}$$

Here, m_1 is the mass of $10kg$ suspended from the tip of the Hydro Muscle, g is the acceleration due to gravity. These equations combined with Bernoulli's equation of energy conservation in fluids allow the use of numerical methods to obtain the mathematical model. Bernoulli's equation is as follows -

$$\rho g h_m + \frac{1}{2}\rho v_m^2 + P_m = \rho g h_v + \frac{1}{2}\rho v_v^2 + P_v \tag{2.5}$$

Here, the h_m, v_m, and P_m represent the height of the fluid in the system providing potential fluid energy, the velocity of the Hydro Muscle, the fluid pressure in the Hydro Muscle respectively. h_v, v_v, and P_v represent the height of the fluid in the system providing potential fluid energy, the velocity of fluid at the valve, the fluid pressure at the valve respectively.

The mathematical model is developed using one of the primitive numerical methods called the Euler linear multistep method. The Euler linear multistep[5] method involves introducing a small but finite increment in the current state of the system to calculate the next state. The Euler method needs pre-requisites in the form of boundary conditions i.e. the initial state and the final state of the system which have been defined earlier. The results of the simulation are in the following section.

2.2 Results

The elongation of the Hydro Muscle never becomes 0. This is due to the mass m_1 which is suspended from the tip of the Hydro Muscle. The results show that the time taken for the Hydro Muscle to reach its relaxed state is approximately 67 milliseconds when the valve is opened at the rate of 1%/ms. This value is slightly

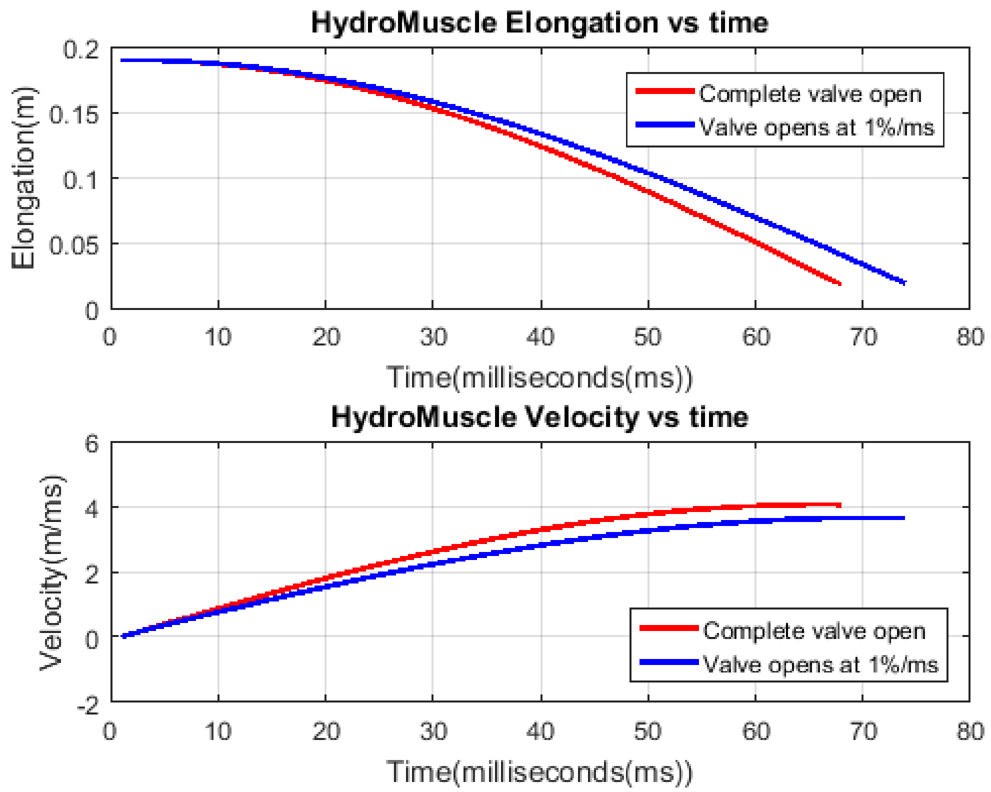

Figure 2.2: Mathematical model simulation of elongation and velocity of a Hydro Muscle during relaxation

higher than the time taken by the Hydro Muscle to reach equilibrium when the valve is opened completely as shown in figure 2.2. This is the result of higher flow rate in the former scenario as the valve area allowing water evacuation is higher. Similarly, the velocity attained by the Hydro Muscle is higher when the valve is completely open. The pressure of water in the Hydro Muscle rises instantly when the valve is opened at a slower rate as seen in figure 2.3. This can be directly attributed to Bernoulli's equation of energy conservation in fluids.

2.3 Inference

The model gives simulated results which are observed in a system without motion resisting any contact forces such as friction and viscosity. To develop a robust model the following must be taken into consideration -

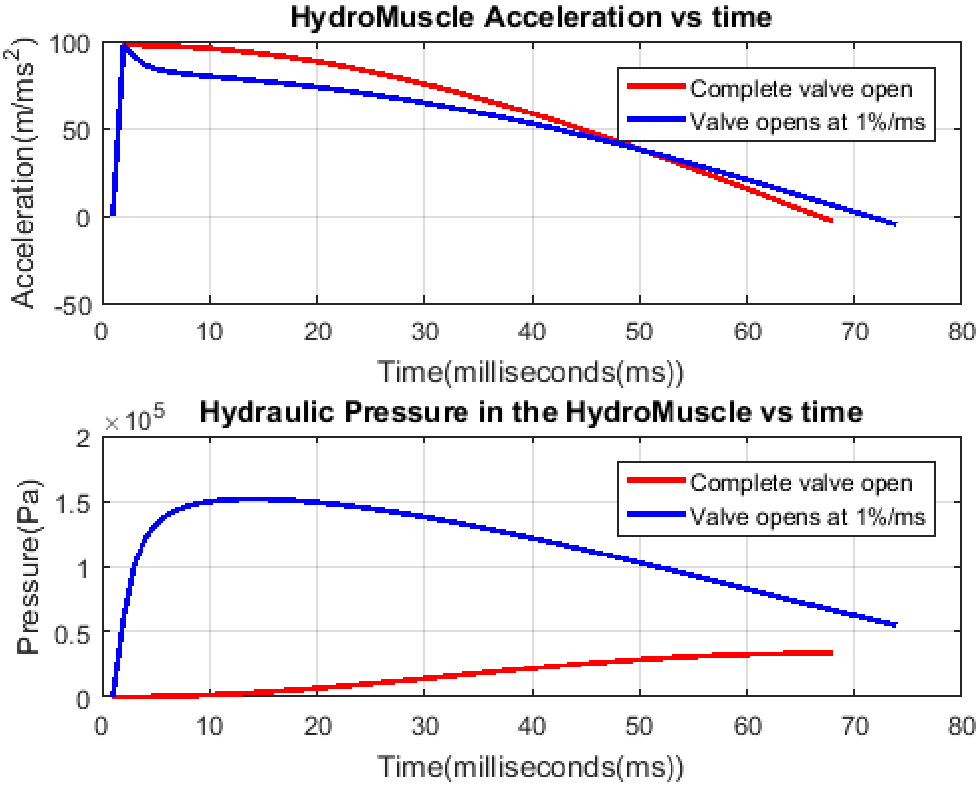

FIGURE 2.3: Mathematical model simulation of acceleration and pressure of a Hydro Muscle during relaxation

- The viscosity of the hydraulic system should be considered.
- The friction in experimental set up should be modeled.
- The variations in the hydraulic pressure source should be accounted for.

These factors are not negligible as their effect increases with the size of the Hydro Muscle used. The combination of all the above factors can cause a significant effect on the mathematical model.

Chapter 3

Standard Viscoelastic Models

Standard Viscoelastic Models use a combination of newtonian dash-pots and hookean springs to depict the viscoelastic properties of a material[6]. The dash-pot is an ideal viscous damper and the spring is considered an ideal elastic element. To obtain specifications of such a combination, the long term(time>2 hrs) effects of constant tensile stress are observed on a material. This is called a creep test. Similarly, a stress relaxation test is also conducted which evaluates the reduction in stress at a constant strain. The combined data from these tests is used to determine the model parameters and thus define the viscoelastic properties of the material.

3.1 Standard Linear Solid Model for Hydro Muscle

The viscoelastic models for the Hydro Muscle have been developed using the stress relaxation and creep tests. The experiments were conducted on the latex core of the Hydro Muscle. In addition to this, a stress-strain analysis was conducted based on the latex core being subjected to varying strain rates. The acquired data have been used to develop a Standard Linear Solid(SLS) Model of the latex core of the Hydro Muscle.

The SLS model is as shown in figure 3.1. It comprises of two parallel branches. One of the branches includes a single elastic spring. The other branch has a spring and a dash-pot in series[7].

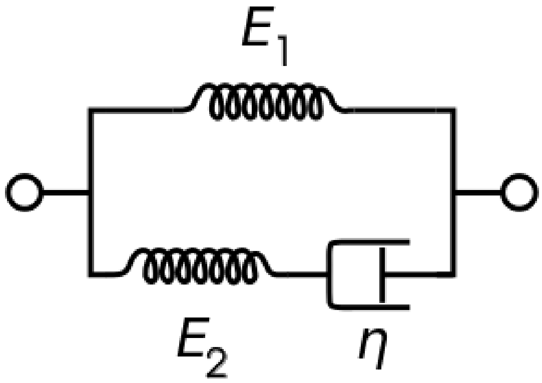

FIGURE 3.1: Standard Linear Solid Model as a combination of ideal elastic springs and viscous dash-pots

The SLS model helps analyze prolonged operation of robotics systems recruiting Hydro Muscles. Although this model explains the behaviour of the latex core of the Hydro Muscle as a viscoelastic material, a dynamic viscoelastic model is required to understand the effect of dynamic stress on the Hydro Muscle. A dynamic approach to develop a viscoelastic model is essential because of the following -

- The Hydro Muscle experiences stress at a faster rate than the rate specified in constant-stress or constant-strain experiments.
- The entire structure of the Hydro Muscle should be subjected to the modeling experiments.
- The modeling experiments should include system parameters which are most likely to be used in an actual robotic system. Eg. fluid pressure, control units(valves).

3.2 Dynamic Loading

The standard viscoelastic models such as the SLS model achieve success in describing a viscoelastic material. The SLS model of the Hydro Muscle[7] has been developed with the consideration of a time scale which is longer than the average actuation cycle of the Hydro Muscle in a real-world robotic system. It is necessary that the experiments for the SLS model be conducted at a time scale comparable to actuation cycle of the Hydro Muscle. This would allow us to come up with a model which could be effectively used to model the dynamics of the Hydro Muscle and eventually design a model-based control system.

To study the effect of stress on a material for a small duration of time, dynamic loading is considered to be the ideal method[8]. Dynamic loading involves subjecting the material to sinusoidal stress. The observed stress-strain characteristics give a better understanding of the behaviour of a material under dynamic stress.

Dynamic loading is apt to study the dynamics of the Hydro Muscle. The Hydro Muscle undergoes multiple elongations and relaxations during a single real-world operating session of any system which employs the Hydro Muscle. This cycle of elongation and relaxation is similar to a sinusoidal dynamic loading cycle. The study of Hydro Muscle in such conditions would allow better understanding of the Hydro Muscle during its real-world operating cycle. This would facilitate design of robust and efficient control algorithms to actuate Hydro Muscle systems.

Chapter 4

Dynamic Viscoelastic Model

The dynamic viscoelastic model of a Hydro Muscle is a mathematical model designed to estimate the behavior of the muscle based on the hydraulic pressure, elongation and the rate of elongation of the Hydro Muscle. The test is conducted using a Hydro Muscle attached to a predefined weight such that the weight would resist the expansion of the muscle. The Hydro Muscle is then extended and relaxed in a proprietary manner for multiple iterations. Sensors are employed to measure the Hydro Muscle force, its elongation and the hydraulic pressure in the system. Multivariate linear regression functions were utilized to interpolate a model which predicts the force exerted by the Hydro Muscle as a function of the hydraulic pressure and the extension and the rate of extension of the Hydro Muscle. Similar work has been attempted by T. Sussman and K. Bathe[9].

4.1 Experimental Setup

The test is conducted on a single Hydro Muscle of length $0.035m(1.38in)$ with the internal diameter of the latex tube $0.031m$ $(0.75in)$ and the outer diameter $0.019m$ $(1.25in)$. The muscle is actuated using an inlet with variable pressure. One end

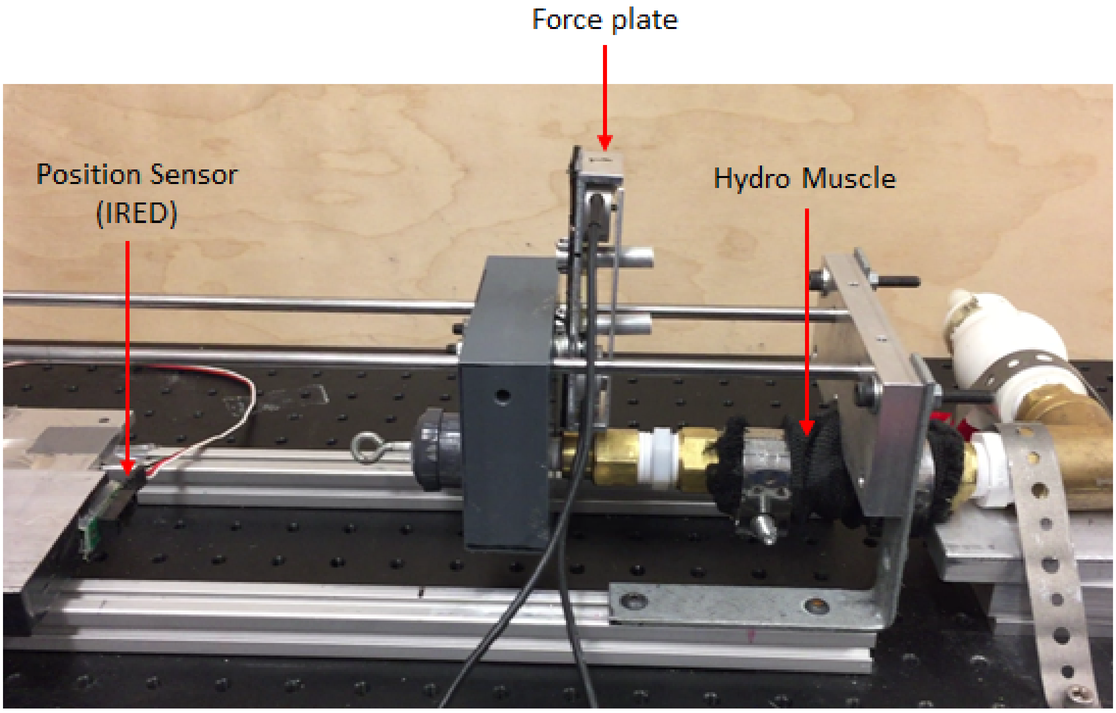

FIGURE 4.1: Experimental setup for developing the dynamic viscoelastic model

of the Hydro Muscle is clamped to a testbed as shown in figure 4.1 and 4.2. The free end is attached to a block placed on a sliding rail which is free to move in the direction of elongation of the muscle. This block has a custom designed force plate assembly (Figure 4.3) with two load cells(range 0-50kg)[10] attached in front of the muscle to measure the force exerted by the muscle. A mass of 0.5kg(1.102lbs) is suspended from the top force plate which registers a reaction force on the load cells. The distance measuring sensor unit is composed of an integrated combination of position sensitive detector(PSD), infrared emitting diode(IRED)[11] and signal processing circuit. The sensor unit utilizes the triangulation method for distance measurement and does not get influenced by the variety of the reflectivity of the object, the environmental temperature, and the operating duration. This device gives the output in form of the voltage corresponding to the detection distance which can be mapped to a corresponding distance based on the sensor model.

The system has a pressure sensor with the range of $1.2MPa(174psi)$. A micro-controller is used to drive the sensors and collect data. The controller uses 10-bit Analog to Digital converters to convert the analog data from the sensors to comprehensible data. Based on the resolution of the sensors and the Analog to Digital converters, the sensors could detect a minimum change of $1171Pa(0.17psi)$ for pressure, $0.02mm(0.79 * 10^{-3}\ in)$ for length and $0.01\ N(2.25 * 10^{-3}\ lbf)$ for force. The data are exported to MATLAB for obtaining the viscoelastic model. Multivariate linear regression[12] functions are used to develop quadratic and cubic functions of elongation(x), rate of elongation(v), and pressure(P) to precisely fit the Hydro Muscle force(F_m) data.

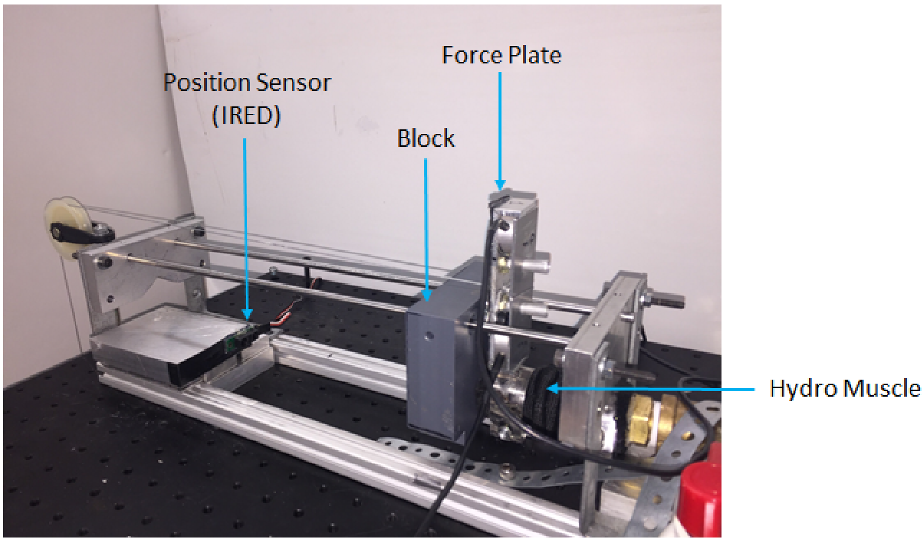

Figure 4.2: Final experimental setup for developing the dynamic viscoelastic model

A second set of test is conducted on the same experimental apparatus without the actuation of the Hydro Muscle. During this set, the Hydro Muscle is disconnected from the system and the suspended mass is free to drag the block till it reaches the end. During this period, the only unknown force in the system is the friction. Friction is modeled as Coulomb friction[13] to reduce the complexity of the system. Coulomb friction model is represented as a constant frictional force independent of any system parameters as long as the sliding surfaces experience the same normal force.

The analytical equation for this system which is utilized to develop the model is as follows -

$$F_m - m_1 g - f_p - f_{block} - f_u = (M + m_1)a \tag{4.1}$$

Here, F_m is the force exerted by the Hydro Muscle, m_1 is the mass suspended from the force plate, g is the acceleration due to gravity, f_p frictional force of the pulley, f_{block} is the friction force of the block sliding on the rails, f_u is a quantity to take into account unknown motion resistance forces e.g. friction in the force plate, the unknown friction and viscous forces in the Hydro Muscle due to its design structure, M is the mass of the block attached to the free end of the Hydro Muscle, a is the combined acceleration of the mass m_1 and the block. This equation is used as a starting point for developing the model. The Coulomb friction modeled is appropriately substituted in the equation 4.1. The force registered on the load cells is given by the following equation -

$$F_l = (M + m_1)a + m_1 g \tag{4.2}$$

Here, F_l is the force output from the load cells.

The numerical value for force exerted by the Hydro Muscle is thus obtained. This force is modeled as a function of the hydraulic pressure(P), elongation(x), and the rate of elongation(v).

$$F_m = f(x, v, P) \tag{4.3}$$

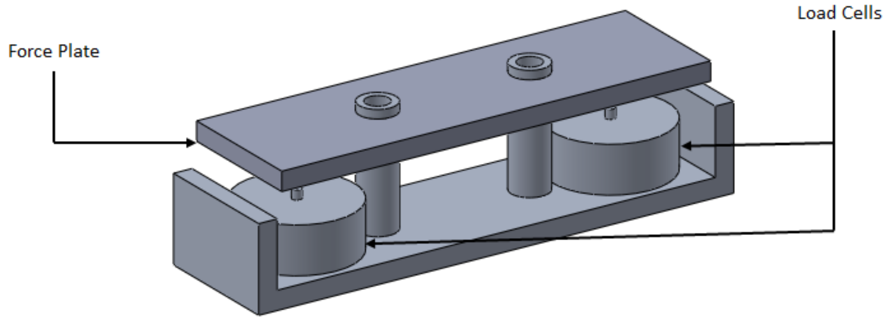

FIGURE 4.3: Custom designed force plate assembly

4.2 Results

The data obtained are filtered using a moving average filter to reduce the spurious noise. The filtered values are used to evaluate a linear regression model for the force produced by the Hydro Muscle.

A polynomial multivariate linear regression was used to obtain the model. The criteria for deciding the order of the polynomial was complexity of the polynomial and a confidence of fit above 0.85. The first model was a second order linear regression model(quadratic polynomial) with predictor variables as elongation(x) and rate of elongation(v) without the inclusion of the hydraulic pressure(P). The confidence of fit obtained was 0.672. The result improved to 0.819 with the inclusion of the pressure term to the quadratic polynomial model. A third order polynomial in x and v with the inclusion of the pressure term yielded the highest confidence of fit of 0.85. The polynomials beyond the third order were not considered as the model would include up to 25 terms and would increase the computational complexity when designing control algorithms.

TABLE 4.1: Viscoelastic Model: Confidence of fit

Model Specification	R^2	Adjusted R^2	RMSE
Quadratic without Pressure terms	0.672	0.661	0.0366
Cubic without Pressure terms	0.816	0.807	0.0276
Quadratic with Pressure terms	0.819	0.808	0.0275
Cubic with Pressure terms	0.85	0.816	0.0256

The cubic polynomial model involving pressure as a variable produced results better than the other models developed. The model equation is as below with the physical quantities in their SI units -

$$\begin{aligned} F_m = {} & C_0 + C_1 x + C_2 v + C_3 P + C_4 x^2 + C_5 xv \\ & + C_6 v^2 + C_7 xP + C_8 vP + C_9 x^3 + C_{10} x^2 v \\ & + C_{11} xv^2 + C_{12} v^3 + C_{13} x^2 P + C_{14} xvP \\ & + C_{15} v^2 P \end{aligned} \tag{4.4}$$

.

The estimated coefficients of the terms in the equation are shown in Table 4.2.

The quadratic as well as the cubic linear regression models exhibit a high confidence of fit. Figure 4.4 shows the prediction of the force exerted by the muscle using the model in equation 4.4, the actual force measured by the load cell and the modeled friction. The initial negative force is because the direction of the pull force is taken to be negative. The increase in the negative force is due to the relaxation pull force of the Hydro Muscle. The Hydro Muscle stabilizes and then registers a small decrease in force when it is allowed to elongate again. The magnitude of force is small and can be attributed to the low mass of m_1 being used($0.5kg$). This variation will increase if a mass of higher value is used.The

TABLE 4.2: Model Co-efficient estimates

Coefficients	Value
$C_0(N)$	-6.426
$C_1(N/m)$	41.744
$C_2(Ns/m)$	-52.309
$C_3(m^2)$	15.135
$C_4(N/m^2)$	-1586.5
$C_5(Ns/m^2)$	2786
$C_6(Ns^2/m^2)$	-137.77
$C_7(m^3)$	-355.69
$C_8(ms)$	73.913
$C_9(N/m^3)$	23321
$C_{10}(Ns/m^3)$	-51458
$C_{11}(Ns^2/m^3)$	6754.7
$C_{12}(Ns^3/m^3)$	622.14
$C_{13}()$	1567.8
$C_{14}(s)$	914.38
$C_{15}(s^2)$	-58.823

results demonstrate high fidelity of the model to the actual behavior of the Hydro Muscle.

4.3 Inference

The cubic linear regression model with a high confidence of fit has been verified with sample data. The model is complex and the coefficients obtained are valid for the given specifications of Hydro Muscle. As a result, a new model with distinct coefficients would be needed for a Hydro Muscle with different specifications.

The model incorporates only the control parameters i.e. the pressure, elongation, elongation rate and their correlations. To make a more generic model, it is necessary to include the specifications of the Hydro Muscle as parameters of the model.

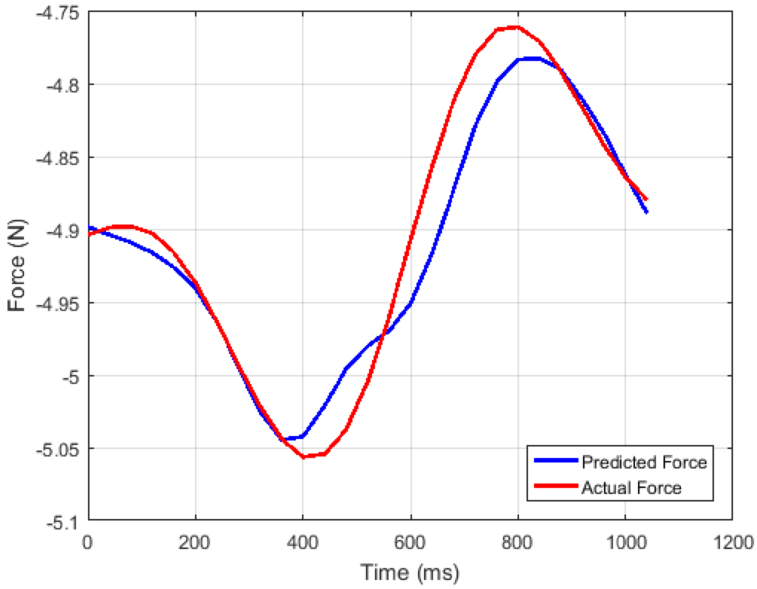

FIGURE 4.4: Plot of actual force exerted by the Hydro Muscle and the predicted force vs time

This would help generate a model which can be utilized for a range of Hydro Muscles without the need to conduct tests for developing separate models for Hydro Muscles of varying dimensions.

Chapter 5

Model Validation

The validation of a model is an integral process of model development. The dynamic viscoelastic model needs to be validated on a real-world system to check its accuracy and real time applicability. The idea is to build a primitive robotic setup and test the accuracy of the model. The predictor variables in this model are the hydraulic pressure, the elongation and the rate of elongation and the resultant force is the dependent variable.

5.1 Experimental Setup

The experiment involves the actuation of a knee joint using a Hydro Muscle to achieve the required force during its actuation. The setup consists of a Hydro Muscle with a latex core of an inner diameter of $0.031m$ ($0.75in$) and an outer diameter of $0.019m$ ($1.25in$). The length of the latex core is $0.035m(1.38in)$. The sheathing used to contain the radial expansion of the Hydro Muscle has an ID of $0.042m(1.64in)$. The total length of the sheathing is $0.1m(3.94in)$. One end of the Hydro Muscle is attached to a test bed. The free end of the Hydro Muscle is attached on a block. This block slides on a pair of steel rods which act as rails.

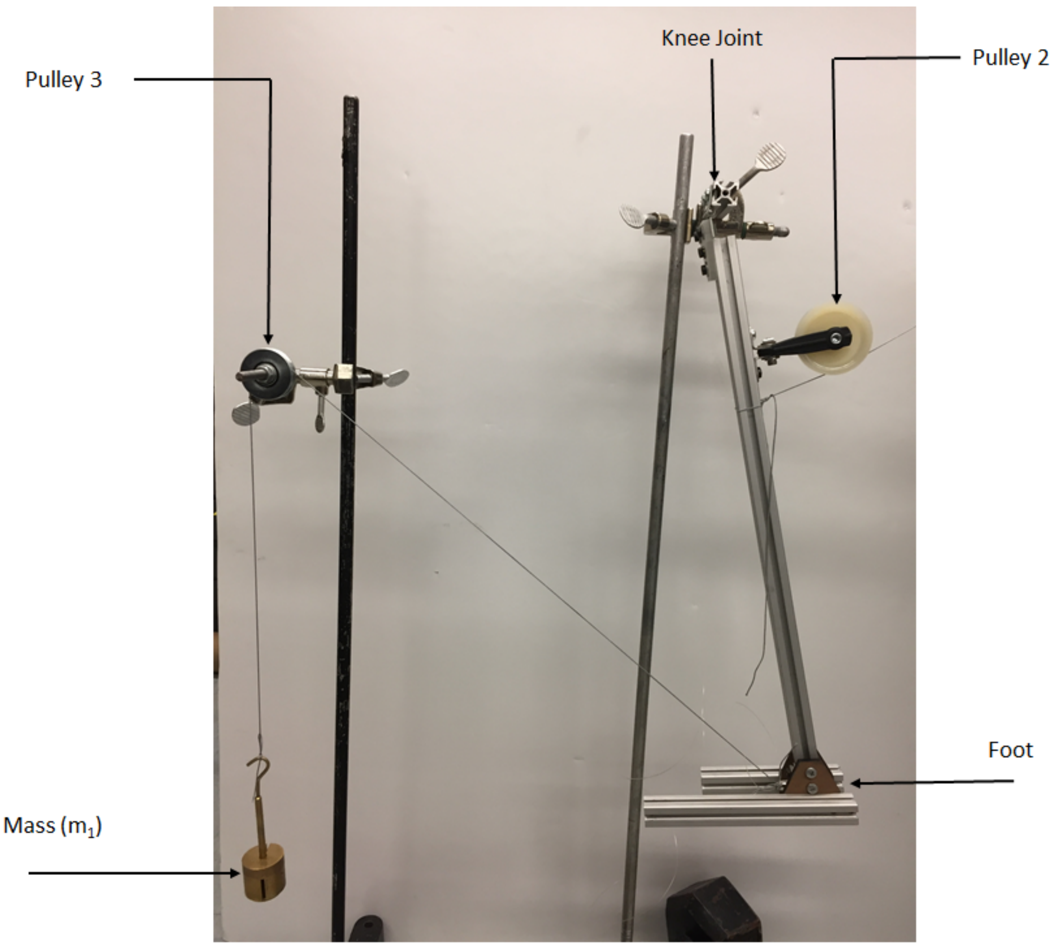

FIGURE 5.1: Experimental setup for Model Validation

This setup restricts the actuation of the Hydro Muscle to a single axis along its length. The block is attached by a string through a set of pulleys to a structure made to represent a knee joint. The pulleys are arranged in a way that the Hydro Muscle force is transmitted through nylon strings to be always perpendicular to point of attachment. This increases the efficiency of force transfer via the string. The lower leg structure is attached to a free hanging weight of $0.5kg(1.10lbs)$. This weight acts as the load for the Hydro Muscle force. An IRED[11] is used to sense the elongation and the rate of elongation of the Hydro Muscle. A pressure sensor with a range of 0-$1.2MPa(174psi)$ is used to observe the hydraulic pressure in the system. The acceleration(a_1) of the load is also measured using a separate IRED to calculate the force exerted by the Hydro Muscle. The data acquisition algorithm is developed in C and an Atmega2560[14] is used as a microcontroller for implementing the algorithm on the system. The experimental setup is as shown in figures 5.1 and 5.2.

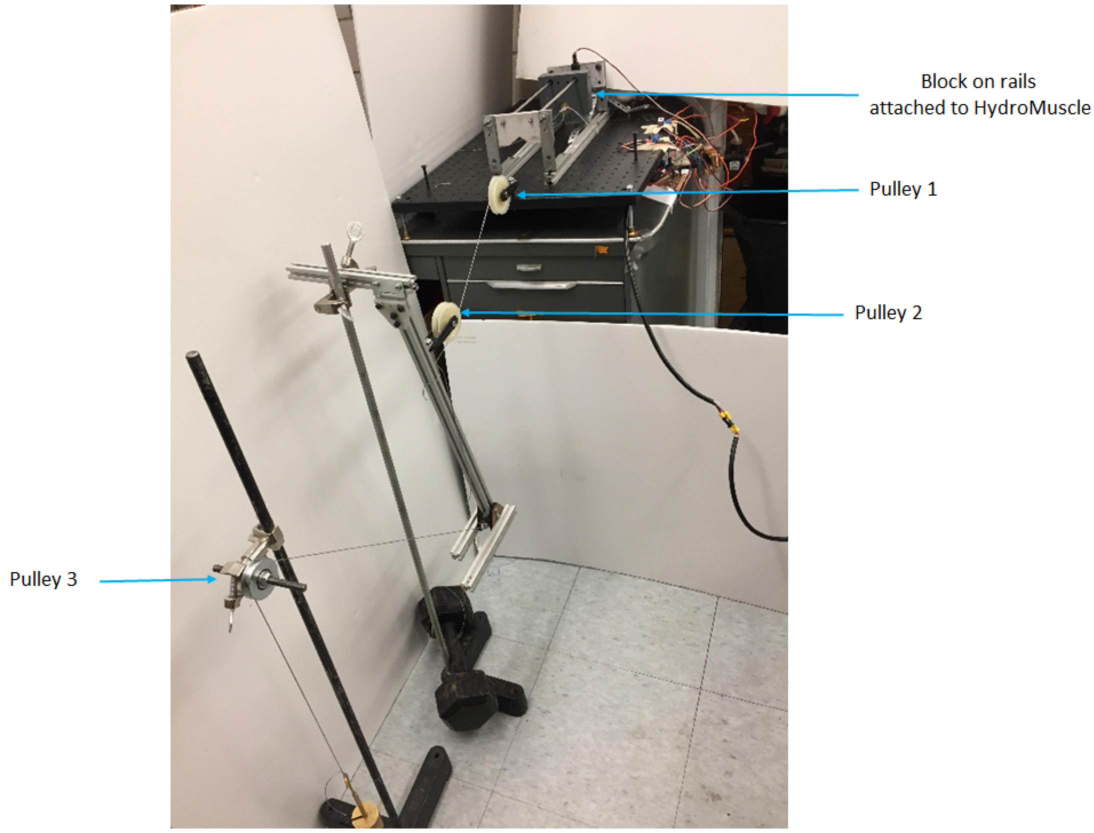

FIGURE 5.2: Experimental setup for Model Validation

The system is also subjected to a set of tests to model the Coulomb friction in the system.These tests involve the free fall of the mass m_1 under the influence of gravity and modeling the friction based on the resistance to the free fall.

The analytical equation for the system is as follows -

$$F_m - f_{block} - f_{p_1} - f_{p_2} - f_{p_3} - m_1 g = (M + m_1)a \tag{5.1}$$

Here F_m is the force exerted by the muscle, f_{p_1},f_{p_2}, and f_{p_3} is the Coulomb friction of pulleys 1, 2, and 3 respectively, f_{block} is the Coulomb friction for the block, m_1 is the mass attached at the end of the pulley 3, M is the mass of the block attached to the free end of the Hydro Muscle, a is the combined acceleration of the mass m_1 and the block, g is the acceleration due to gravity.

In this system, load cells are not used to register the reaction force of the Hydro muscle. Instead, the acceleration of the mass m_1 is used to determine the unknown quantities in the equation 5.1. Upon proper substitution, a numerical value of the Hydro Muscle force is obtained and this is compared with the predicted values of the dynamic viscoelastic model. The maximum error, variance of error and the root mean square error is calculated to gauge the performance of the model.

5.2 Results

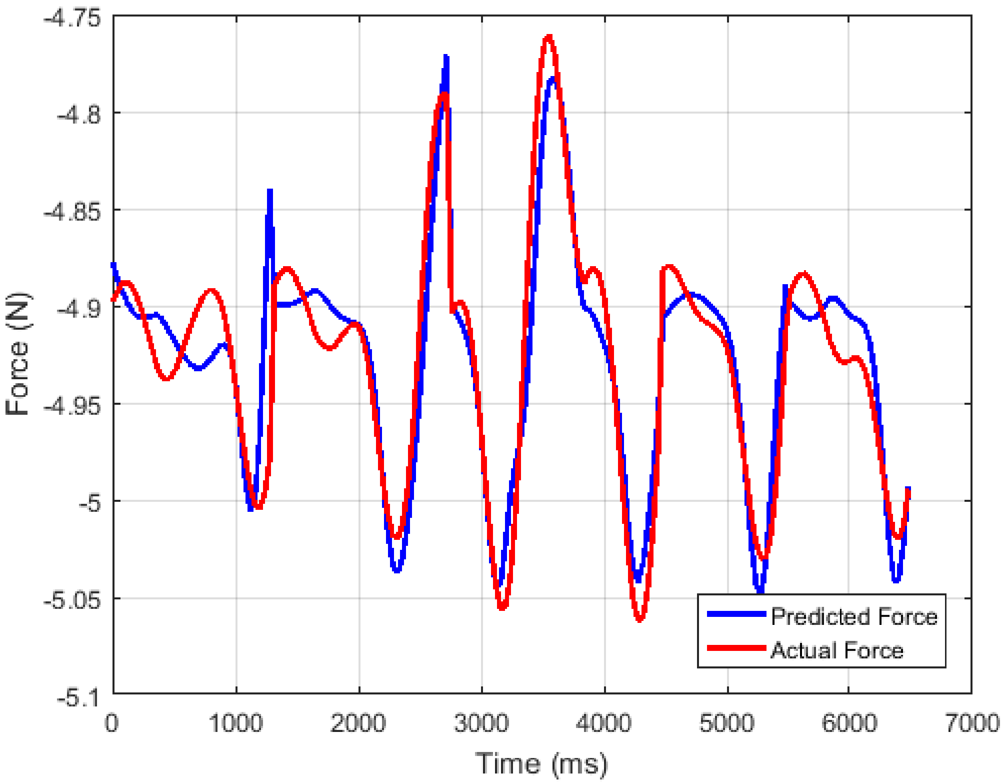

FIGURE 5.3: Plot of actual force exerted by the Hydro Muscle and the predicted force vs time for Model Validation

The dynamic viscoelastic model is accurate at the prediction of the forces exerted by the Hydro Muscle. As seen in the figure 5.3, the results of the prediction closely follow the actual forces.

The maximum error between the predicted data and the actual data is about $0.14N$. The variance of error in prediction is $5.9 * 10^{-4}$. That confirms the high accuracy of the model. The root mean square error is 0.025.

5.3 Inference

The dynamic viscoelastic model has been validated for the mentioned specifications of the Hydro Muscle. Hence, it can be confirmed that dynamic loading experiments help understand behaviour of Hydro Muscle when they are subjected to dynamic stress. The experimental model is able to explain 85 percent of the variations in the data.

A more robust model could be developed with multiple iterations of model validation and parameter adjustments. Regular model verification and validation processes should be conducted to nullify redundancies and introduce viable parameters so as to achieve an absolute dynamic viscoelastic model. A keen understanding of the individual terms of the model will help tune the model efficiently.

Chapter 6

Multi-fiber Bionic Ankle

6.1 Introduction

A planar leg with one degree of freedom ankle joint is designed. The developed prototype system is used to study the multi-fiber actuation of the ankle joint[15]. The aim of the project was to examine the control strategies involved in actuating a single degree of freedom joint with multiple soft actuators.

6.2 Multi-fiber Musculoskeletal Leg Structure

The major muscle groups actuating the human ankle are the Gastrocnemius and the Soleus. An antagonistic muscle group pair, the Tibialis Anterior, assists in the control of the ankle. The specifications of the Hydro Muscles utilized for the design of these three muscle groups were based on the following design goals -

- achieve 40 percent of the maximum forces produced by an average male human ankle
- achieve variable joint stiffness similar to an average male human ankle

FIGURE 6.1: Designed Muscles (left to right) the Tibialis Anterior, the Gastrocnemius, ant the Soleus

- achieve the complete range of motion as an average male human ankle

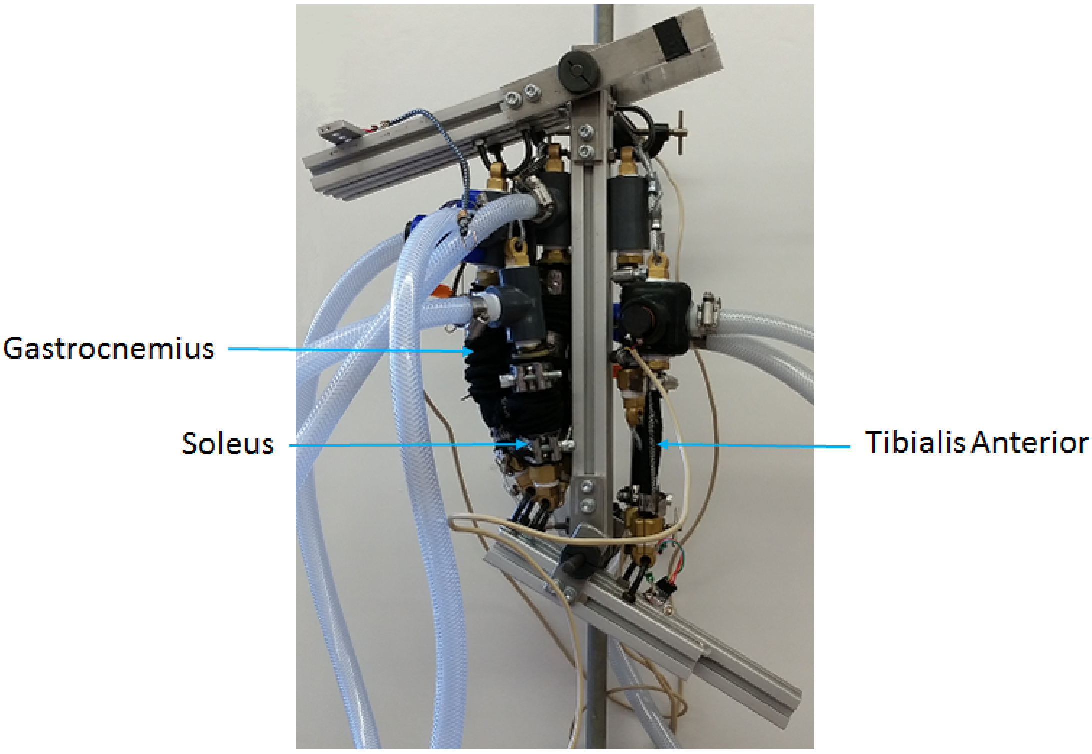

FIGURE 6.2: Leg Structure

Two Gastrocnemius, three Soleus were designed to be the primary actuators for the bionic ankle. The Tibialis Anterior was designed as a set of three passive antagonistic muscles. The attachment points of these designed muscles were chosen to be similar to the respective points of attachment of the average human muscles. The designed muscles can be seen in figure 6.1 In summary, the Gastrocnemius and the Soleus were attached to the posterior of the ankle and were actively controlled with pressurized fluid. The Tibialis Anterior were attached to the anterior of the ankle and behave as passive elastic elements. This can be seen in figure 6.2.

6.3 Results

6.3.1 Full Force Test

To verify that the designed system met the initial design goal a full force test was conducted. The Hydro Muscles were designed to achieve 40 percent of the force produced by an average human male ankle. So each of the muscle was subjected to a full force test in which the Hydro Muscle was elongated with hydraulic pressure and then the fluid was allowed to evacuate. The relaxation of the Hydro Muscle was constrained so that the maximum force could be measured. For the Gastrocnemius muscle, the maximum force recorded was $307N$ against a desired of $327N$, and for the Soleus muscle was $356N$ against a target of $516N$. The resultant torque is $109Nm$. The average male human requires $1.5Nm/kg$ of torque in the ankle for level-ground walking[16]. The average adult human mass is $62kg$[17]. The designed ankle would produce approximately $1.76Nm/kg$ which is above the $1.5Nm/kg$ threshold needed for walking[16].

6.3.2 Range of Motion

The average human ankle is able to achieve a backward bending motion(dorsiflexion) of 13°-33° and a forward bending motion(plantar flexion) of 40°-56°[18].

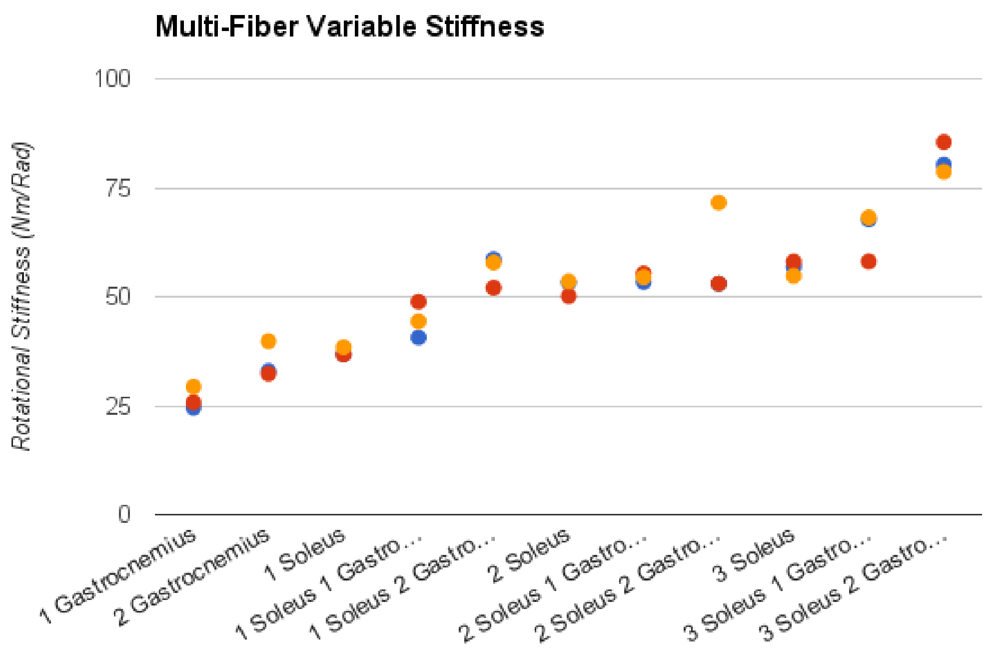

FIGURE 6.3: Variable Rotational Stiffness Results

The designed multifiber bionic ankle could achieve a dorsiflexion of 20° and could achieve a plantarflexion of 40°.

6.3.3 Varible joint stiffness

The ankle was tested under all rear muscle recruitment combinations to show the ability to vary the rotational stiffness of the ankle using the selective recruitment capabilities of the multi-fiber design. A weight of 9.1 kg (20 lbs) was hung on the back of the ankle while only one or both Gastrocnemius muscles were recruited. 18.1 kg (40 lbs) was used for all other recruitment configurations. Muscle fibers were disengaged by elongating them more than the other fibers. The rotation of the ankle when the muscles were stretched by the added weight was measured with a potentiometer rotational sensor in order to calculate the stiffness of the muscles when engaged. Each experiment started with the ankle fully in plantarflexion.

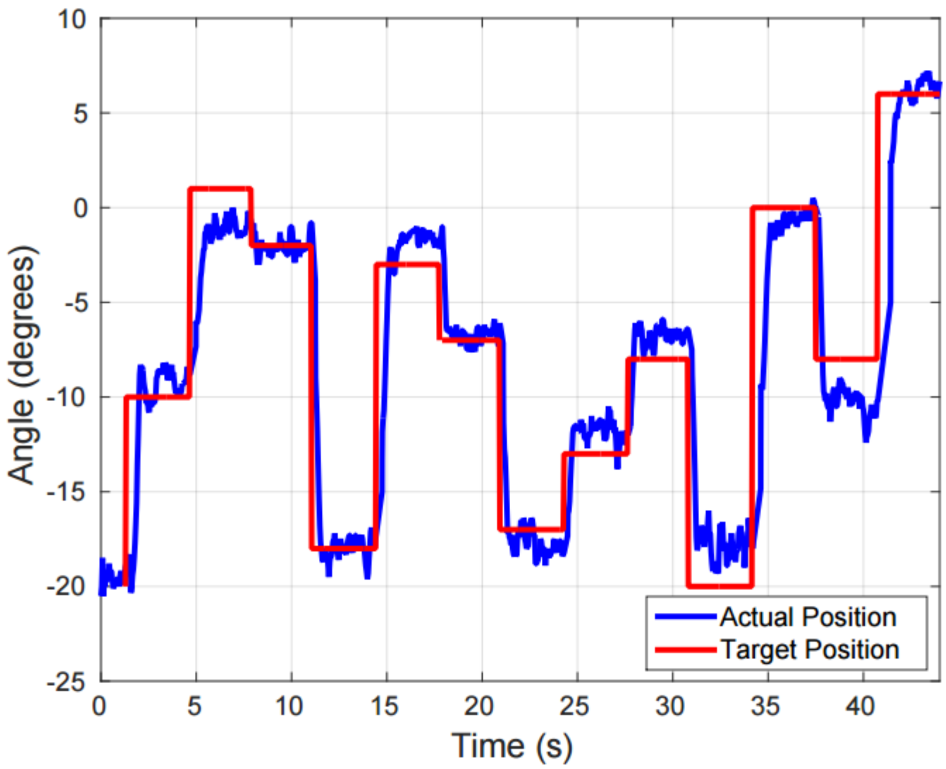

FIGURE 6.4: Results of position control

6.3.4 Position Control

The result shown in the figure 6.4 displays a successful implementation of a set point tracking control system with a Proportional Derivative controller. A potentiometer is used to sense the position of the ankle. The noticeable factor in the results is that, the time taken to travel the same magnitude of angle changes with the change in the direction of travel. This effect may be attributed to the mismatched opening and closing times of commercial valves used in the system.

6.3.5 Variable force using multi-fiber Hydro Muscle

By sequentially engaging individual muscles of the multi-fiber system, it is possible to achieve a modular variation in the force exerted by the ankle. This can be seen in figure 6.5. The results show the sequential relaxation of the Soleus muscles.

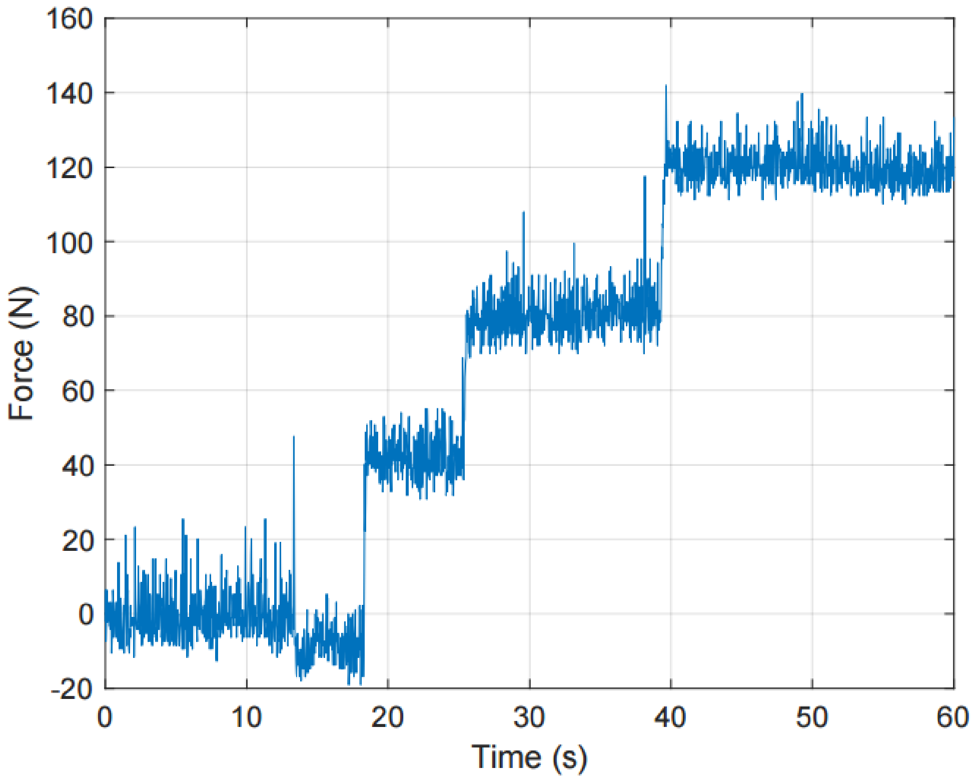

FIGURE 6.5: Results of modular force with sequential recruitment of Hydro Muscles

The relaxation of a Soleus muscle increases the force exerted by the system by a value of approximately $40N$. This modular change in the exerted force may be leveraged for devising active force control schemes for systems with a large number of artificial muscle fibers.

Chapter 7

Conclusion

7.1 Dynamic viscoelastic model

A novel method to develop a dynamic viscoelastic model for the Hydro Muscle is introduced. The method uses multivariate linear regression to correlate the force exerted by the Hydro Muscle to hydraulic pressure, the elongation, and the rate of elongation of the Hydro Muscle.

The model achieves an 85 percent confidence of fit. The experiment based dynamic viscoelastic model has been partially validated with the help of a physical system. Hence, the possibility of implementing model-based control algorithms on a system actuated by Hydro Muscles could be proposed.

7.2 Multi-fiber bionic ankle

An approach to control biological-inspired robotic joints using multiple Hydro Muscles is illustrated. The ankle structure is able to produce the necessary torque for level-ground walking of an adult human. A proportional derivative controller is implemented for tracking and minimising the angular position error. A modular variation of force is achieved with sequential actuation of Hydro muscle fibers.

Chapter 8

Future Recommendations

8.1 Dynamic viscoelastic model

The procedure for developing the dynamic viscoelastic model strictly allows for the model to be specific to a particular Hydro Muscle. As a result, a new model has to be generated for a Hydro Muscle with different specifications. This can be countered with inclusion of the structural and material specifications of the Hydro Muscle as variable parameters during the experimental stages of the modeling. It will allow the model to become generic. Such a model can be implemented with Hydro Muscles of a variety of dimension without changing any model parameters.

The next important factor is the modeling of friction. Developing a more complex model for contact friction could improve the accuracy of the model. Coulomb friction has been explored here because of the simple modeling procedures that it utilizes. Using a parametrized friction model might increase the computation complexity as well as the time, but will result in a robust model.

Another recommendation would be to experiment with finer control elements in addition to traditional valves. These elements include proportional valves, flow controllers, flow meters, etc. These components could essentially increase the controllability of a robotic system actuated by the Hydro Muscle.

8.2 Multi-fiber bionic ankle

The current multi-fiber system is bulky. The system has considerable delays to to be considered for a commercial product development. Smaller efficient valves need to be implemented to realize efficient locomotion tasks.

Using flow control elements such as proportional valves, flow controllers will help improve efficiency and reduce delays in the system. A thorough study of human muscles, ligaments, etc. needs to conducted to improve the understanding and realize the potential of the multi-fiber muscle recruitment systems.

Bibliography

[1] G. McCarthy, D. Effraimidis, B. Jennings, N. Corso, C. D. Onal, and M. B. Popovic. Hydraulically actuated muscle (ham) exo-musculature. In *Robotics Science and Systems Conference (RSS)*, July 2014.

[2] S. Sridar, C. J. Majeika, P. Schaffer, M. Bowers, S. Ueda, A. J. Barth, J. L. Sorrells, J. T. Wu, T. R. Hunt, and M. Popovic. Hydro muscle -a novel soft fluidic actuator. In *2016 IEEE International Conference on Robotics and Automation (ICRA)*, pages 4014–4021, May 2016. doi: 10.1109/ICRA.2016.7487591.

[3] Chae H. AN. *Model-based Control of a Robot Manipulator*. MIT Press, 2003.

[4] Dr. Korondi Peter, Halas Janos, Dr. Samu Krisztian, Bojtos Attila, and Dr. Tams Peter. *Robot Applications*, chapter 8. 2014. ISBN 978-963-313-136-7.

[5] Nikesh S. Dattani. Linear multistep numerical methods for ordinary differential equations. Department of Applied Mathematics, University of Waterloo.

[6] R. Lakes. *Viscoelastic Materials*. 2009.

[7] Francesco Mainardi and Giorgio Spada. Creep, relaxation and viscosity properties for basic fractional models in rheology. In *The European Physical Journal*, pages 133–160, 2011.

[8] D. Roylance. Engineering viscoelasticity, 2001. URL http://web.mit.edu/course/3/3.11/www/modules/visco.pdf.

[9] Theodore Sussman and Klaus-Jurgen Bathe. A model of incompressible isotropic hyperelastic material behavior using spline interpolations of tensioncompression test data. *Communications in Numerical Methods in Engineering*, 25:53–63, February 2009.

[10] Phidget-button load cell (0-50kg). URL http://www.phidgets.com/products.php?category=34&product_id=3136_0",.

[11] Sharp analog distance sensor 10-150cm, 5v. URL https://www.pololu.com/product/2474.

[12] Ethem Alpaydin. *Introduction to Machine Learning*. 2nd edition, 2010.

[13] V. Geffen. A study of friction models and friction compensation, 2009.

[14] Arduino mega 2560. URL https://www.arduino.cc/en/Main/arduinoBoardMega2560.

[15] A. Agrawal A. Kashyap J. Tai M. Bowers, C. Harmalkar and M. Popovic. Design and test of biologically inspired multi-fiber hydro muscle actuated ankle. In *Proceedings of IEEE International Workshop on Advanced Robotics and its Social Impacts*, 2017.

[16] Samuel Au, Max Berniker, and Hugh Herr. Powered ankle-foot prosthesis to assist level-ground and stair-descent gaits. In *Neural Networks*, pages 654–666, 2008.

[17] Sarah Catherine Walpole, David Prieto-Merino, Phil Edwards, John Cleland, Gretchen Stevens, and Ian Roberts. The weight of nations: an estimation of adult human biomass. *BMC Public Health*, 12(1):439, 2012. ISSN 1471-2458. doi: 10.1186/1471-2458-12-439. URL http://dx.doi.org/10.1186/1471-2458-12-439.

[18] Susan Doan-Johnson and christian Veillette. Biomechanics of the foot and ankle. 2011. URL `http://www.orthopaedicsone.com/x/mwK-Aw`.