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ABSTRACT

FINGER JOINT IMPEDANCE CONTROL APPLICATIONS TO INVESTIGATE SPASTICITY

by David Naisby Paglia

In order to investigate how spasticity disrupts the capabilities of the human body, a better understanding of how joint impedance control operates in healthy individuals is necessary. In this investigation, a second order rotary torque model was implemented to investigate the impedances at the metacarpophalangeal (MCP) joint of the index finger. The model was fit to approximately 25 milliseconds of force and displacement data to determine the mechanical impedances at the finger tip. Ranges of damping and stiffness were optimized over a range of mean finger tip force (0-12 N) for extension. The equilibrium-point hypothesis was examined when compared to the theory that joint stiffness changes linearly with applied initial force, presented by researchers including Hajian and Howe.

Results confirm Feldman's findings that stiffness and damping are relatively constant across levels of increasing applied force. Equilibrium angle R as presented by Feldman and represented by theta-not in this analysis was shown to be the driving control mechanism in active force regulation. The equilibrium angle increased nearly linearly as force increased. This also contradicts the notion that joint stiffness increases linearly with applied initial force. Protocols for conducting experiments on individuals with spasticity were developed. Future work will implement these protocols to conduct individuals. investigation of the joint impedance of spastic an

FINGER JOINT IMPEDANCE CONTROL APPLICATIONS TO INVESTIGATE SPASTICITY

by David Naisby Paglia

A Thesis Submitted to the Faculty of New Jersey Institute of Technology in Partial Fulfillment of the Requirements for the Degree of Master of Science in Biomedical Engineering

Department of Biomedical Engineering

January 2008

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To my parents for all their support, both monetarily and otherwise To my friends for helping to guide me through the tough decisions I faced along the way

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CHAPTER 1

INTRODUCTION

Spasticity is a neuromotor disorder which significantly limits the capabilities of the human body. Persons with spasticity have an increase in muscle tone or tension (hypertonicity). They also have a hypersensitivity of the reflex. When spastic individuals are moved at velocities that would not normally elicit a reflex in those without spasticity, a premature exaggerated reflex is elicited (hyperreflexia). For these reasons, living with spasticity is a significant burden on both the individual and his/her family. Future care of persons with spasticity will be highly based on correctly understanding how spasticity operates within various neuromotor disorders. One way to investigate this is to examine how impedance control at joints of spastic individuals differs from those of individuals with no known disability. This can be accomplished by dividing hypertonicity and hyperreflexia and examining the origins of each disorder. Hyperreflexia is generally considered to be a neural condition, while hypertonicity's origins are debated. A proper understanding of joint impedance theory for healthy individuals will be an invaluable tool for understanding how to treat individuals with spasticity. Investigation into this area will provide a larger understanding of how joints operate prior to the afferent signal from the periphery reaching the reflex arc. This will allow an investigation of joint impedances prior to the stretch reflex and any neural communication with the periphery. Investigation into the period after the signal reaches the reflex arc is also important. This will provide information regarding joint impedances

as the velocity of the finger approaches zero.

Another area of investigation is how the central nervous system regulates forces during active tasks. This is particularly important in spasticity, where several researchers have shown linearly increasing impedances as force is increased. Feldman's hypothesis of a shifting equilibrium-point in the spring of a joint also warrants investigation. The theory of regulating joint equilibrium-points warrants investigation with respect to individuals with no known disability and spastic individuals. (Hajian and Howe, 1997), (Hogan, 1989), (Jindrich, Balakrishnan, and Dennerlein, 2004), etc.

1.1 Motivation / Problem Statement

This need for the characterization of both central nervous system operation and the origins of spasticity, make the current study extremely important. Potential benefits of the study include, the evolution of impedance control theory in the current academic climate, a better understanding of how the central nervous system operates, and an improved characterization of how the joint impedance of spastic individuals differs, if at all, from the impedance of individuals with no known disability, prior to the influence of muscle contraction.

This study involves two main branches. The first is an investigation into how the central nervous system operates when regulating forces during active movement in the metacarpophalangeal (MCP) joint of the human index finger. Feldman's equilibrium-point hypothesis will be discussed and supported when compared to the theory of impedance regulation, implemented by several researchers over the past twenty years. (Hajian and Howe, 1997), (Hogan, 1989), (Jindrich, Balakrishnan, and Dennerlein,

2004), etc.

The second branch of this study involves an investigation into the origins of hypertonicity. Joint impedances will be examined prior to any communication between the periphery and the central nervous system effectively occurs. This will indicate whether hypertonicity is a mechanical, neural, or combined disorder. Hypertonicity is expected to be primarily driven by a malfunctioning central nervous system. For this reason, the impedances of spastic subjects should compare closely to subject with no known disability. Investigators involved in this study hypothesize that differences in impedance values may be mechanical tissue changes in spastic subjects. There is a possibility is that higher resting levels of muscle activity exist in this case, which is neurally controlled.

1.2 Background Information

Hajian and Howe of Harvard conducted a study in the 1990's which examined the impedances of individuals with no known disability prior to influence of the monosynaptic stretch reflex, during active movement. Their studies dealt with the mechanical joint impedance of the human index finger tip. This type of investigation was novel for its time. The results obtained from the 1994 proceedings have been referenced in several related books and in much of the current research as well. Hajian and Howe also published a journal article in 1997 which includes all the findings of the 1994 study, in addition to abduction tests. The current study being presented, tries to reproduce, using different methods, the experimental conditions in Hajian and Howe's research. (Hajian and Howe, 1997)

Hajian and Howe's study considered five subjects with no known disability subjects, four of which were men. Hajian and Howe mainly considered the mechanical joint impedance of the metacarpophalangeal (MCP) finger joints alone. As was commented by Hajian and Howe,

"For fingers in particular, the impedance can be expected to vary with the angles of other joints in the wrist, finger, and thumb. In addition, a complete representation of the finger impedance requires measurements of responses at longer time scales."(Hajian and Howe, 1994, p. 323)

Other studies have considered the joint impedance of all three primary interphalangeal (IP) joints in the human finger. Hajian and Howe's research made important strides towards understanding the mechanical joint impedance of the human finger tip. (Hajian and Howe, 1997)

Hajian and Howe's experiment was conducted by asking all five healthy graduate student subjects to grip a handle with their extended index finger. They were also asked to rest their hand, wrist, and forearm on a rigid horizontal surface. A piston was attached to a pneumatic cylinder, which rested on a table. Subjects were instructed to gradually increase finger force past a variable threshold. The applied initial force level was incremented from 0-20 N throughout trials. Subjects were told to view the force sensor output on an oscilloscope. Simultaneously, the piston quickly displaced the tip of their fully extended index finger by approximately 5mm in 20 milliseconds. After every four trials, the threshold weight was lowered to both minimize anticipation and to limit the fatigue of the subject's finger. (Hajian and Howe, 1997)

The main findings of Hajian and Howe's study provide quantitative parameter estimates for a second order linear model, displaying the dynamics of the MCP joints extension across a range of mean force levels that were applied at the finger tip. The estimated mass parameter of study generally remained constant, but the stiffness and damping of the parameters, increased linearly with the force levels. These impedances are not explained thoroughly. Hajian and Howe argue that the finger impedances vary linearly with force. (Hajian and Howe, 1997)

Generally, this stiffness-damping characteristic corresponded to the expected linear trend that was found in earlier studies of other joints. The damping ratio however, was shown to be significantly greater for flexion-extension in the MCP joints. This is probably due to the unique physiology of the fingers in flexion-extension. Many of the joints that were analyzed before this study such as the ankle "are served by muscles adjacent to the joint with relatively short tendons." (Hajian and Howe, 1997)

At 70 milliseconds, the monosynaptic stretch reflex may occur. The short latency response may occur as early as 30 milliseconds after initial stimulus. This reflex may be elicited due to velocity of the index finger. The only synapse in the reflex arc is the synapse between the afferent neuron and efferent neuron. This stretch reflex occurs when an afferent neuron originating at a stretch-detecting receptor in a skeletal muscle terminates directly on the efferent neuron. The efferent neuron supplies the skeletal muscle to cause it to contract and counteract the stretch. By sampling data prior to the monosynaptic stretch reflex, any neural communication is eliminated. Due to this, the reflex arc response can also be neglected. The current study samples relevant data within the first 25 milliseconds. (Sherwood, 2007)

The damping and stiffness values obtained from Hajian and Howe's analysis were optimized from the MATLAB software package, but are not explained physiologically. Hajian and Howe might have assumed that the stiffness constant obtained from MATLAB optimization itself changes as force increases. They presumably operated under the assumption of total apparent joint stiffness presented by Hogan (1989). This assumption warrants investigation. The current study seeks to support a possibly better explanation of force regulation during active tasks. (Hajian and Howe, 1997)

An investigation of work regarding dynamics of interactions between humans and machines, attempts to address the idea of impedance control by breaking the joint's overall stiffness into two components. Hogan expresses the overall apparent stiffness is expressed as a combination of the passive stiffness of the joint (symmetric component), and the stiffness generated through continuous active motion (anti-symmetric component). The symmetric component described by Hogan is representative of passive motion. (Hogan, 1989)

While Hogan's relations, regarding anti-symmetric stiffness are obviously logical. Hogan presents a description of the stiffness behavior that is physiologically incomplete. Hogan's theory suggests that an additional stiffness coefficient for the spring is generated during active tasks. The current study under investigation seeks to provide evidence that as power is extracted from the hand continuously along a closed path, the equilibriumpoint of the joint's internal spring is regulated by the central nervous system. (Hogan, 1989)

The current study under investigation seeks to provide a better understanding of isometric force control. It builds on research conducted by Feldman. Feldman's research defined the joint as a spring with a set point. As more force needs to be generated from the joint, Feldman provides evidence that the joint's internal spring is stretched and the

equilibrium-point angle is shifted. The dependency of the net joint torque on the angle is referred to as the invariant characteristic in this study. Feldman describes a value R (reciprocal command), which specifies the joint angle (R) at which the transition of active net flexor to extensor torque can be observed as changes the joint angle are elicited by an external force. The value R also addresses transition from extensor to flexor torques. Feldman also references variable C (co-activation command) or angular range at which the flexor and extensor muscles may be simultaneously active. Both values of R and C are reference angles which change during active movement. The control variable μ is responsible for the reflex damping in Feldman's model. Feldman's model assumes there are two levels of dissipation. These levels are velocity-dependent change in muscle activation, which is due to proprioceptive feedback and velocity-dependent force generation by muscle sarcomeres. Changes in Feldman's R command results in shifts of the system's equilibrium state. This results in EMG production and movement. (St-Onge, Adamovich, and Feldman, 1997)

Control variables C and μ provide movement stability and effective energy dissipation. This prevents oscillations at the end of movement. Muscle stiffness is non-linear and cannot be described as a single value. Feldman's study shows that joint stiffness (combination of stiffness for all muscles acting on the joint) is approximately linear. (St-Onge, Adamovich, and Feldman, 1997)

Another important investigation was performed by Jindrich, Balakrishnan, and Dennerlein. The introduction of multiple joints allowed an analysis of the theory that finger joints function similarly during tapping. This theory was not proven in the study. The function of multiple joints during active tasks may be useful information, should other finger joints besides the MCP index are investigated in future studies. (Jindrich, Balakrishnan, and Dennerlein, 2004)

Jindrich and colleagues studied the dynamic behavior of the finger joints while they were in the contact period of tapping on a computer keyswitch. This was done to characterize and parameterize joint function with a lumped-parameter impedance model. They tested whether the MCP and IP joints acted similarly in terms if kinematics, torque, and energy production during the tapping. This rotary model was an alternative approach to Hajian and Howe's linear model. (Jindrich, Balakrishnan, and Dennerlein, 2004)

Several interesting conclusions were made in this study. One interesting finding was that each IP finger joint functioned differently during the contact period with the keyswitch. During the loading phase of contact the MCP joints flexed. It also produced energy, unlike the proximal and distal IP joints. These joints extended and absorbed energy. Finally, the results presented in this study suggest that the MCP joints do work on the other IP joints and keyswitch. This work would have been exerted regardless of whether the finger was splinted. This supports Hajian and Howe's findings that it was not necessary to splint the index finger. It also confirms the un-splinted procedures conducted in the current study under investigation. (Jindrich, Balakrishnan, and Dennerlein, 2004)

A limitation of this study is that the experimental apparatus and task differed from tapping on a computer keyboard in many ways. The first difference that must be considered is that this test only examined the index finger impedance in computer key depressions. In actual touch typing, other fingers besides the index contact the various keyswitches. Secondly, the test would have been more reliable if it also considered various arm-wrist postures, aside for the fully supported horizontal typing position. Finally, as stated in this study "the lumped-parameter model that we fit to the data is linear, and it assumes that the model parameters are time independent." (Jindrich, Balakrishnan, and Dennerlein, 2004, p. 1593) Future investigation could create a model with a dependent time variable. (Jindrich, Balakrishnan, and Dennerlein, 2004)

Jindrich and colleagues performed another investigation in March of the same year. The goal of this study, was to examine the effects of postural and keyswitch characteristics on musculoskeletal tissue during tapping on computer keyswitches. The experimenters measured the joint kinematics and calculated joint torques while tapping on different keyswitches. Different postures were also analyzed the data using mechanical impedance models. The main results determined by this study, were that more extended finger postures were associated with greater joint torques, energies, and stiffnesses. The greater the forces that were imposed on the keyswitch, the greater the resulting forces, joint torques, and joint stiffness. The assumption of changing antisymmetric impedances is present in this research as well. Equilibrium-point incorporation into the presented model would yield different results than those obtained from this study. (Jindrich, Balakrishnan, and Dennerlein, 2004)

Not all of the studies considered the joint impedance of individuals with no known disability. The investigation conducted by Kamper, Harvey, Suresh, and Rymer examined the joint impedance of stroke victims. One benefit of this study is that the experimental subjects had a physiological limitation. This characteristic differentiated the investigation from other studies, such as the previously mentioned experiments conducted by Hajian and Howe. Another excellent characteristic of the study is that the

initial hypothesis of the investigators was proven. They also produced very relevant data, as to the effects of stroke on the mechanical joint impedance of the human finger. (Kamper, Harvey, Suresh, and Rymer, 2003)

The fact that only the MCP joints were considered in this study is an area of investigation for future studies. The experimenters could not have been expected to examine the other finger joints. To do so, would have overcomplicated the already sufficient study. (Kamper, Harvey, Suresh, and Rymer, 2003)

All of these subjects experienced a stroke at least one year prior to testing. The subjects had a variety of lesion sites. They had less than 50% of full finger extension against gravity, but some flexion. The subjects were tested with anesthetic in the median and ulnar nerves of the elbow, to reduce the activity of the muscles flexing the MCP joints. This was done to "distinguish mechanical from neuronal resistance to imposed MCP rotation." (Kamper, Harvey, Suresh, and Rymer, 2003, p. 309) From this study it was determined that the nerve blockade resulted in a reduction in velocity-dependent torque. This suggests that spasticity significantly affects joint impedance. Across subjects, the results indicate that the finger extension deficits following stroke, have a primarily neural origin. The non-voluntary flexor activity aggravates a decreased ability to voluntarily excite extensor motor neurons. Posture-dependent static torque was also reduced due to the blockade. This blockade most likely reduced neural sensations due to local anesthesia, without the full blockade of general anesthesia. The improvements during the study were likely due to a decrease in the improper flexor activity during the movement. In all cases of this study the inappropriate flexor activation was compounded by weaknesses. These weaknesses were apparent in both extensor and flexor muscles.

This study was an excellent example of how joint impedances are significantly different in spastic subjects. Most importantly, it indicates that neural activity serves and extremely important role in spasticity. This role can be further investigated by research such as the current study. (Kamper, Harvey, Suresh, and Rymer, 2003)

Another group of investigators were Dong, Welcome, McDowell, Wu, and Schopper. Their study yielded many advantages to the vibration power absorption (VPA) approach, such as the promise of the palm VPA method. The purpose of this investigation was to derive the frequency weighting from three VPA methods, and to determine if these energy methods are superior to the currently accepted acceleration method. This was done by measuring the mechanical impedance of eight subjects, thus exposing them to a broadband random vibration spectrum in the z(h)-axis. Eighteen combinations of hand couplings and applied forces were measured. (Dong, Welcome, McDowell, Wu, and Schopper, 2006)

The study did identify some disadvantages as well. Some disadvantages include, uncertainty of results at low frequencies and other uncertainties in the power absorption in the fingers, at frequencies that are higher than 100 Hz. The VPA density was not fully examined in this study. (Dong, Welcome, McDowell, Wu, and Schopper, 2006)

This same group performed another study that is relevant to the investigation of mechanical impedance. This study involved the all of the same project members as the previously discussed study, but was conducted in 2004. The results from this study are easily accessed, because the group's 2005, and 2006 experiment addressed these findings. The general consensus that was determined from these two studies was that the VPA

method has its advantages and disadvantages, but does hold promise for future investigation. (Dong, Welcome, McDowell, Wu, and Schopper, 2004)

This investigation theoretically demonstrated that the mechanical impedance (MI) in a hand power grip, as a measure of the biodynamic response of the system, can be divided into the finger MI and palm MI. The main result of this study found that the characteristics of the hand driving-point MI, distributed at the fingers and the palm are extremely different. The results suggest that the VPA measured at the fingers might be a better measure than the VPA of the entire hand-arm system, for studying vibration induced finger disorders. The two studies conducted by this group suggest an alternative and possibly better method for measuring joint impedances through VPA. This method is a reasonable option for consideration, should another method of impedance measurement be needed to confirm the results presented in the study under investigation. (Dong, Welcome, McDowell, Wu, and Schopper, 2004)

The final investigation that will be discussed was conducted by Burne, Carleton, and O'Dwyer in 2004. This study involved thirteen normal and eight hemiparetic subjects, with mild/moderate spasticity, with no significant contracture. O'Dwyer and colleagues found that when background contractions were matched to contraction levels of normal subjects, no significant evidence of hyperrelexia or hypertonicity was present. The investigators argued that reduced capacity to modulate reflex activity dynamically over the normal range of motion may contribute to movement disorders. The mean age of hemiparetic subjects in this study was nearly 60 years, with a maximum age of 70. This large elderly subject population most likely skewed the results due to a gradual mechanical contracture, associated with aging. Other studies examining spasticity incorporated a much younger subject population. (Burne, Carleton, and O'Dwyer, 2004)

1.3 Objective

There are several goals that this study seeks to accomplish. The first goal of this study is to clarify what is physiologically occurring in the central nervous system, during active force regulation. The primary theory that many previous researchers have operated under is that joints automatically alter their stiffness when regulating forces. While the stiffness of joints does increase in this case, there is a reasonable explanation for the phenomenon. Feldman's equilibrium-point hypothesis will be examined and compared to other theories of force regulation. (Hajian and Howe, 1997), (Hogan, 1989), (Jindrich, Balakrishnan, and Dennerlein, 2004), etc.

The other objective of this study is to determine how the hypertonicity operates in spasticity. This study seeks investigate the idea that hypertonicity has a neural link and prior to the monosynaptic stretch reflex. It explores the possibility that the joint impedances of subjects with no known disability subjects are the same as those of spastic subjects prior to the monosynaptic stretch reflex. Experiments to explore this theory will take place in future work.

CHAPTER 2

MODELING APPROACH

The next step after conducting background research regarding the topic was creating an appropriate mathematical model to correctly represent the MCP joint of the index finger while interacting with the Haptic Master. The purpose of this chapter is appropriate modeling of the index finger. Section 2.1 focuses on derivation of the equations of motion for the index finger. This will allow us to appropriately model the motion of the index finger during active tasks and determine joint impedances. Sections 2.2 and 2.3 describe how Simulink modeling software in MATLAB can be utilized to verify optimized impedance values.

2.1 Derivation of Equations of Motion

The equation of motion of the index finger is a variation of the general second order equation of motion for any joint at equilibrium. This equation is given by:

$$I * \ddot{\theta} + B * \dot{\theta} + K * \theta = mgl * \sin(\theta)$$
(2.1)

Where I is the moment of inertia, B is the damping constant, K is the stiffness constant, and θ , θ' , and θ' represent angle, angular velocity, and angular acceleration of the leg, respectively.



Figure 2.1 Free Body Diagram of index finger during active movement.

To begin with, the current investigation involves the MCP joint of the index finger. The finger is also performing active motion. Due to this fact, Equation (2.1) must be modified to include the initial forces of the finger. The fact that the finger is pushing the Haptic Master with a certain force means that the force of the Haptic Master must also be taken into consideration. The angle, theta must be rewritten as the difference between the angle itself and the initial angle. In this investigation, that angle is equal to zero. The sine term must also be changed to cosine because of the resting angle is 90 degrees with respect to the vertical direction. In order to bring this angle to zero degrees with respect to the horizontal, the cosine must be implemented. This setup is illustrated by the free body diagram of the index finger during active movement in Figure 2.1. The new equation becomes:

Where $M_{intrinsic}$ is the intrinsic moment, M_{init} is the initial moment of that the subject maintains, and M_{HM} is the moment that the Haptic Master senses.

$$I * \ddot{\theta} + B * \dot{\theta} = T_{HM} - T_{init} - mgl * \cos(\theta)$$
(2.2)

Where T (HM) is the torque that is being applied on the Haptic Master, T (init) is the initial torque that is set in the GUI as the force that the subject must maintain in order to elicit motion, and θ (rest) is the resting angle.

$$T_{HM} - T_{init} = K^* (\theta - \theta_{rest})$$
(2.3)

Equation (2.2), while an accurate representation of index finger motion, it does not describe Feldman's equilibrium point angle. To describe this angle appropriately, the initial force must be rewritten as:

$$T_{init} = K * (\theta_{rest} - \theta_0)$$
(2.4)

Where $\theta(0)$ is Feldman's equilibrium-point angle.

The finger system may now be solved using a MATLAB optimization of the damping and stiffness constant B and K using Equation (2.2). The equilibrium point angle thetanot may then be computed via Equation (2.4). This is done by plugging the optimized K into Equation (2.4). Implementation of Equations (2.2) and (2.4) into the model of the index finger MCP joint will allow appropriate investigation impedances and the equilibrium point angle change.

$$m * \ddot{x} + B * \dot{x} = mg + F_{\mathcal{M}} \tag{2.5}$$

Where m is the effective mass, B is the damping constant, and x', and x'' represent velocity, and acceleration of the finger, respectively. The force F(M) is equal to the stiffness K multiplied by the distance the finger is moved x.

Hajian and Howe use Equation (2.4) to describe the motion of the index finger in their experiments. They conclude that stiffness changes linearly with applied initial force. They achieved this result by keeping theta-not equal to theta, or in their case x-not equal

The current study uses a method which accounts for isometric forces and allows for a constant stiffness. Although muscle stiffness is non-linear and cannot be described as a single value, Feldman shows that joint stiffness is approximately linear.

2.2 Selection of Rotary Torque Model

The equation of motion for the MCP finger joint was altered to reflect a rotary system. This is because, while minimal, the angle of the finger joint does provide slightly different impedances for a rotary than a linear system. For this reason, a rotary model is may be implemented for other joints. This is especially important when examining the impedances of the knee and elbow joints where the angular change is significant, even in subjects with spastic contracture.

CHAPTER 3

METHODOLOGY

Once the mathematical model was justified, appropriate calibration and data collection methodology had to be created. This methodology is crucial as it describes how all relevant data is collected and processed. The Haptic Master robot is discussed. This robot was the principal tool used in data collection. The software that was used for filtering, data collection, and other methods is also discussed.

The current study utilizes the Haptic Master force feedback system to measure index finger tip forces. The measured forces of the Haptic Master are very close to those found by Hajian and Howe. A substitute device for Hajian and Howe's oscilloscope display system was accomplished with a GUI (Graphical User Interface) in the current study. This GUI allows the subject to interact with the Haptic Master through visual feedback until they are given Haptic feedback. Eight trials were conducted at six different threshold levels in Hajian and Howe. Eight trials were also examined in the current study, at seven different levels of applied force. (Hajian and Howe, 1997)

3.1 Description of the Haptic Master

The Haptic Master is a Haptic robot that was designed by MOOG. It can sense the force of objects that interact with it and provide Haptic (force) feedback to the user. The Haptic Master can also be programmed to move under conditions set by the programmer of the interface. The images on the computer monitor also provide visual feedback to the user. This allows subjects to interact with the virtual world on their computer screen and feel everything they see.

To calibrate the Haptic Master, the operator must ensure that the machine is powered up and communicating correctly with the computer. The operator must then initiate Spasticity.exe, which is the executable file utilized the current study. It was written by doctoral student Qinyin Qiu in C++ programming language. Once initialized, this executable file opens a GUI (Graphical User Interface) that allows the operator to set the vertical distance the Haptic Master will move up or down, once the desired force is reached and maintained. The GUI also has a parameter to set the force threshold at which it will move. Figure 3.1 shows the GUI that was used throughout data collection. The operator sets the velocity at which the Haptic Master will move from a set of equally incremented symbolic velocities. These velocities have symbolic levels assigned as values (1, 2, 3, etc.). The final parameter which must be set is the number of trials.

| Property Page | |
|--------------------|--|
| ForceThreshold (N) | 2.000 |
| Distance (m) | 0.015000 |
| # of trials | 8 |
| Velocity Level | 2 |
| Save at | C:/Documents and Settings/adamo [,] |
| ОК | CANCLE |
| < | 3 |

Figure 3.1 Graphical user interface used to set operating conditions of the Haptic Master.

3.2 Software

The software that was used to collect the data was a Haptic API (Application Programming Interface). This interface is called from C++, and is coded in the language as well. The API is a library of functions that allow the C++ program to control the Haptic Master. The C++ program collected data, which was analyzed using MATLAB software. The equation of motion of the index finger was modeled in Simulink, a modeling feature of MATLAB.

3.2.1 Data Collection

The program collects time in milliseconds, position of the Haptic Master in meters, force that the Haptic Master is feeling in Newton's, and velocity at which the Haptic Master is moving in meters/millisecond. Data are collected at 1000 samples per second. Data collection begins when the GUI is initiated, and stops to when the finger no longer maintains the desired force. If the finger reaches and holds the desired force immediately after it has been moved, the program will run again. This will result in the finger being translated the same distance it had already been moved. The data primarily considered in this analysis are the forces and positions in the vertical (z-direction) and time. This data is imported into the MATLAB workspace. The GUI implemented in Haptic trials is shown in Figure 3.1. The desired positions and forces that were collected within the first 25 milliseconds of finger movement are then formatted into arrays in the primary code.

| Property Page | | × |
|---------------|---------|---|
| | Trial # | |
| | START | |

Figure 3.2 Haptic Master graphical user interface used during experimental trials.

3.2.2 Filtering

The tool used to remove noise and other data disturbances in this investigation is a Butterworth filter. It is a fourth order zero lag low pass filter, implemented using MATLAB's Signal Processing Toolbox. The cutoff frequency is 100 Hz. and the sample rate is 1000 samples per second. The Nyquist frequency that sets the highest the cutoff frequency can be set is 500 Hz. Every set of force, position and time data was run through this filter. The filter was appropriate because time was collected in one millisecond increments. At such a small time increment, a filter with a high frequency is necessary.

3.2.3 Optimization and Statistical Plots

Other methods were used to perform an analysis of this data. The MATLAB Optimization Toolbox as discussed in chapter five was implemented to determine ideal values of damping and stiffness. The values were validated by comparing them to results of the same model using SAS software. These values were substituted into the equation of the initial force of the finger to solve for the equilibrium point angle thetanot. Minitab software was implemented for a regression model of the first five subjects.

Equation 2.2 was implemented in the current study to represent the finger system under analysis. All values are known in this equation except stiffness (k) and damping Accelerations, velocities, angular accelerations, and angular velocities were (b). calculated through a derivative function that was created via MATLAB software. The function computed the derivative of positions and angles with respect to time. The initial torque computed in Equation 2.4 is not expanded in Equation 2.2 because initial force is equal to the target torque the subject must maintain to initiate Haptic Master movement and the equilibrium point angle theta-not is not known. These impedances are optimized using a least squares linear model. The best possible values of damping and stiffness were computed via the MATLAB Optimization Toolbox. There may have been another set of impedance values that could fit Equation 2.2, but the computed impedances were the first closest fit that MATLAB could optimize. Once the impedances were determined, the stiffness was substituted into Equation 2.4 to solve for the equilibriumpoint angle theta-not.

CHAPTER 4

EXPERIMENTAL SETUP AND PROCEDURE

Once the methodology was created, it was necessary to created guidelines for how the experimental equipment would be designed and setup. Protocol guidelines needed to be created to accommodate both individuals with no known disability, and those with spasticity. This chapter outlines the experimental setup of the Haptic Master, the principal data collection tool. It also outlines the experimental setup of all elements in the design. The procedure is finally discussed, along with protocol when operating with spastic patients.

4.1 Haptic Master Setup

The Haptic Master was the principal tool for collecting data in this study. The Haptic Master was initialized and then turned on prior to subject setup. The Spasticity.exe executable program was then run. This executable served two purposes. The first purpose was the calibration of the Haptic Master. This was typically done prior to subject setup to allow unimpeded motion of the Haptic Master. If the Haptic Master is disturbed during calibration, there is the potential for incorrect results. For this reason, full calibration should be done before subject setup whenever possible. Once the subject has been secured with a Velcro strap in the splint and positioned properly on the table, the GUI for Spasticity.exe can be filled out by the operator.

Forces are programmed by the user to set the initial force at each set of trials. Force increments in the study are of two Newtons. The increments range from zero Newtons to twelve Newtons. Eight experimental trials were conducted at each force level in analysis. The velocity of the Haptic Master is set at 0.12 meters/second.

4.1.1 Index Finger Moved Upward

To program the index finger to move upward, a positive value of distance must be entered into the GUI in the distance field. This distance was set at 15mm throughout the current study. A distance of 15mm was selected to investigate a large region of motion of the index finger throughout the assumed linear region of index finger impedances. This value is held constant during the current study.

4.1.2 Index Finger Moved Downward

To program the index finger to move downward, a negative value of distance must be entered into the GUI in the distance field. This distance was set at -15 mm throughout the study. This value is held constant during the current study.

4.1.3 Index Finger Free Fall

Free fall data was not taken into account in the statistical analysis. Any free fall could be programmed by setting the negative distance moved to a very low negative number (i.e. far from zero) in the GUI. The falling data can be programmed for a free fall with no force application, or a forced fall, requiring the subject to exert a specified force on the Haptic ball. This force is again entered in the GUI force input field.

4.2 Splint and Table Setup

The splint and table setup was the same for all trials. The table height is 30 in. in the zdirection. The stiff foam elevation that was used to boost the splint is 4.5 in. in the zdirection. This foam is also used as a device to ensure safety. Had the Haptic Master exerted a force on the finger enough to move the splint in which the arm is fixated, the foam would have absorbed the shock. The vertical height of the splint is 11.85 in. This allows the index finger of the subject to be elevated directly above the Haptic Master ball. The table is positioned next to the Haptic ball. The foam and ramp are finally set on top of the table in their proper position.

4.2.1 Index Finger Moved Upward

The neutral index finger position for this study was approximately 45 degrees below its position in full upper extension while the arm is also elevated at a 45 degree angle.

Under isometric contractions, the stiffness of the finger when moved within 45 degrees in either direction is nearly linear. This linear approximation only works within this finite range as the series elastic component is under tension during isometric contractions. It is therefore stretched a finite amount. The overall length of the muscle must remain constant, which causes the series elastic component to be stretched. This can only occur if the contractile element is internal shortening of the muscle. This relationship is demonstrated in Figure 4.2. (Winter, 2005, pp. 212-213).



Figure 4.1 MCP joint 45 degree angle diagram.



Figure 8.8 Contractile element producing maximum tension F_c along with the tension from F_p from the parallel elastic element. Tendon tension is $F_i = F_c + F_p$.

Figure 4.2 Contractile element producing maximum tension F(c) along with parallel elastic element F(p).

4.2.2 Index Finger Moved Downward

The neutral index finger position for this study was 45 degrees above its position in full lower extension. The arm is elevated at a 45 degree angle on the splint ramp.

4.2.3 Splint Ramp Design

The design of a prototype for the splint ramp was a long and complicated process. The first task in the design process was determining the purpose of the ramp in the design. This became highly dependent on exactly what angle was desired between the table and the lower arm. This decision came with a trade off of benefits.

The 45 degree ramp incline was constructed from a single board of pine wood. It was cut into 45 degree angles using a chop saw. The lengths of the cuts were determined prior to construction by modeling the ramp as a right triangle.

The splint utilized in the design was purchased online from RehabMart. Below is a picture of the splint's appearance, prior to machining.

The splint was modified through various machining processes to achieve its desired function. Initially, a piece of the thermoplastic that was decided would be cut, was used to test the material's response to heat. The finger rest was then heated and gradually rolled inward using the heat gun. Once the plastic had cooled and set, a Dremel was used to remove all excess splint material, and cut an opening to allow free range of motion for the index finger.

Once the splint was finished, two holes were drilled for screw seating. Two metal screws were run through the holes and screwed into the diagonal wood surface of the ramp. This secured the splint ramp together. Figure 4.3 shows the actual splint ramp

prototype. This ramp's top view is shown in Figure 4.4.



Figure 4.3 The completed pine ramp prototype.



Figure 4.4 The completed pine ramp prototype (top view).

4.3 Positioning of Subjects

The subjects were seated in an elevated chair next to the table. They placed their arm in the splint ramp with the index finger above the clearance hole. The patient's thumb was inserted into the lowest surface of the thumb shield, and their middle finger was tucked under the rolled surface of the splint hand. The patient was strapped into the splint to secure the lower arm.



Figure 4.5 Subject positioned in splint.

Figure 4.5 shows a subject positioned in the resting arm splint (w/o restraint strap)

4.3.1 Index Finger Moved Upward

For movements upward, the subjects were instructed to maintain neutral finger position while resting of the Haptic Master ball. The subjects were then told to move their finger upward through the index finger groove to ensure the finger was not being impeded by a portion of the splint.

4.3.2 Index Finger Moved Downward

For movements upward, the subjects were instructed to maintain neutral finger position while resting of the Haptic Master ball. The subjects were then told to move their finger downward through the index finger groove to ensure the finger was not being impeded by a portion of the splint.

4.3.3 Selection of a 45 Degree Arm Angle

One possibility was building the ramp to ensure functional arm position to allow the subject as much relaxation as possible. The benefit of this method is a clear difference in the amount of lower arm movement and forces required to perform the same tasks. While an important goal, this decision would involve problems as well. The primary shortcoming of this method is the range of motion of the index finger in this position. The functional position of the arm allows a significantly lower range of motion of the index finger than when the elbow is bent. The other problem with this method is without anesthesia, the human body will never be completely relaxed. Co-contractions of arm muscles generate additional forces during active motion of the index finger. The muscles of all the finger joints are coupled together. This makes it difficult to ever assume that only one muscle in the arm is active during such a motion. Hajian and Howe (1997) utilized such a system during their similar experiment. One might wonder whether they were truly able to eliminate the forces of the other lower arm muscles. Their handle setup does not incorporate a splint to restrict lower arm movement. For this reason, without anesthetic, functional arm position was neglected.

The other design option was building a ramp at an elevated angle. The this angle

would require a uniform range of motion in each direction, while not moving the arm unreasonably far from the resting arm position. A 45 degree angle was chosen, as it fulfills all of these requirements. The elevation of the arm above the resting arm position, guaranteed force contributions form other arm muscles. This downside of the design was undesirable, but necessary for full MCP joint range of motion. The arm was secured on this incline with the machined resting arm splint. The lower arm was strapped to the splint to eliminate movement of the lower arm during testing. This ensured that the subject's arm remained in the same position throughout trials.

4.4 Procedure

Subjects in this study were first informed of the study's importance. They were then given the IRB consent forms and informed of how their index finger would be moved. The subjects were strapped into the splint and then instructed to move their finger through its full range of motion. Based on this motion, the subject's hand was moved into the appropriate position inside the splint. Subjects were then shown the graphical user interface (GUI) and instructed how to interact with it correctly. Trials were then conducted and data was collected at each of seven different force levels. Trials in which the index finger moved downward were also conducted. If the subject felt uncomfortable inside the splint at any time, their arm was released from the splint. After a short break, they were re-strapped into the splint and instructed to move their finger through its full range of motion again.

4.4.1 Subjects with No Known Disability

Subjects with no known disability ranged in age from 23-35 years. The mean age of subjects was approximately 26 years. Subjects were instructed to fill out the appropriate paperwork corresponding to the IRB for subject treatment and rights. They were then given the general instructions regarding how to interact with the GUI. They practiced moving their index finger movements to ensure free range of motion. Trails then commenced.

4.4.2 Subjects with Spasticity

Subjects with spasticity will be instructed to fill out the appropriate paperwork corresponding to the IRB for subject treatment and rights, with assistance if necessary. They will then be given the general instructions regarding how to interact with the GUI. They will practice moving their index finger movements to determine each subject's range of motion was within the maximum distance of the Haptic ball movement. The trails will then commence.

CHAPTER 5

RESULTS AND DISCUSSION

Once the trials were conducted and the data were analyzed, it was time to investigate the results of the current study. The hypotheses made previously were compared to the data that was measured in the study. Chapter 5 address both the findings of the current study as compared to the previously made hypotheses, and the statistics associated with these results. Hypertonicity in patients with spasticity and Feldman's equilibrium-point hypothesis are also discussed.

5.1 Data to be Analyzed

Figure 5.1 shows how position changes throughout the first 29 milliseconds of time. Table 5.1 lists the applied initial forces levels for all subjects and the applied initial force levels for each subject. The applied initial torque at each level is computed by multiplying the applied initial force by the length of the index finger from the MCP joint to the point of force contact on the index finger tip.



Figure 5.1 Position vs. time for a trial collected from subject 5.

| Al- Applied Initial | Subject 1 | Subject 2 | Subject 3 | Subject 4 | Subject 5 |
|-----------------------------|--------------------|------------------|-------------------|-------------------|-------------------|
| Applied Initial Force(N) | Al Torque (N*m) | Al Torque(N*m | AI Torque(N*m) | AI Torque(N*m) | AI Torque(N*m) |
| 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0.1778 | 0.1905 | 0.1778 | 0.1778 | 0.1727 |
| 4 | 0.3556 | 0.381 | 0.3556 | 0.3556 | 0.3454 |
| 6 | 0.5334 | 0.5715 | 0.5334 | 0.5334 | 0.5182 |
| 8 | 0.7112 | 0.762 | 0.7112 | 0.7112 | 0.6909 |
| 10 | 0.889 | 0.9525 | 0.889 | 0.889 | 0.8636 |
| 12 | 1.0668 | 1.143 | 1.0668 | 1.0668 | 1.0363 |

Table 5.1 Applied Initial Force and Applied Initial Torque for Five Subjects

5.2 Discussion

Fatigue was not as significant a factor in the current study as it was in Hajian and Howe's study. This is because subjects were only required to maintain a maximum force threshold of 12 Newtons. This threshold was to be held in the current study to minimize anticipation and allow subjects with spasticity to appropriately adjust their equilibrium point angle. This 12 Newton limit is important because it is impractical to expect spastic subjects to regulate more than 12 Newton force. The splint ramp setup which was implemented in the current study, angled at 45 degrees, differs from Hajian and Howe's function arm position handle setup. (Hajian and Howe, 1997)

Larger time scales must be investigated in future work. Analysis of these scales should encompass data at which the velocity of the Haptic Master reaches zero meters/second. This will significantly widen the scope of the analysis. (Hajian and Howe, 1997) A continuation of the current study might incorporate a functionally angled splint ramp, with median and ulnar nerve anesthetic in the elbow. This procedure was implemented in the study conducted by Kamper, Rymer and Suresh. (Kamper, Harvey, Suresh, and Rymer, 2003)

Control variables C and μ presented in Feldman's equilibrium-point hypothesis provide movement stability and effective energy dissipation. This prevents oscillations at the end of movement. In the current study, the Haptic Master produced its own oscillations at the end of movement. Due to these oscillations, data immediately after movement in the current study are not analyzed. This could be corrected in future work, by the proper Haptic Master machine impedance settings. (St-Onge, Adamovich, and Feldman, 1997)

Feldman's equilibrium-point angle R is represented by theta-not in the current study. Muscle stiffness is non-linear and cannot be described as a single value. Feldman's study shows that joint stiffness is approximately linear and can be represented as such in the present analysis. (St-Onge, Adamovich, and Feldman, 1997)

Figures 5.2, and 5.3 displays the change in torque, as time and angle change. They demonstrate that velocity is never truly equal to zero, as Haptic Master oscillations prevent a thorough analysis of the finger impedances when the finger velocity is equal to zero. The region investigated is within the first 25 milliseconds of movement. It is represented the region to the left of by the solid black line running vertically through both figures.



Figure 5.2 Torque vs. time graph for subject 2 through movement.



Figure 5.3 Torque vs. angle graph for subject 2 over approximately 2 seconds.

When the analysis began it was necessary to determine how angles changed across increasing levels of applied force. Figure 5.4 demonstrates that at each increment on two Newtons initial force, the force of the finger tip increased by two Newtons. This trend can be seen by examining the force increment over the first 0.09 radians. This result confirms results presented by O'Dwyer's study. Hajian and Howe's measured forces also reflect this trend. As the Haptic Master was depressed slightly for each increasing force level, the angle readings were measured relative to a zero radian staring position in each case. This depression is represented by the line drawn from the origin to the 12 Newton force curve and intersecting the beginning of each other force curve as well. As applied initial forces are increased, the depression gradually increases by approximately the same amount for each force. Future data collection will incorporate an improved damping condition for the Haptic Master to eliminate this depression.



Figure 5.4 Force versus angle for subject 1 over approximately 140 ms.

Trials were also conducted when the index finger was allowed to drop, instead of being pushed upward by the Haptic Master when applying an active force. For these trials, the Haptic Master was programmed to drop 15mm. once the target force was maintained. Figure 5.5 displays five trials of a six Newton force, when the Haptic Master is moving downward, compared with a sample six Newton trial of the Haptic Master moving upward. The force profiles in both cases are approximately symmetrical over the



Figure 5.5 6N force versus angle for subject 1 over approximately 280 ms.

Figure 5.6 shows the values of overall joint impedances as collected from four male subjects and one female subject from the current study. These combined impedances are what previous researchers such as Hajian and Howe considered the impedances of the MCP joint. This value was obtained in the present analysis by multiplying the equilibrium-point angle by the stiffness. As indicated in Figure 5.6, the stiffness and damping computed via this method follow the same general trend as those

measured by Hajian and Howe. The change in equilibrium-point angles allows joint impedances to increase linearly. At the point at which the angle theta is equal to zero, the subjects in these studies apply torque. Thus the subjects stiffness multiplied by their angle is equal to the torque. The inconsistency with this method is that when the angle theta is equal to zero, the torque must equal zero. The Hajian and Howe optimization of stiffness at various levels of applied force masks this inconsistency with incorrect stiffness values when the angle theta is equal to zero.



Figure 5.6 Impedances optimized using Hajian and Howe's method (four men and one woman).

5.2.1 Hypertonicity in Subjects with Spasticity

A correct quantification of hypertonicity would require a much larger spastic subject population than presented in the current study. Reasonable conclusions cannot be drawn from data collected form one individual with spasticity. Future research will examine a large spastic subject population and attempt to quantify hypertonicity in spasticity.

5.2.2 Feldman's Theory (Study Applicability)

Feldman's equilibrium-point hypothesis states that to regulate forces in a joint, the central nervous system changes a particular offset, called the set-point in that joint. The results of this study support the findings of Feldman completely. As indicated in Figure 5.7 as finger tip force is increased, the set point or equilibrium point (theta-not) of the internal joint spring shifts to the right (spring is extended). This stretching of the spring results in a nearly linearly increasing change in the stiffness of the spring. What is important to note, is this linear increase in stiffness, is directly related to the joint's shifting set point. As indicated in Figures 5.9 and 5.10 for stiffness and damping respectively, these constants do not change during force regulation. These impedance results differ from those presented by Hajian and Howe. The stiffness presented in the current analysis is relatively constant throughout force levels.



Figure 5.7 Variations of stiffness in extension for five healthy subjects involved in the study (four men and one woman).

When impedances at a six Newton Haptic Master drop were calculated for Subject 1, they were found to have an average stiffness of 32 N/m*rad. This value is almost identical to the average stiffness found when the Haptic Master moved upward, for the same subject. This similarity is shown is Figure 5.8. The preliminary analysis showed the impedances of all six Newton forces to be approximately equal, regardless of movement direction. This confirms results presented by Feldman regarding the regulation of equilibrium angle R (theta-not in current study).



Figure 5.8 Variations of stiffness in extension for five healthy subjects involved in the study (four men and one woman).



Figure 5.9 Variations of damping in extension for five healthy subjects involved in the study (four men and one woman).



Figure 5.10 Variations of Feldman's equilibrium point angle in extension for five healthy subjects involved in the study (four men and one woman).

The equilibrium-point angle sampled data for five of the subjects (four male, one Female) that was found by optimizing for stiffness values using MATLAB software and substituting the stiffness into Equation (2.3) to solve for theta-not. This theta-not value was analyzed using Minitab software. This software fitted a linear regression to the angles computed across the range of applied initial torques. This linear line corresponds to the best line that fits the trend of data. In this case, that is a nearly linear increase in the equilibrium point angles with increasing torque. The R-Sq value is above 85 percent across the range of subjects. Figures 5.11, 5.12, and 5.13 confirm two hypotheses presented in this analysis. Each figure is plotted with a 95% confidence band.



Figure 5.11 Linear regression of equilibrium-point angle vs. applied initial torque trials for subject 1.



Figure 5.12 Linear regression of equilibrium-point angle vs. applied initial torque trials for subject 2.



Figure 5.13 Linear regression of equilibrium-point angle vs. applied initial torque trials for subject 4.

CHAPTER 6

CONCLUSION

Based on the results from this study many conclusions can be drawn. The approximately constant level of stiffness across various force levels during active tasks provides additional support to Feldman's equilibrium-point hypothesis. It also presents different results than those described in Hajian and Howe study. The stiffness values optimized in this analysis may not be the correct stiffness of the MCP joint. This is because the MATLAB Optimization Toolbox chooses the best possible values of damping and stiffness to fit the given equation. There may have been many different values of B and K that fit the same equation. If values of stiffness are large, values of equilibrium angles are small, and vice-versa. For this reason, future analysis should either choose an ideal value of stiffness to fit the equation based on credible information or explore other ways to determine stiffness, other than an optimization.

The impedance values presented in the current study may be affected by several experimental conditions, which could potentially provide error. The measurement of the index finger lengths was performed using a protractor. A more exact measurement could have been achieved with a micrometer. The Haptic Master is a temperamental robot which occasionally crashes. Such a system is likely to produce error throughout large sets of experimental trials. Finally, the processing of the data collected from the Haptic Master is performed manually. This may account for some human produced error.

Future work should include a flat surface for force application, rather than the Haptic Master ball. Another improvement for future designs is the programming of a

proper damping condition for the Haptic Master. This will minimize oscillations of the Haptic Master robot after it has traveled in its desired path and allow investigation of impedances when the velocity of the index finger reaches zero. The velocity at which the Haptic Master moves could be increased in future studies when proper damping is achieved.

The study should be performed individuals with spasticity. This will allow appropriate investigation of the origins of hypertonicity. A support for the remainder of the arm, not placed in the splint could be built to improve patient comfort and ensure the arm is more relaxed during experimentation.

APPENDIX

MATLAB CODE TO PROCESS DATA

The following MATLAB code is used to format and process the data collected from the

Haptic Master. It also determines values of stiffness, damping, and the equilibrium point

angle.

```
%Here is where I input Haptic data, either manually or through the
MatLab
%workspace
%The equation is F-I*angacc-mgl*cos(thta)
%=k*(thta-thtarest)+k*(thtarest-thtanot)+B(angvel)
x1=HMrecordBrooke8up_2(:,4);
x1=x1(4981:5009);
F1=HMrecordBrooke8up_2(:,5);
F1=F1(4981:5009);
F2=HMrecordBrooke8up_2(:,6);
F2=F2(4981:5009);
F3=HMrecordBrooke8up_2(:,7);
F3=F3(4981:5009);
%F1 and F2 can be neglected in the current analysis, but may become
%important for a continuation of this study
j=HMrecordBrooke8up_2(:,1);
t=i(4981:5009)/1000;
%Here I format and filter the data that will be plotted and analyzed
lf=0.09525;
m=0.005;
g=9.81;
%xnot is the initial position that the haptic master is at immediately
%prior to movement
xnot=0;
%The forces that are measured are negative so they must to converted
via
%absolute value
F1=abs(F1);
F2 = abs(F2);
F3=abs(F3);
[b,a]=butter(2,100/(1000/2));
a1=filtfilt(b,a,x1)';
a2=filtfilt(b,a,F1);
a3=filtfilt(b,a,F2);
a4=filtfilt(b,a,F3);
x2=(a1'-xnot);
v1=Deriv(x2,t)';
acc1=Deriv(v1,t)';
```

```
theta=atan2(x2, 1f) - 0.4775;
thtanot=atan2(xnot,lf);
angvel=Deriv(theta,t)';
anga=Deriv(angvel,t);
I=45.4*10e-006;
%Here I format my matrices prior to the optimization
for i=1:25
    newpos(i)=a1(i);
   b1(i) = a2(i);
    b2(i) = a3(i);
    b3(i) = a4(i);
    x2m(i) = x2(i);
    angv(i) = angvel(i);
   thta(i)=theta(i);
end
%Here I compute the gravitational force exerted on the finger
slpe=thta*(180/pi);
gravity=m*g*lf*cos(slpe);
Here I multiply the force in the z-direction by the length of the
%finger to compute the torque of the finger acting on the Haptic Master
% F=(b1+b2+b3)*lf;
T=(b3)*lf;
Tinit=8*1f;
Ttot=T-Tinit;
thtarest=0;
t4=t3';
% ck=[t4;F];
% save Fck4 'ck'
Iner=(I*anga);
%Here I define matrices C and D that are used to determine damping and
%stiffness
C=([thta; angv])';
d=([Ttot-Iner-gravity])';
%Here I conduct my optimization
[x,resnorm,residual,exitflag,output] = ...
              lsqlin(C,d,[],[],[],[],[],x0);
%Here I set my negative angle convention, by taking absolute values of
the
%impedances
K = abs(x(1));
B=abs(x(2));
%Here I compute the equilibrium point angle thtanot
thtanot=(Tinit/K)-thtarest;
```

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