Articulated Spine for a Robot to Assist Children with Autism

Brandon M. Norton

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Articulated Spine for a Robot to Assist Children with Autism

Brandon M. Norton

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

Articulated Spine for a Robot to Assist Children with Autism

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Master of Science

Autism spectrum disorder (ASD) affects about 1.5 million individuals in the US alone. The consequences of ASD affect families, caregivers, and social structures. This thesis adds to a growing group of people performing research on mitigating the effects of autism through robotics.

Children with ASD tend to interact with robots more easily than with other humans. The goal of robotic therapy is not to help children interact with robots, but to generalize the behavior to humans. An articulated spine is a key to human emotional expression through shaping, weight shifting, and flow. Despite this importance, this feature is all but lacking in robots.

The primary contribution of this work is a novel 3-link planar spine with compliant, partial-gravity-compensating springs, capable of reproducing simple emotion-conveying poses for use in robot-based therapy for children with ASD. The design was based on the movements of expression experts using motion tracking markers. This information was used to optimize the number of links in the spine and their corresponding lengths.

It is the goal of this research to make robotic therapy more effective for the children, raising the potential for life-changing results.

Keywords: assistive robotics, robot spine, optimization, motion capture, compliant mechanisms, compliant spring, autism
ACKNOWLEDGMENTS

I would like to thank my family, especially my wife, for being so supportive of me during this work, even when they had no idea what I was talking about. I couldn’t have done this without them. I would also like to thank Dr. Colton for mentoring me through all my wild ideas. I also thank my colleagues (Jeff, Jacob, Dallin, Ariana, and Marcus) for their brilliant (at times) ideas and for keeping me sane. A big thank you to those in the Magicc Lab for their pool of knowledge and use of the motion capture system. I also would like to thank Pat and Kathie Debenham for their time and talents in the motion capture work.

Most importantly, I would like to thank all the children with ASD and their families for inspiring me during this project. They have taught me about their amazing potential and to recognize their abilities, not their disabilities. It is my hope and prayer that this research can move forward technology that can help children reach their fullest potential. Finally, I thank my Father in Heaven for putting me in a position to do this work.
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CHAPTER 1. INTRODUCTION

In 2008 one in 88 children was diagnosed with some form of Autism Spectrum Disorder (ASD) in the United States [1]. ASD influences not only those diagnosed with the disorder, but also the many caregivers, educators, and others close to them. For children with ASD, achieving social engagement behaviors such as eye contact, emotional sharing, joint attention, and reciprocal exchanges is fundamental to the development of communication and other higher social behaviors. For robot-based therapy to be successful, the child with ASD needs to be able to generalize the social skills learned with the robot for use with other people. Despite showing signs of improvement during therapy sessions, current approaches have not yet reliably generated this result outside the clinical setting.

A long-term hypothesis of the whole project is that a robot with increased human emotional expression will facilitate higher engagement and thereby have potential benefits for the generalization process. This thesis focuses specifically on an articulated spine (bendable, with multiple joints) for a new therapy robot. Our team is creating a new highly expressive upper-body humanoid robot for clinical interactions with children with ASD. This thesis presents the development of the key element in the robot design, an articulated spine that enables emotional expression through shaping, weight shift, and flow; these are principles from Laban Movement Analysis (LMA) that are typically untapped in creating expressive robots [2] [3]. LMA is a study of human movement that is actively studied at BYU, and that is typically applied in the dance and animation fields.

1.1 Previous Work in Robot-Assisted Autism Therapy

Several robots have been created to be used during autism therapy and thorough reviews of them can be seen in [4–6]. Many of these robots are commercial or research robots, not originally designed for autism therapy. This requires modifying the clinical activities to the robot’s capabilities. Some of these robots include: Nao [7], Keepon [8], Pleo [9], and iCub [10]. A no-
table exception is the robot KASPAR [11] which was design specifically for ASD research at the University of Hertfordshire. While KASPAR has an expressive face, it does not include the ability to express emotion through posture, which is the key focus of this thesis.

1.1.1 Previous Work at BYU

Researchers and clinicians at the BYU Comprehensive Clinic previously established criteria for a robot in an ASD therapy team [12, 13]: (a) It must have a size, appearance, and mobility that are likely both to engage a child with ASD and to trigger dyadic and triadic social interactions. (b) It must be capable of engaging in a range of socially-based clinical activities with children, such as taking turns, imitating movement, and performing songs with actions. Other important criteria for the robot included safety and affordability.

To satisfy these requirements, a robot (called Troy) was designed to be the same size as an average 4-year-old child (see Figure 1.1). Troy was situated so that its face was at the eye level of the average seated child, which is important for minimizing any intimidation that the child would feel. Troy was designed to use its arms for simple interaction activities such as pushing a toy car, pressing buttons, pointing, waving hello, and performing actions associated with children’s songs. Troy is a stationary robot mounted on a stable base and controlled by a laptop computer that sits out of the child’s immediate reach [14].

Figure 1.1: A Clinician Engaging a Child in the Clinic Using the Robot Troy
Activities in a typical therapy session emphasize situationally appropriate affect, expressed using sound and facial expressions. The robot was designed with a seven-inch computer screen “head” encased in plastic and mounted on a two-DOF (pan and tilt) neck. The screen presents a simple, cartoon-like face that can display happy, sad, or neutral emotions. A speaker inside the torso allows Troy to vocalize pre-recorded exclamations, sentences, and songs. A student from BYU’s Music-Dance-Theater program recorded customized greetings for each participant, positive-affect sounds (such as “Woo hoo!”) and negative-affect sounds (such as “Whoops!”). During therapy sessions, the clinician selected robot behaviors and activities using a wireless Wii remote.

Professor Debenham (Department of Dance) previously worked with our team to evaluate the expressive capability of Troy. Using techniques from LMA, the limitations of Troy guided our team to a set of subjective requirements for the design of a new, more expressive upper-body humanoid robot. These requirements include an articulated spine. Although there are a small number of robots being researched that have spines [15] [16], most are focused on being as realistic as possible, whereas the objective for our robot is to best convey human emotion. One notable exception is the WBD-2 robot developed at Waseda University which was designed to mimic the emotional expressions used by belly dancers [17].

1.2 Research Objectives

The driving motivation behind this research was to design a robot that will be maximumly effective at helping children with ASD generalize social behaviors. The specific contributions of this thesis are the design, modeling, analysis, and control of an articulated spine for a clinical upper body humanoid robot to interact with children with autism.

The primary considerations were:

1. Safety of the child during interaction.

2. Emphasis of motion and posture over realistic appearance to convey emotion.

(a) Express many different types of emotion while maintaining simplicity.
(b) Maximize the number of possible expressive postures while minimizing the number of joints and motors needed.

3. Non-threatening in order to encourage social engagement.

(a) Mechanical look and features maintained while having an inviting appearance so the children are not afraid of it.

(b) Avoid having irritating or frightening noises often generated by traditional RC servos that would cause the child to escalate to uncontrolled behavior.

4. Inexpensive to manufacture and maintain.

1.3 Approach and Contributions

This thesis is primarily focused on constructing a robot capable of executing poses and dynamic motions that reflect distinguishable emotional cues and states. In order to accomplish this, the following tasks were completed and will be discussed in this thesis:

• Analysis of the motion of the human spine during various emotional expressions using motion capture techniques.

• Optimization of the number of spinal joints and joint locations for effective emotional expression.

• Development of a computer simulation model of the new robot spine.

• Development of the forward and inverse kinematics, including the D-H parameters, needed for simulation and control.

• Design and construction of a physical robot spine for testing and later use in clinical studies.

• Design of a new partial-gravity-compensating spring system using compliant beams

• Testing of the robot to ensure that it is well controlled and durable enough to be used safely around children.
1.3.1 Motion Analysis of Human Spine During Various Emotional Expressions

To determine the number of joints and range of motion needed in the articulated spine to accurately convey critical emotions, the human spine was analyzed. Motion capture techniques were used to record the motion of LMA experts as they formed various expressions of interest to the clinicians. This differs from the approach used at Waseda University where the expressions were simply estimated visually using a computer model [17].

These data were used to optimize the number of joints as well as the distance between them to find the best design. To find the number of joints, a least squares method was used to fit the data into linear sections, representing robot links. The optimization goal was then to minimize the number of these linear sections while being able to form the expressions as accurately as possible. As this was a multi-objective problem with competing objectives, a Pareto front was generated of many possible optimal solutions [18]. The final design was chosen based on the weighting factors between the objective goals and also using the intuition and experience of the team. Details of the motion capture will be described in Chapter 2, and the optimization will be described in Chapter 3.

1.3.2 Articulated Spine for Enhanced Expressiveness

Using the results of the optimization, an upper-body humanoid robot with an articulated (jointed) spine was developed. Spine articulation is of particular importance in our approach to ASD treatment, wherein robot shaping, weight shifting, and flow are emphasized as means for expressing engagement, interest, and emotion. The type of expressions needed were researched and determined with recommendations from LMA experts and clinicians.

In the design process, simplicity was emphasized as the key to minimizing costs, facilitating control, and maximizing repeatability and reliability. Where possible, the number of joints were minimized, while still maintaining acceptable motion characteristics. For example, the initial robot is only capable of spinal flexion/extension, but lateral bending and/or rotation may be added in future work, if necessary to achieve the motions specified by clinicians and LMA experts.
The final design for the spine was chosen based on the result of the motion analysis and joint optimization model described earlier. The final design is discussed in greater detail in Chapter 4 and can be seen in Figure 1.2

Figure 1.2: Robot Spine Design

Although achieving the desired spine motion characteristics was the primary consideration in our design, we also designed for safety, affordability, and modularity. The stresses that the robot will need to withstand were based on the weight of the robot head, arms, and upper body in addition to anything that might be placed on it. The robot was tested for accuracy, repeatably, and overheating using methods similar to those used with Troy [14].

The forward and inverse kinematics, including the D-H parameters, were developed for use in simulation and control. A computer simulation of the model, including link dynamics, was created to assist in the design and control process. The joint motors are controlled by a local microcontroller.
1.3.3 Partial-Gravity-Compensating Compliant Springs

In the process of designing the articulated spine, a need was found for gravity-compensating springs to decrease the torque requirements of the motors. Traditional torsional springs are only able to assist in a single direction. This led to a new spring design (described in Section 4.4) using the Pseudo-Rigid-Body Model [19]. This design is novel because it uses information about the characteristic pivot to place the equivalent spring in line with the motor axis, acting as a continuous, multi-directional torsional spring.
CHAPTER 2. POSE CAPTURE FOR DESIGN OF A ROBOT SPINE

This chapter describes the motion capture experiment used to design the robot spine. The motion of dance experts was recorded to measure the location of different parts of the spine during various expressions. These expressions are used to determine the poses that the robot should be able to imitate.

To design the robot spine, two important parameters needed to be defined: how many links and how long these links should be. These parameters would define where the joints and motors needed to be, rather than using a best guess approach. We decided to model the robot based on the shape of the human spine during several key poses, discussed later. To ensure that the shapes were modeled correctly we used the motion of two Laban Movement Analysis (LMA) experts from the Department of Dance.

To measure the spinal movement of the LMA experts, motion capture tracking was used. The movements of the experts were recorded as they enacted several poses representing different emotional states. The recordings were analyzed to identify the important positions and orientations that the robot should be able to reach.

2.1 Key Expressions

The most important poses that the robot should be able to imitate are those that will bring the greatest benefit to children with ASD. The poses were selected in consultation with clinicians in the Department of Communication Disorders. They indicated that the most important emotions for robot-based therapies are neutral, happiness, and sadness. These are followed by the other basic emotions of fear, anger, surprise, and disgust [20]. We added interest as an expression that the clinicians thought could be useful in showing joint attention.
2.2 Experimental Setup

Two LMA experts from the Department of Dance at BYU were instrumented with reflective markers (1/2” diameter balls) to measure the pose of their spine as they enacted the emotional states described above. These markers were tracked using the Cortex Motion Analysis System© and 8 Hawk Digital© cameras with a resolution of 640x480. The frame rate was set to the default 200 frames per second. The accuracy of the measurements can vary depending on how well the cameras are calibrated and how large an area is being recorded. A calibration routine described in the Cortex user manual was performed just prior to the testing. Results are reported in thousandths of a mm, but true accuracy is much less than that. We chose to round to the nearest mm because that is sufficiently small for the design of the robot and is within the accuracy of our setup.

The motion capture setup was designed to accurately model the human spine with as few markers as possible to reduce computational expense and avoid markers interfering with each other. The different regions of movement in the human spine are documented by White and Panjabi [21]. There are several coupled regions of the spine that have similar movement characteristics. These regions are described in Table 2.1.

<table>
<thead>
<tr>
<th>Spine Region</th>
<th>Spine Vertebrae</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Cervical</td>
<td>C0-C2</td>
</tr>
<tr>
<td>Middle Cervical</td>
<td>C3-C5</td>
</tr>
<tr>
<td>Lower Cervical</td>
<td>C5-T1</td>
</tr>
<tr>
<td>Upper Thoracic</td>
<td>T1-T4</td>
</tr>
<tr>
<td>Middle Thoracic</td>
<td>T4-T8</td>
</tr>
<tr>
<td>Lower Thoracic</td>
<td>T8-L1</td>
</tr>
<tr>
<td>Lumbar</td>
<td>L1-L5</td>
</tr>
<tr>
<td>Lumbosacral</td>
<td>L5-S1</td>
</tr>
<tr>
<td>Sacroiliac</td>
<td>S1</td>
</tr>
</tbody>
</table>

Using this information, markers were placed at the following vertebrae: C2, C4, C7, T4, T8, L1, L3, and L5, as shown in Figure 2.1. This set of vertebrae included one from each region with an additional marker in the lumbosacral region because of the increased range of motion in that area [22].
The markers were attached to a tight-fitting shirt, with double-sided sticky tape, to reduce movement between the markers and the skin. Skin movement was not considered significant compared to the increase in complexity to account for it. Tight-fitting wig caps were worn on the head to enable a marker to be placed there.

Two extra markers were placed in the shoulder and hip regions to measure any axial twist in the spine. This would be important to show if there was significant enough twist to justify adding that type of motion to the robot. The dancers were aligned in the room such that their body started along the principle axis for the motion capture software. This made it so that if there was no significant twist, no transformations would be needed to get the data into a two dimensional plane.

The participants were recorded one at a time, finishing the set of expressions before the next person started. Both were in the room during the recording process and had a list of the expressions to practice. Instructions were given to the participants one at a time, for example, “Please show a happy expression.” The recording was then started and the participant moved from neutral position, through the expression and back to the neutral position. This was repeated twice.
for each expression. There were two motion capture directors in the room during the recordings, one to give instructions and one to operate the recording equipment.

2.3 Capture of End Points

The robot design was based on the endpoints of the poses, when the LMA experts reached a static pose corresponding to a given emotion. Each expression had a noticeable stopping point where, for example, the expert had finished leaning forward and came to a stop. Another example would be during a sad movement when the expert had finished slouching and stopped any other movement. Each expression had a moment like this, and these were defined as “end points.”

2.4 Results of Motion Capture

The output from the motion capture software for each expression was a file listing the position, velocity, and acceleration of each reflective marker for each sample period. The velocity and acceleration were ignored for our purposes. Each capture could also be played back, showing a wire frame similar to those in Figure 2.2. This was used to find the end points of each expression. For example, Figure 2.2 shows the capture of the sad expression in the neutral position and then in the end point position. The frame at which each end point occurred was used for the end point interpolation, described later.

Each end point was analyzed to make sure it stayed within the starting plane to confirm that no transformation was needed. No noticeable out of plane motion was observed in the end points, helping to confirm the motivation for only forward/back and up/down movement.

During the analysis and review of the data it was found that one reflective marker on one of the participants was placed too close to an adjacent marker. When this happens the computer is no longer able to distinguish the two and the separate information is lost. We were unable to consistently correct this and decided to move forward with only one individual. This was done for two primary reasons: first, the data that we were able to see seemed to match closely between the two; secondly, we were not trying to model exact human motion, just construct a robot capable of displaying certain emotions. Capturing multiple trials from a single participant was determined to be sufficient for our purposes.
2.4.1 End Point Interpolation

A polynomial curve was fit to the motion capture data to interpolate between the markers. The polynomial fit was necessary to compare the captured spine positions with the robot link positions at points other than where the markers were placed. The y-axis values were treated as the independent variable while the x-axis values were the dependent. This is the inverse of traditional curve fitting to allow for more than one y value corresponding to a given x value as when the spine curves back on top of itself.

A 4th-order fit was chosen because it matched the data well while still maintaining a smooth spine-like shape. Figure 2.3 shows the difference between 3rd-, 4th- and 5th-order polynomial fits. The higher order used, the better the polynomial will match the given data set of points but the more likely that it will become very specific to that set. A high order polynomial fit would match the data perfectly but not accurately portray what happens between the points. For this reason the 4th order was chosen such that it still closely matched the data points but was not so specific as to not work with the shape of other instances of the same pose.

Before fitting a polynomial to the data, the origin was placed at the lowest marker, creating a good reference point to compare the different poses. The fit curves were made by first creating a set of points in one mm increments from zero to the height of the top marker in the y direction.
Each point was then evaluated using the curve fit to find the corresponding x values. An example of this can be seen in Figure 2.4.

2.5 Conclusion

Motion capture was used on LMA dance experts to create a model of the human spine during several key poses. Eight reflective markers were used to capture the position of the spine in important regions of the spine. A curve was fit to these positions and interpolated to estimate the shape of the human spine in each pose. As discussed in Chapter 3, the curve fits were used to optimize the number and length of links in a robot spine capable of imitating the recorded poses.
Figure 2.4: Polynomial Fit Example Poses. Top: Neutral. Bottom: Sad.
CHAPTER 3. SPINE GEOMETRY OPTIMIZATION USING POSE CAPTURE DATA

This chapter describes the optimization approach used to determine the number and length of links and optimal angles used in the robot design. The goal for this optimization work was to find the right balance between simplicity in design and flexibility in human expression. Different numbers of links were explored and the optimal design found for each one, generating a Pareto frontier. These designs were then compared against each other to select the final design.

3.1 Motivation for Optimization

Most current research on robot spines is based on an approach similar to [17], where the design of the robot is based on intuition and a subjective evaluation of what looks right. This leads to an arbitrary selection of the number of joints/links and where to place them in the spine. Because we have a specific set of expressions that the clinicians will be using, the robot could be designed to have the capability to generate those poses.

The purpose of the robot is to help children with ASD to recognize and respond to different human emotions. Because of this, the robot spine does not need to be designed to precisely match the human spine. To keep the robot simple, affordable, robust, and easy to use, we emphasized achieving sufficient accuracy with as few links/joints as possible.

3.2 Two Dimensional Analysis

It was decided to build a robot that could only move in the sagittal plane. This decision was made for two reasons. First, the robot should be as simple as possible—when working with children with ASD, the simpler the better. Second, it was seen that most expressions start and end in that plane (as described in the previous chapter).

For many children with ASD, it takes longer to process what they are seeing as it is happening [23]. This makes large elaborate expressions ineffective for the learning of emotions. The robot
will be most effective if it moves from different poses quickly and then holds there for enough time for the child to recognize the emotion.

Although it is beyond the scope of this thesis, the robot spine will be used and tested in a clinical setting. If the spine is confirmed to be effective, and thought that the children could benefit from more complex motion, then a more expensive and complex spine should be considered in the future.

3.3 Optimization Approach

To quantify the difference between candidate designs, an objective was created. The objective was to minimize the difference between the curve fit of the motion capture data in a given pose and the candidate robot design in that same pose. The variables in the optimization were the number of links, the lengths of those links, and the angles of each link (described in detail later).

The number of links the robot could have was a discrete variable ranging from one to five. Once the number of links had been chosen, the best set of link lengths was found using a multilevel optimization approach, described later.

To compare the optimized links to the motion capture data the area between the two was measured. To do this, the absolute difference was found in the x direction for each point along the y axis and then multiplied by the difference in the y direction as seen in the following equation:

\[
\text{Objective : Minimize } \sum_{i=1}^{\text{Poses}} \text{Error}_i
\]

\[
\text{Error}_i = \sum_{j=1}^{Y_{\text{max}}} \text{WeightFactor}_j \times |\text{Human}X_j - \text{Robot}X_j| \times \Delta Y_j
\]

where \(X_j\) represents the position in the x direction, \(\Delta Y_j\) represents the displacement in the y direction, and \(\text{WeightFactor}\) is a weighting factor discussed later. Figure 3.1 shows an example of what this might look like for a single-link case. The shaded area was summed for each of the poses to find a total error in \(mm^2\) for that set of lengths.
3.3.1 Multilevel Optimization

The angles that the robot links need to fit each pose cannot easily be found directly with more than two links because of the redundant degrees of freedom. This means that an optimization solver is needed to solve for the angles that get the robot the closest to matching each motion capture pose.

A challenge for the optimization approach in this application is that the robot can only have one set of lengths for all expressions. The angles, on the other hand, need to be different for each expression. This means that the optimal lengths and angles need to be solved separately, causing the need for multilevel optimization [24]. The different levels of optimization were the following:

- **Number of Links/Joints**: Discrete values from 1-5 (changed by hand)
  
  - **Link Lengths**: Optimal set of link lengths for each number of links (outer loop)
  
  - **Angles**: Optimal set of angles for each pose (inner loop)

The multilevel optimization approach allows each expression to have its own set of angles optimized for the minimum difference area. This area is then added to a total combined area for
the objective of the link-length optimization. The most important expressions (neutral, happy, and sad) were given an increased weighting factor of two (see Equation 3.1).

The multilevel approach allows for the use of multiple core processors using parallel computing. While this dramatically decreases the amount of time to solve, this method is still computationally expensive. The higher the number of links, the more time is needed to solve, sometimes taking an hour or more to converge for five links. The optimization was done using an Intel Core i7-4770 CPU @3.4GHz using 64-bit Windows 7.

3.3.2 MATLAB Optimization

MATLAB was used for the optimization with the following algorithms:

- fminsearch
- fmincon
  - SQP
  - Interior-Point
  - Active-Set

The fminsearch method does not allow constraints, but none were required because of the nature of the objective. Constraints were added for the other methods to limit the lengths to be greater than zero and the angles to be within 0° and 360°, helping the solver converge quicker. Each solver algorithm gave slightly different results depending on which combination was used for the length and angle optimizations (inner and outer loops). Every combination was tried and the best algorithm and results chosen for each number of links. Multiple starts were used on the final results to confirm that a global optimum had been reached.

3.4 Results

Table 3.1 shows the results of the optimization for candidate spines with one to five links. Figure 3.2 shows the error objective as a function of the number of link lengths. This plot follows the expected trend of decreasing as the number of links increases. As the number of links increase,
the amount of improvement decreases and reaches a horizontal plateau. For example, there is much less improvement between three and four links as there was from one to two. The percent relative improvement as a result of adding additional links can be seen in Figure 3.3.

Table 3.1: Optimal Link Length Results

<table>
<thead>
<tr>
<th>1 Link</th>
<th>2 Links</th>
<th>3 Links</th>
<th>4 Links</th>
<th>5 Links</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm)</td>
<td>Error (mm²)</td>
<td>Length (mm)</td>
<td>Error (mm²)</td>
<td>Length (mm)</td>
</tr>
<tr>
<td>588</td>
<td>3.0E+5</td>
<td>232</td>
<td>7.8E+4</td>
<td>271</td>
</tr>
<tr>
<td>377</td>
<td></td>
<td>253</td>
<td></td>
<td>129</td>
</tr>
<tr>
<td></td>
<td></td>
<td>85</td>
<td></td>
<td>245</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>68</td>
</tr>
</tbody>
</table>

Figure 3.2: Objective Error by the Number of Robot Links
3.4.1 Number of Links

Optimization was used to find the minimum difference between the human motion capture spine and a robot spine with various link lengths. There was a competing objective of minimizing complexity, causing human judgment to come into play for the final result. Figure 3.3 was a valuable tool to help show how much improvement is gained as the number of links increase. This effectively forms a Pareto front, comparing the competing objectives of error to the complexity and cost, increasing as the number of links increases.

The improvement of over 300% from one link to two is a very large improvement, and therefore, worth the added complexity. The improvement of 51% from two links to three is also worth the increase in complexity. With the change from three to four links only bringing an improvement of 17%, the question then became a matter of engineering judgment.

If each increase in the number of links adds the same amount of complexity (which is a conservative estimation) then the increase from one to two links has a relative increase in the complexity of 50%. The relative increase from two to three is 33% and the relative increase from
three to four is 25%. This means that the change from three to four links increases the relative complexity more than it decreases the relative expression error.

The figures in Appendices A and B show a visual representation of the robot spine matching the motion capture data poses. The capability of the four link robot was deemed an insufficient reason for the added cost and complexity of the design. The three link robot was chosen as the design for our needs.

3.4.2 Optimal Angles for Each Pose

Each pose had a set of optimal angles for each link length that best fit the objective. Figure 3.4 shows the optimal angles for each pose, represented by the “pose number.” For example, the first motion capture pose was best fit with link 1 at -5 degrees, link 2 at 30, and link 3 at -35 degrees. Using this information, ranges of motion were determined for each joint.

![Figure 3.4: Optimal Robot Joint Angles Corresponding to Different Poses](image)
3.5 Scaling for Robot Design

Since the data were captured from the motion of an adult, the dimensions that were found for the new robot needed to be scaled down to the size of a child. The new robot will be approximately the same size as the robot Troy, that was based on the size of a four-year-old child. The average four-year-old child has a length of 16 in from the waist to the middle of the head [25], corresponding to the locations of the motion capture markers. The corresponding distance of the dance expert used in this experiment gives a measurement of 23.2 in.

To scale the measurement down, the ratio of child to dance expert was found to be 0.70. This gives a corresponding length of 7.5 in for the bottom link, 7.0 in for the middle link, and 2.3 in for the top link (see figure 3.5). The bottom link starts at the waist, and the top link extends to the midpoint of the head.

Figure 3.5: Final Robot Link Lengths
3.6 Conclusion

The curve fit data for each expression captured during the motion capture was used to select the geometry of the robot spine. The number and length of the links, as well as the optimal angles, were found using a multi-level, multi-objective optimization. A robot with three links in the spine was determined to be sufficient, and the link lengths were scaled to the size of a four-year-old child.
CHAPTER 4. ROBOT DESIGN AND TESTING

The new robot, Helen, was designed to be as useful as possible to the children and therapists. It was based on the design of its predecessor, Troy, and meant to be able to work beside Troy if desired. The size and proportions were based on a four-year-old child with measurements from [25].

Special care was taken to account for the appearance of the robot both with and without power supplied to the motors. If the robot was turned off in the presence of the child, to avoid traumatizing the child, it was designed to not quickly crumple to the ground as if dead. Motor noise was also minimized to avoid agitating sounds. The final design can be seen in Figure 4.1.

4.1 Spine Links and Joints

The spine is comprised of two torso links and a neck link, each with their own motor. The lengths of each link were found using the optimization in the previous chapter. Directly driving each link with servo motors at the joints was determined to be the simplest way to drive the links. Initial research was conducted to examine the possibility of driving each link using Bowden cables connected to motors at the robot base [26–28]. This method would have worked, but was found to have a large amount of energy losses. The weight of each motor was also small enough that placing the motors at each joint, rather than at the base, was found to be a practical solution.

To assist in body shaping, and to accommodate the compliant springs (talked about later in this chapter), the torso links were designed with two vertical parallel members (see Figure 4.1). One side of each link is actuated. A second motor can be added to the other side of the link in the future if more torque is needed. This could be important if hands or other improvements are added in future development.

The robot’s neck and head regions are a direct continuation of the spine. The third link found in the optimization is used as the neck and spans the distance from the second link to the
middle of the head. This distance is small enough that it is essentially comprised of the pan and tilt combination of the motors. The pan motion was included to give Helen the same head rotation capabilities as Troy.

The total mass of the robot, including the neck motors, is 3.6 kg. The base of the robot (beneath the links) is 2.0 kg, including the controller and power supplies. The total mass of the spine is 1.6 kg. With the extra weight in the wide base, the robot is stable and not likely to be tip over, even if a child were to push on it with reasonable force.

Future work, beyond the scope of this thesis, will add a head to link 3 and arms to link 2. The head will be placed such that the midpoint of the head, just behind the eyes, is placed at the
top of the neck link. The arms will be placed approximately 3.5 inches above the second joint to maintain the proportions given in [25].

4.2 Spine Kinematics

The forward and inverse kinematics of the spine were developed using a modified version of Craig’s Denavit-Hartenberg (D-H) parameters [29]. The D-H parameters can be seen in Table 4.1, where $L_1$ is the length of link 1, $L_2$ is the length of link 2, $L_3$ is the length of link 3, and $\theta_1$, $\theta_2$, $\theta_3$, and $\theta_4$ represent the rotations from the zero configurations about the z-axis of motor 1, motor 2, motor 3, and motor 4 respectively. $\theta_1$ is measured from the vertical axis and defined to be zero when link one is straight up. $\theta_2$ is referenced from link 1 and defined to be zero when link 2 extends parallel from link 1. $\theta_3$ measures the twist of the neck attached to the top of link 2 and defined to be zero when the head is looking straight. $\theta_4$ is defined to be at zero when the neck link (link 3) extends parallel from link 2. The transformation parameters $a$, $d$, $\theta$, and $\alpha$ are described in [29]. The coordinate frames, link lengths, and joint angles can be seen in Figure 4.2.

<table>
<thead>
<tr>
<th>Rotational to Frame</th>
<th>$a$</th>
<th>$d$</th>
<th>$\theta$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>$\theta_1 - 90^\circ$</td>
<td>$-90^\circ$</td>
</tr>
<tr>
<td>2</td>
<td>$L_1$</td>
<td>0</td>
<td>$\theta_2 - 90^\circ$</td>
<td>$0^\circ$</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>$L_2$</td>
<td>$\theta_3$</td>
<td>$-90^\circ$</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>$\theta_4$</td>
<td>$90^\circ$</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>$L_3$</td>
<td>$180^\circ$</td>
<td>$-90^\circ$</td>
</tr>
</tbody>
</table>

Using the D-H parameters, the forward kinematics were solved using traditional robotics rotation matrices. Equation 4.1 shows the local homogeneous transformation matrix $(i-1)A_i$ which relates the previous link coordinate frame $\{i-1\}$ to the current frame $\{i\}$.

$$i-1A_i = \begin{bmatrix}
\cos(\theta_i) & -\sin(\theta_i) & 0 & a_i \\
\sin(\theta_i)\cos(\alpha_i) & \cos(\theta_i)\cos(\alpha_i) & -\sin(\alpha_i) & -\sin(\alpha_i)d_i \\
\sin(\theta_i)\sin(\alpha_i) & \cos(\theta_i)\sin(\alpha_i) & \cos(\alpha_i) & \cos(\alpha_i)d_i \\
0 & 0 & 0 & 1
\end{bmatrix}$$

(4.1)
where, for revolute joints, $\theta_i$ is the joint angle variable and $d_i$ is a constant displacement. $\alpha_i$ and $a_i$ are always constants [30]. The robot specific values for each frame are shown in Table 4.1.

Multiplying each individual transformation matrix gives the final homogeneous transformation ($T$), relating the position and orientation at the final frame (at the neck) to the global frame ($[X_0, Y_0, Z_0]$), located at the base. The result is given in Equation 4.2, which uses standard robotic
trig notation (e.g. \( S_{12} = \sin(\theta_1 + \theta_2) \)).

\[
T = \\
\begin{bmatrix}
S_{12}S_4 - C_{12}C_3S_4 & S_{12}C_4 + C_{12}C_3S_4 & -C_{12}S_3 & L_2S_{12} + L_1S_1 - \frac{L_3C_{12}C_{34}}{2} + L_3S_{12}S_4 - \frac{L_3C_{3-4}C_{12}}{2} \\
-C_4S_3 & S_3S_4 & C_3 & -L_3C_4S_3 \\
C_{12}S_4 + S_{12}C_3C_4 & C_{12}C_4 - S_{12}C_3S_4 & S_{12}S_3 & L_2C_{12} + L_1C_1 + \frac{L_3C_{34}S_{12}}{2} + L_3C_{12}S_4 + \frac{L_3C_{3-4}S_{12}}{2} \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(4.2)

Following the solution procedure in [31], the elements in \( T \) are renamed in Equation 4.3 to simplify later equations.

\[
T = \\
\begin{bmatrix}
n_x & s_x & a_x & p_x \\
n_y & s_y & a_y & p_y \\
n_z & s_z & a_z & p_z \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(4.3)

The inverse kinematics (i.e., finding joint angles given the Cartesian endpoint location and rotation matrix, \( T \)) had to be solved in two different segments because of the mathematical singularity that occurs when the neck rotation (\( \theta_3 \)) is zero. The inverse kinematics were tested by first using the forward kinematics to produce the end point (head) position and rotation matrix using known joint angles. The result was then substituted into the inverse kinematics equations and solved to ensure that the same angles resulted. The correct results were found using any joint angles that the robot can physically attain. Special cases dealing with signs were tested until all possible robot positions could be inverted to the correct joint angles, matching the angles possible for the human spine.

### 4.2.1 Inverse Kinematics When \( \theta_3 \) is Not Zero

When \( \theta_3 \) is not zero, the top two angles can be solved based on the displacement in the \( y \)-direction. The remaining two angles can be solved based on the displacement from the origin in the \( x \)- and \( z \)-directions. Equations 4.4 – 4.15 (with atan2(\( y, x \))) show the method used to solve for the angles, including any correction factors to ensure that the angles are reasonable for the human spine.
\[ \theta_3 = \tan^{-1} \left( -\sqrt{1-a_y^2}, a_y \right) \] \hspace{1cm} (4.4)

\[ \theta_4 = \tan^{-1} \left( \frac{s_y}{\sin(\theta_3)}, \frac{-n_y}{\sin(\theta_3)} \right) \] \hspace{1cm} (4.5)

\[ \text{if } \theta_4 \geq \frac{\pi}{2} : \theta_4 = \theta_4 - \pi, \theta_3 = \tan^{-1} \left( \sqrt{1-a_y^2}, a_y \right) \] \hspace{1cm} (4.6)

\[ \text{if } \theta_4 < \frac{\pi}{2} : \theta_4 = \theta_4 + \pi, \theta_3 = \tan^{-1} \left( \sqrt{1-a_y^2}, a_y \right) \] \hspace{1cm} (4.7)

\[ \sin(\theta_1) = p_x - L_3 n_x - L_2 n_x \sin(\theta_4) - L_2 s_x \cos(\theta_4) \] \hspace{1cm} (4.8)

\[ \cos(\theta_1) = p_z - L_3 n_z - L_2 n_z \sin(\theta_4) - L_2 s_z \cos(\theta_4) \] \hspace{1cm} (4.9)

\[ \theta_1 = \tan^{-1} (\sin(\theta_1), \cos(\theta_1)) \] \hspace{1cm} (4.10)

\[ \text{if } \theta_1 < -\frac{\pi}{2} : \theta_1 = \theta_1 + \pi \] \hspace{1cm} (4.11)

\[ \text{if } \theta_1 > \frac{\pi}{2} : \theta_1 = \theta_1 - \pi \] \hspace{1cm} (4.12)

\[ \sin(\theta_2) = s_x \cos(\theta_4) + n_x \sin(\theta_4) \] \hspace{1cm} (4.13)

\[ \cos(\theta_2) = s_z \cos(\theta_4) + n_z \sin(\theta_4) \] \hspace{1cm} (4.14)

\[ \theta_2 = \tan^{-1} (\sin(\theta_2), \cos(\theta_2)) \] \hspace{1cm} (4.15)

### 4.2.2 Inverse Kinematics When \( \theta_3 \) is Zero

When \( \theta_3 \) is zero, the inverse kinematics can be solved using any method for three link planar robots. With \( \theta_3 = 0 \), the final rotation matrix simplifies to Equation 4.16. Equations 4.17 –
4.27 show the method used to solve for the joint angles.

\[
\begin{bmatrix}
    n_x & s_x & a_x & p_x \\
    n_y & s_y & a_y & p_y \\
    n_z & s_z & a_z & p_z \\
    0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
    -C_{124} & S_{124} & 0 & L_2S_{12} + L_1S_1 - L_3C_{124} \\
    0 & 0 & 1 & 0 \\
    S_{124} & C_{124} & 0 & L_2C_{12} + L_1C_1 + L_3S_{124} \\
    0 & 0 & 0 & 1
\end{bmatrix}
\]

(4.16)

\[i f \ p_y = 0 : \theta_3 = 0\]

(4.17)

\[x_2 = p_x - L_3n_x\]

(4.18)

\[z_2 = p_z - L_3n_z\]

(4.19)

\[L = \sqrt{x_2^2 + z_2^2}\]

(4.20)

\[\cos(\theta_2) = \frac{L^2 - L_1^2 - L_2^2}{2L_1L_2}\]

(4.21)

\[\theta_2 = \text{atan2} \left( \sqrt{1 - \cos^2(\theta_2)}, \cos(\theta_2) \right)\]

(4.22)

\[\alpha = \text{atan2} (L_2 \sin(\theta_2), L_1 + L_2 \cos(\theta_2))\]

(4.23)

\[\beta = \text{atan2} (z_2, x_2)\]

(4.24)

\[\theta_1 = \frac{\pi}{2} - \alpha - \beta\]

(4.25)

\[\Theta = \text{atan2} (s_x, s_z)\]

(4.26)

\[\theta_4 = \Theta - \theta_1 - \theta_2\]

(4.27)

4.3 Robot Dynamics and Torque Requirements

Using the method of Lagrange [32], the dynamics of the robot were analyzed to solve for the torques at each joint. This was done for simulation purposes and to choose motors that could drive the robot links. The full joint torque equations can be found in Appendix D.
In deriving the dynamic equations, the arms were considered part of the second link, as they would be attached to the shoulders there. The inertia of the second link was calculated to include the inertia of the arms. Because the arms are still in development, the size and weight of the robot Troy’s arms were used. This gave a total weight for each arm as 0.52kg and a weight of 0.36kg for the head.

Based on the expected speeds and positions of the joints, the maximum motor torques were found using the dynamic equations. To do this, assumptions had to be made regarding the maximum link velocities. It was assumed that the spine should be capable of moving back and forth across the joint ranges with a period of two seconds. Figures 4.3, 4.4, and 4.5 show the torque required for each motor given the joint angles, velocities, and accelerations described. Motor 1, motor 2, and motor 4 were moving at the same time, meaning each joint was in phase, adding to the motion of the subsequent joints.

The expected torques (with the arms straight out) for motor 1, motor 2, and motor 4 were 4.0, 2.8, and 0.25 Nm respectively. The high torques for motor 1 and motor 2 were undesirable because of the cost of motors that could produce that much torque. This led to the development of the compliant springs explained below. The torque requirement for motor 4 was low enough that spring assistance was not necessary. Since motor 3 does not support the weight of the symmetrical head and only needs to overcome the inertia effects, the torque required will be less than that of motor 4.

<table>
<thead>
<tr>
<th>Motor #</th>
<th>Max Expected Torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.0</td>
</tr>
<tr>
<td>2</td>
<td>2.8</td>
</tr>
<tr>
<td>3</td>
<td>0.25</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Figure 4.3: Dynamic Torque Estimate for Joint 1

Figure 4.4: Dynamic Torque Estimate for Joint 2
4.4 Compliant Springs for Partial-Gravity-Compensation

Springs have been proposed as a means to reduce the amount of torque that a motor needs to produce to overcome gravity in large robots [33–35]. Designs with traditional torsional springs only allow assisted rotation in one direction, for example leaning forward. The robot spine needs to be able to be assisted in leaning both forward and backward. This is why we chose to design a flat, compliant spring to accomplish the needed motor assistance.

Howell proposed in [19] that a compliant beam in bending can be modeled with two rigid links, a pin joint, and a torsional spring (see Figure 4.6). This is known as the Pseudo-Rigid-Body Model (PRBM). If designed with the characteristic pivot in line with the robot joint, the beam can act like a two-direction torsional spring. By placing the characteristic pivot in line with the motor axis (see Figure 4.7), the spring maintains the linear relationship between torque and the robot joint angle. Another advantage of the pivot in line with the motor axis is that the top of the spring has minimal linear movement as the robot rotates.
Different spring constants can be achieved by changing the thickness, length, and width of the beam. The length and thickness are important for the maximum deflection of the beam, $\delta_{\text{max}}$,

$$
\delta_{\text{max}} = \frac{2 \cdot \text{Yield Strength} \cdot \text{Length}^2}{3 \cdot \text{Young's Modulus} \cdot \text{Thickness}}.
$$

(4.28)

The longer and thinner the beam, the farther it can deflect without failing. The equivalent torque constant, $K_{eq}$, is found by

$$
K_{eq} = \gamma K_\Theta \frac{\text{Young's Modulus} \cdot \text{Width} \cdot \text{Thickness}^3}{12 \cdot \text{Length}}
$$

(4.29)

where $\gamma$ and $K_\Theta$ are constants described in [19]. The thickness is a key factor as it appears with a cubic factor in Equation 4.29. Width only appears in the torque constant equation, allowing the beam to be stiffer without adverse affects on the maximum deflection.

The springs designed for our robot were optimized to reduce the torque in each motor assuming that the robot is stationary. This means that the spring will assist in removing the effect of gravity, but not the dynamic torques caused by inertia. This was done so that the robot could
potentially remain in place given a loss of power to the motors. The orientation of the future arms has a large impact on the torque required at each spine joint. Multiple arm orientations were simulated and the springs were designed to minimize the worst case torque required by each motor.

4.4.1 Spring Material and Geometry

The spring dimensions were optimized to provide the best spring torque with the lowest stress at the maximum expected deflection. The length was fixed at the longest possible because it appears as a squared factor in Equation 4.28. Thickness was changed to give a reasonable safety factor against yield and fatigue during the maximum deflection. The width was set at the widest possible while still allowing the robot to fit within the size of an average four-year-old child’s torso.
The springs were made from fully hardened 301 stainless steel, giving them a high yield strength of 979 MPa, an elastic modulus of 190 GPa, and an ultimate strength of 1380 MPa. To lower the stress in the springs while maintaining the correct stiffness, four springs were placed back to back, cantilevered at the bottom, and allowed to slide relative to each other at the top as they curve, as shown in Figure 4.7.

The lower spring was designed with a thickness of 0.020 in, a length of 7.5 in, and a width of 2.36 in. The length was effectively pinned at the top with rollers at a height of 6.51 in. This kept the characteristic pivot in line with the motor. The upper spring was designed with a thickness of 0.015 in, a length of 5.75 in, and a width of 2.17 in. Similar to the lower spring, the upper spring was pinned at the height of 4.76 in. To best offset the weight of the robot, having the correct torque at a given angle, the springs are undeflected when $\theta_1$ and $\theta_2$ are at angles of 8 degrees and -15 degrees respectively (see Figure 4.7). The springs were cut using an abrasive water jet because of the hardness of fully hardened stainless steel (Rockwell Hardness C40-C45).

Each spring was designed to avoid failure in yield and fatigue. Given the worst case scenario of always moving between the extreme angles in each joint, the safety factor against infinite life fatigue failure is 1.3 for the lower spring and 1.6 for the upper spring. This is sufficient given that the robot will rarely go to the extreme limits of its motion. The safety factors against yield at the extremes were much higher at 3.2 and 2.5 (joints 1 and 2 respectively).

The fatigue limits were calculated using Marin correction factors [19], given by

$$S_e = c_{surf}c_{size}c_{load}c_{reliab}c_{misc}S_e'$$

where $S_e$ is the modified endurance limit, $S_e'$ is the theoretical endurance limit and the remaining variables are correction factors. Table 4.3 shows the values used to solve for the endurance limit.

### 4.4.2 Final Motor Torque Requirements

The final static motor torque requirements at various positions can be seen in Figures 4.8 and 4.9. As seen in the plots, use of the compliant springs (torque shown in green) greatly reduces the required motor torque (shown in red) compared to the uncompensated case (shown in blue). These springs may appear to not match the uncompensated torques as well as they could, but these
Table 4.3: Fatigue Endurance Limit Factors

<table>
<thead>
<tr>
<th>Factor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_e'$</td>
<td>690 MPa</td>
</tr>
<tr>
<td>$c_{surf}$</td>
<td>0.66</td>
</tr>
<tr>
<td>$c_{size}$</td>
<td>1.1</td>
</tr>
<tr>
<td>$c_{load}$</td>
<td>1.0</td>
</tr>
<tr>
<td>$c_{reliab}$</td>
<td>0.81</td>
</tr>
<tr>
<td>$c_{misc}$</td>
<td>1.0</td>
</tr>
</tbody>
</table>

figures only show the torques at a single arm orientation. When all arm orientations are considered, the chosen spring design minimizes the maximum motor torques required.

![Figure 4.8: Static Torque Estimate for Joint 1 with Compliant Spring](image)

The dynamic torque was improved greatly with the addition of the springs; the dynamic torque plots can be seen in Figures 4.10 and 4.11. The expected maximum dynamic torque for motors one and two (shown in red) was decreased to the reasonable values 1.4 Nm and 1.2 Nm respectively. Addition of the springs has the added benefit of keeping the robot upright when the motors are not powered.
Figure 4.9: Static Torque Estimate for Joint 2 with Compliant Spring

Figure 4.10: Dynamic Torque Estimate for Joint 1 with Compliant Spring
4.5 Hardware Design

The following sections discuss the construction of the robot spine in detail. CAD drawings have been used when pictures of the actual robot would not be practical or clear. Appendix C contains detailed drawings of all custom parts.

4.5.1 Base, Link 1, Motor 1, and Spring 1

The robot is constructed on a sturdy, rigid base made from gray ABS plastic as seen in Figure 4.12. This enclosure, sold by polycase.com, is marketed as an electronic enclosure and works well for housing the power supplies and microcontroller (see Figure 4.13). The electronics are mounted via tapped screw holes to a 1/8 inch piece of blue acrylic. This acrylic sheet is attached to the enclosure’s existing mounting holes (see Figure 4.14). The specifics of the electronics will be discussed later.

Link 1 is attached to the top of the base via two blue stands made from 1/2 inch Tivar 88 (Figure 4.15). This material was chosen for high strength and appearance. A blue theme was used for aesthetic purposes (BYU’s school color). These stands have a hole with 1/2 inch nylon sleeve

Figure 4.11: Dynamic Torque Estimate for Joint 2 with Compliant Spring
Figure 4.12: Robot Base

Figure 4.13: Open Robot Base

Figure 4.14: Transparent Base View
bearings. A 1/2 inch stainless steel retaining ring rod acts as the pivot, in-line with the motor shaft. Nylon washers are used to ensure a tight fit (see Figure 4.16).

![Figure 4.15: Base Stands and Lower Spine](image1)

Motor 1 is attached to the base with 4 screws which fit into stands that come with the Herkulex motors. The motor shaft attaches to link 1 using a Herkulex plate, sold separate from the motors (Figure 4.17). Spring 1 is attached to the base using 1/2 inch Tivar 88 (Figure 4.17). The springs are fit between two pieces of Tivar, held tightly by three screws passing through the springs and both mounts. Each mount piece is fixed to the base via two screws. The mounts are cut to
allow the springs to rest undeflected at the designed 8 degree offset. The angled cuts were difficult to manufacture, but the improvement to the gravity compensation was determined to be worth it.

Figure 4.17: Motor #1 and Spring #1 Attachments

The blue stands were designed with a width such that link 1 could travel up to 15 degrees forward and backward. This acts as a physical stop to prevent the spring from being deflected beyond their capabilities (see Figure 4.18).

Figure 4.18: Link #1 Physical Stops

Link 1 is constructed from 1 inch x 2 inch hollow rectangular PVC tubing with a wall thickness of 0.078 inch (Figure 4.19). This material is lightweight, sturdy, and easily machined.
This is the same material used to construct the arms in Troy. The hollow tubing provides a convenient channel to run electrical wires for power and control. Spring 1 slides between two 3.5 inch nylon spacers between the two pieces that comprise link 1 (Figure 4.19). These spacers are hollow with female threads at either end. They are attached to link 1 with screws on each side (Figure 4.21). Although they are free to slide along the spacers (with enough space between them for an additional spring if needed), there is little movement because the pseudo-pin joint was placed in line with the motor shaft (Figure 4.17).

![Figure 4.19: Link #1 with Spring Spacers](image)

4.5.2 Link 2, Motor 2, and Spring 2

Similar to how link 1 is attached to the base, link 2 connects to link 1 using a 1/2 inch retaining ring rod on one side (Figure 4.20). The other side is connected directly to motor 2 (Figure 4.21). Motor 2 is nested at the top of link 1 and secured using screws attaching to the...
existing screw holes at the front of the motor. A circular notch is cut into link 1 to allow the shaft of motor 2 to rotate freely. The bottom of link 2 is cut to allow for assembly (Figure 4.21).

Figure 4.20: Lower Link 2 Assembly

Figure 4.21: Motor #2 and Assembly
Notches were cut into the bottom of link 2 to allow joint 2 to rotate forward up to 45 degrees and then reach a physical stop (Figure 4.22). Link 2 does not need to rotate backwards, so it reaches a hard stop when in line with link 1.

![Figure 4.22: Link #2 Physical Stops](image)

Spring 2 is mounted to the top of link 1 so that it rests undeflected at a 15 degree angle (see Figure 4.20). Spring 2 connects with link 2 using 3 inch nylon spacers (Figure 4.23) in the same manner as spring 1.

### 4.5.3 Motor #3, Motor #4, and Link #3

Motor 3 is mounted to a 1/8 inch acrylic plate that fits into link 2 (Figures 4.24 and 4.25). Motor 4 connects via motor stands to the Herkulex plate on motor 3. This creates a pan-tilt mechanism that acts as the neck joint. The distance between the axes of rotation for motor 2 and motor 4 corresponds to the length of link 2 found via optimization in Chapter 3. Link #3 is an attachment available from Herkulex that happens to be the correct length. The head will attach to the top of link 3 after it is constructed in future work. A top plate is press fit into the top of link 2 and is held loosely between motors 3 and 4. There is a built in physical stop that limits motor 3 from being able to spin completely around. This is done to prevent the cables from becoming twisted.
Figure 4.23: Link #2 and Spring #2

Figure 4.24: Motors #3 and #4
A head is currently being designed by a member of the research team that will be effective at displaying emotions. At the time of this thesis the face design has been tested on Troy (Figure 4.26). Future work will involve creating an enclosure that is compatible with the new robot.

### 4.5.4 Supporting Electronics

The robot is powered by an A/C cord that then runs through an emergency stop (Figure 4.27). This can be pressed at any time to eliminate power to all motors simultaneously. Two 150W, variable voltage power supplies provide the needed power to the spine motors and potentially the future arm motors. Motors 1 and 2 are set to run at 9V while motors 3 and 4 can run at no higher than 7.4V. Because the power supplies can only provide voltage between 9 and 12V, a high current switching regulator was used (7.4V, 10A). These power supplies and regulators ensure that the motors get enough current to supply the rated maximum torque.
Figure 4.26: New Robot Face on Troy

Figure 4.27: Supporting Electronics
The microcontroller used is included as part of an Arduino Mega 2560 Rev3 board. This board was chosen because of the supported Herkulex library that is freely available. Because the motors (discussed in the next section) communicate via Tx/Rx serial communication (as opposed to PWM control with standard servo motors), the 4 communication ports made the Arduino Mega a better choice than the Arduino Uno which only has 1. One port is used for the USB communication to a computer and another port is used to communicate with up to 254 Herkulex motors. The Arduino Mega can be powered through an internal voltage regulator (Vin pin) with 7-12V or through the USB cable.

4.6 Actuation and Control

The RC servo motors used in the robot Troy tend to act jittery and produce a high pitched buzzing noise when they could not quite reach the commanded angle. For this reason, different servos were chosen for the new robot. Smart servos made by Dynamixel and Herkulex are a popular, but still affordable, higher-performance alternative to hobby motors. They are much less jittery than hobby motors and make little noise while stationary, even while generating torque.

These motors have internal position feedback that can be read externally via serial communication to a computer or micro-controller. They can be controlled through an internal PID controller. This loop follows a trapezoidal velocity profile. This control involves a desired position (angle), speed, and maximum acceleration. The motors are preprogrammed with a maximum acceleration and the user (through the USB cable) can command the desired angle in degrees and a time to complete the move. Currently the robot is being controlled in joint space (not with a commanded end position) because of the simplicity and intuitiveness of that method.

The motors are capable of other types of control that were outside the scope of this thesis. In addition to reporting the position, these servos also report the motor temperature. This is useful in preventing the motors from over heating. If a maximum temperature is reached, the motors will shut off.

Herkulex motors were chosen because of the torque range available for a given price. No Dynamixel motors are currently made that meet our needs without excessive cost and torque. Table 4.4 shows the Herkulex motors chosen for each joint. Figures 4.28, 4.29, and 4.30 show the speed-torque plot of each motor, (assuming the motors behave like ideal brushed DC motors) as well as
the expected torques at a given speed (based on the motion profiles discussed earlier and shown in figures 4.5, 4.10, and 4.11). These figures show that the motors will have sufficient torque to move the links at the expected speeds.

Table 4.4: Herkulex Motor Selection

<table>
<thead>
<tr>
<th>Joint Number</th>
<th>Model Number</th>
<th>Stall Torque (Nm)</th>
<th>No Load Speed (RPM)</th>
<th>Voltage Range (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DRS-0201</td>
<td>2.4</td>
<td>68</td>
<td>7-12 (torque and speed rated at 7.4)</td>
</tr>
<tr>
<td>2</td>
<td>DRS-0201</td>
<td>2.4</td>
<td>68</td>
<td>7-12 (torque and speed rated at 7.4)</td>
</tr>
<tr>
<td>3</td>
<td>DRS-0101</td>
<td>1.2</td>
<td>60</td>
<td>7.4</td>
</tr>
<tr>
<td>4</td>
<td>DRS-0101</td>
<td>1.2</td>
<td>60</td>
<td>7.4</td>
</tr>
</tbody>
</table>

Figure 4.28: Torque vs Speed Motor Ratings and Expected Robot Requirements for Motor 1

4.7 Testing

The robot spine was tested to ensure that it is able to be used consistently and reliably during autism therapy sessions. Three primary concerns were tested: accuracy, repeatability and
Figure 4.29: Torque vs Speed Motor Ratings and Expected Robot Requirements for Motor 2

Figure 4.30: Torque vs Speed Motor Ratings and Expected Robot Requirements for Motors 3 and 4
temperature. To test these, the robot was loaded with weights in the appropriate areas to simulate the arms and head (Figure 4.31). The robot was commanded to move to different positions and the results are discussed in the following sections.

Figure 4.31: Motion Capture Testing Setup
4.7.1 Angular Position Accuracy

To test angle accuracy and repeatability, reflective motion tracking markers were placed on the robot spine in key areas (Figure 4.31). Markers were placed in the following locations: joints 1 and 2, the base, and the top of link 2. The markers were placed directly in line with each other in the horizontal direction. With this marker setup, the motion capture software can return the joint angles for motors 1 and 2. The joint angles were used as truth data to determine the accuracy of the motor angles reported by the internal potentiometer. Motors 3 and 4 were not tested for accuracy because of the relatively small length of link 3. Small angle errors will not result in easily perceptible differences to humans. A marker was placed at the top of the neck to test for repeatability (discussed later).

The microcontroller was programmed to read the internal angles, commanded angles, and PWM (pulse width modulation) command from the motors. PWM commanded values (between -1024 and 1024) are proportional to the motor torque with a value of 1024 corresponding to maximum motor torque and -1024 corresponding to full torque in the reverse direction. The angle and PWM information was then sent through serial communication (via a USB cable) to a computer. The computer stored the information along with a time stamp for later comparison. The data were sampled at 0.08 second intervals.

In the first test, the spine was commanded to follow the path used in Section 4.3 to determine the dynamic forces. A period of 2 seconds was used initially, as in Section 4.3, but this caused the robot base to slide across the floor. The 2 second period was chosen as the fastest movement the robot would experience, not a sustainable back and forth speed. Increasing the period to 3 seconds improved performance while still moving quickly. This path commanded the robot to go back and forth between the physical stops for each joint, making it the most difficult for the robot to accomplish.

Figure 4.32 shows the results of the first test for motor 1. The blue line shows the internal position reported, the red line shows the angles measured from the motion capture system, and the green line shows the desired (commanded) angle given to the motor. The PWM values (torque) required at the corresponding times are in the lower plot. Figure 4.33 shows the same information for motor 2. Figures 4.34 and 4.35 show the differences between the internal, motion capture, and desired angles for motors 1 and 2 respectively.
Figure 4.32: Angular Position Test for Motor 1 - 3s Period

Figure 4.33: Angular Position Test for Motor 2 - 3s Period
Figure 4.34: Angular Error for Motor 1 - 3s Period

Figure 4.35: Angular Error for Motor 2 - 3s Period
The error plots produced some useful results. The difference between the internal and motion capture angles show a constant offset (bias) of the internal readings. Motor 1 had an average bias of -1.7 degrees and motor 2 had an average bias of -4.4 degrees. The motors have a programmable setting that allows for bias error compensation if the error is known. The difference between the internal and desired angles shows the expected lag of the motor behind the commanded positions.

The PWM results show a similar pattern to the expected results (Figure 4.10 and 4.11). The expected maximum torque was 1.4 Nm and 1.2 Nm for motors 1 and 2. This is approximately half the rated motor torque of 2.4 Nm for motors 1 and 2. The PWM ranges were typically around ±500 for both motors, corresponding to half the motor torque. Because the commanded positions had the motors going to the physical stops, unpredictable behavior occurred when the motors reached the highest and lowest angles.

To validate the accuracy of the internal position reading, the test was repeated using a longer period of 4 seconds and angle ranges that were farther away from the physical stops. The angle ranges and results can be seen in Figures 4.36 – 4.39.

![Figure 4.36: Angular Position Test for Motor 1 - 4s Period](image-url)
Motor 2 - Internal, Actual, and Desired Angles vs Time - 4s Period

Motor 2 - PWM Input - 4s Period

Figure 4.37: Angular Position Test for Motor 2 - 4s Period

Motor 1 - Difference Between Internal and Actual Angles - 4s Period

Motor 1 - Difference Between Internal and Desired Angles - 4s Period

Figure 4.38: Angular Error for Motor 1 - 4s Period
4.7.2 Position Repeatability

The robot spine was tested for repeatability. A reflective marker was placed at the top of the neck, as shown in Figure 4.31. The position of this marker was recorded during a similar test to those performed in the previous section, with the exception that the robot held the farthest forward and backward angles for several seconds (angles defined in Tables 4.5 and 4.6).

The robot was commanded to go back and forth between these two positions 15 times. A plot of the held positions can be see in figure 4.44. The red dots represent the position of the head while the robot was commanded to the backward position while the blue dots represent the forward position. The top plot shows the scaled back view while the lower plots show a close view of each motor.
Figure 4.40: Angular Position Test for Motor 1 with Bias Compensation

Figure 4.41: Angular Position Test for Motor 2 with Bias Compensation

Table 4.5: Forward Repeatability Motor Angles

<table>
<thead>
<tr>
<th>Motor Number</th>
<th>Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-10</td>
</tr>
<tr>
<td>2</td>
<td>-35</td>
</tr>
<tr>
<td>3</td>
<td>-20</td>
</tr>
<tr>
<td>4</td>
<td>-20</td>
</tr>
</tbody>
</table>
Motor 1 - Difference Between Internal and Actual Angles - 4s Period - Bias Removed

Motor 1 - Difference Between Internal and Desired Angles - 4s Period

Figure 4.42: Angular Error for Motor 1 with Bias Compensation

Motor 2 - Difference Between Internal and Actual Angles - 4s Period - Bias Removed

Motor 2 - Difference Between Internal and Desired Angles - 4s Period

Figure 4.43: Angular Error for Motor 2 with Bias Compensation

Table 4.6: Backward Repeatability Motor Angles

<table>
<thead>
<tr>
<th>Motor Number</th>
<th>Angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>-15</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
</tr>
</tbody>
</table>
position cluster. The range of values is relatively small for each position. The different trials for the backward position have a range of \{0.76, 2.78, and 1.02\} mm in the \{X, Y, Z\} directions. The forward position has a smaller range of \{0.79, 0.64, 1.55\}. According to [14] during similar testing for the robot Troy, the motion capture system has an average residual error of 0.71 mm with error reaching as high as 2.0 mm. This error means the repeatability range is almost too small to be measured by this system. The robot can claim a repeatability of 2.8 mm at worst, which is too small to be noticed.

Figure 4.44: Repeatability Test

4.7.3 Temperature

To test the motor temperatures, the robot was commanded to move between three different poses (happy, neutral, and sad) every 5 seconds. In real therapy sessions the robot is only used for 10 min. Changing poses every 5 seconds represents a realistic time frame, giving the child time
to process and react to the pose. After an hour of changing between poses, the temperature of the motors increased by varying amounts, as reported by each motor’s internal temperature sensor (Table 4.7). At room temperature, the sensors indicate an internal temperature of 27 °C. Motor #1 increased to 43 °C while motor #2 increased to 55 °C. This felt warm to the touch but was not too hot to do damage to the motors. They have a built in stop at 65 °C to prevent harm. Motors #3 and #4 did not increase temperature significantly, both measuring 32 °C. After completing the tests, motor #2 returned to room temperature after 20 minutes. Because the therapy sessions are only expected to last 10 min, this temperature range is acceptable and the motors will not see any harm from the increased temperature.

<table>
<thead>
<tr>
<th>Motor Number</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>43</td>
</tr>
<tr>
<td>2</td>
<td>55</td>
</tr>
<tr>
<td>3</td>
<td>32</td>
</tr>
<tr>
<td>4</td>
<td>32</td>
</tr>
</tbody>
</table>

### 4.8 Cost

The cost for the robot was kept to a minimum while still constructing a sturdy and reliable robot. The final cost for the robot was $750. The motors were the most expensive components, costing $132 for each larger motor and $40 for the head/neck motors with a total cost of $344. To provide the required voltage for the motors with enough current to sustain them, two 12V, 150W power supplies were used. To run the head/neck motors a 7.4V 10A switching voltage regulator was added to one of the power supplies for a total cost of $110. Depending on the future design of the arms, this could be enough to power the entire robot. Table 4.8 presents the total cost of the major robot components. Based on the amount of time spent with the on-campus machinist, at $75/hour, machining and labor costs to create another robot are on the order of $1000.
Table 4.8: Major Robot Costs

<table>
<thead>
<tr>
<th>Description</th>
<th>Distributor</th>
<th>Part Number</th>
<th>Qty</th>
<th>Cost/Part</th>
<th>Subtotal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herkulex DRS-0201</td>
<td><a href="http://www.robotshop.com">www.robotshop.com</a></td>
<td>RB-Das-06</td>
<td>2</td>
<td>$132.00</td>
<td>$264.00</td>
</tr>
<tr>
<td>Arduino Mega 2560</td>
<td><a href="http://www.robotshop.com">www.robotshop.com</a></td>
<td>RB-Ard-33</td>
<td>1</td>
<td>$46.98</td>
<td>$46.98</td>
</tr>
<tr>
<td>Base Enclosure</td>
<td><a href="http://www.polycase.com">www.polycase.com</a></td>
<td>WA-42</td>
<td>1</td>
<td>$44.39</td>
<td>$44.39</td>
</tr>
<tr>
<td>5ft PVC Tubing</td>
<td><a href="http://www.mcmaster.com">www.mcmaster.com</a></td>
<td>85095K91</td>
<td>1</td>
<td>$21.43</td>
<td>$21.43</td>
</tr>
<tr>
<td>12V 150W Pwr Supply</td>
<td><a href="http://www.digikey.com">www.digikey.com</a></td>
<td>285-1811-ND</td>
<td>2</td>
<td>$37.65</td>
<td>$75.30</td>
</tr>
<tr>
<td>7.4V 10A Volt Reg</td>
<td><a href="http://www.helidirect.com">www.helidirect.com</a></td>
<td>GSR-3030</td>
<td>1</td>
<td>$34.99</td>
<td>$34.99</td>
</tr>
<tr>
<td>Emergency Stop</td>
<td><a href="http://www.digikey.com">www.digikey.com</a></td>
<td>Z1504-ND</td>
<td>1</td>
<td>$27.30</td>
<td>$27.30</td>
</tr>
<tr>
<td>Misc Stock and Supplies</td>
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<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total Cost</td>
<td>$750</td>
</tr>
</tbody>
</table>

4.9 Conclusion

Based on the optimal link lengths determined in the previous chapter, a robot spine was constructed. Kinematics and dynamics for the spine were solved and used to select the motors needed to actuate the robot. To assist the motors and lower the torque requirements a compliant spring was designed and constructed. The robot construction was illustrated and the control method described. The robot was tested to show accuracy, repeatability, and resistance to overheating. The angular position bias was found and removed using motion capture data. The spine was found to have a position repeatability error of, at most, 2.8 mm. Motor operating temperatures were found to be acceptable for the demands of clinical trials. Future work will adds arms and a head to the spine and introduce it in clinical trials.
CHAPTER 5. CONCLUSIONS

This thesis described the design of a new articulated robot spine. Human motion was modeled during various poses using motion capture techniques. The motion capture data was used to optimize the design of the number of links and the length of each link. The robot spine was designed and constructed based on the optimal lengths.

5.1 Contributions

The primary contribution of this work is a novel 3-link planar spine with compliant gravity-compensating springs, capable of reproducing simple emotion-conveying poses for use in robot-based therapy for children with ASD. This work contributes to a growing number of researchers studying the potential for mitigating the effects of autism through robots. Interdisciplinary cooperation between computer scientists, engineers, clinicians, and the dance department has been important for keeping the robot as effective as possible. The following specific contributions have been made from this research:

• Motion capture analysis of a human spine forming various expressions
• Optimal number of spinal joints and their locations based on the motion capture data
• Design and analysis of a new clinical robot spine to be used in clinical trials during therapy sessions in future work
• A robot spine capable of performing LMA-defined expressive motions such as slouching, leaning towards the child to show interest, leaning away to express uneasiness or fear, etc.
• A novel partial-gravity-compensating compliant spring design

The robot spine was designed to be capable of moving to a specific set of poses representing emotions. Although the focus of this design has been for children with ASD, this robot spine
design can be used for other applications as well. The greatest benefit for adding a spine to a robot is for expressiveness. The extra complexity and cost of the spine mean that most humanoid robots will likely continue without a spine, unless the design is specifically seeking greater expressive capabilities.

5.1.1 Partial-Gravity-Compensating Spring Design

The partial-gravity-compensating spring design could be particularly useful for larger, heavier robots as they become more expressive. In addition to the use in a robot spine, this spring design can be used for other applications, particularly where a long, thin spring can be used (robot arms, legs and heads). A large benefit to this design is that the equivalent spring constant can be customized to exact design needs and not limited to standard values available commercially.

The material used in our spring design was chosen because of the high stiffness needed. Materials that tend to work well as compliant springs include, but are not limited to: Polypropylene, 1095 Steel, 301 Stainless Steel, and 7075 T651 Aluminum. For more compliant mechanism designs and material suggestions see [19, 36].

Outside of the field of robotics, this partial-gravity-compensating compliant spring design has potential to be useful. These springs will be most effective in designs that are typically upright, such as a spine, that have gravitational forces pulling in different directions depending on orientation. Single directional torsional springs can also be replaced by this design, but it is left to the designer to evaluate the advantages of doing so.

5.2 Lessons Learned

Several important lessons were learned during the course of this thesis project including:

• Ensure that all motion capture markers are spaced far enough away to be distinguishable.

• Fully hardened 301 stainless steel is a great material for the strength and stiffness, but it cannot be machined easily without a waterjet or plasma cutter.
• The 1 mm resolution used for the link optimization was simple to implement, but made the algorithm take a significant amount of time to converge. A larger step size may have aided in a quicker convergence.

• Cost was an important factor in the motor choice. Although the motors are sufficient, higher torque motors would provide greater confidence for future expandability.

• Motor 1 sticks out from the robot, making it exposed to more potential damage. A redesign might consider moving it inside link 1, similar to the design of motor 2 inside link 2. This was not done in the current design to allow for a second base stand to support the weight of the robot.

• The top plate and the extension of link 2 beyond motor 3 may not be necessary and may take away from the appearance of a neck. They were included in the design of the robot to protect motors 3 and 4.

5.3 Future Work

Future work for this robot will include the design and construction of the head and arms. The head should enable the same expressive capabilities as the robot Troy while possibly improving on the aesthetics. The design of the arms should include the exploration of compliance in the joints to increase the safety of the robot.

Robot joint compliance is actively being studied and offers a way to increase the safety of human-robot interaction [37, 38]. If the robot with compliant joints comes into contact with a human, it will deflect rather than causing serious harm. Torque-controlled compliance as well as physical compliance [19, 39, 40] should be considered in the future design of the robot as a way to increase safety and even allow the child to touch the robot during operation.

Simple hands may be added to allow Troy to interact with hand gestures and by holding small objects. In the past Troy was able to press buttons or push a toy car. With simple one degree of freedom hands, the new robot would be able to interact more effectively. These hands must be lightweight enough to be lifted by, not only the arm motors, but the spine when the arms are extended.
If needed, each of the two lower motors in the spine can be exchanged with higher torque versions from the same manufacturer without any change in the robot control. Second motors can also be used on the right hand side of the robot in place of the idle pin joints. This would require changing the design to mirror the left side links and slight additions to the control (keeping the motors moving in sync).

If the robot is to be used continuously for long periods of time (more than 30 min) the temperature in motors 1 and 2 may become too warm. To minimize the heat, higher torque motors can be used. Another possible solution is to construct the links out of aluminum to act as a heat sink, especially for motor 2. A final option is to add a small fan near each motor to increase convective cooling.

To be used in a clinical setting, a user friendly GUI interface needs to be created, similar to that used with Troy [41]. This will enable the clinicians to control the robot without the knowledge of a low-level programming language. The interface should include the control of the spine, arms, and head. The interface will most likely continue to command each joint individually.

Research has been done to capture the arm movements of therapists using an Xbox Kinect camera. This information is then used to command the angles to pose the arms of Troy. This work can be extended to capture the pose of the spine as well, making it easy for the therapists to act out the expressions they want to see the robot make, and customize the robot for each individual child.

The completed robot will be used in clinical tests to evaluate the effectiveness of the robot, particularly the spine. If the spine is confirmed to be effective it will be evaluated and determined if a more complex spine (with more degrees of freedom) is needed to best help the children. As autism therapy robots are able to improve in their functionality, more and more children will benefit from their use.
REFERENCES


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APPENDIX A. OPTIMIZATION FIGURES WITH THREE LINKS

Optimal robot design based on three links in various poses. The green line shows the best three link robot in the optimal configuration while the red line shows the polynomial fit to the spinal motion capture data.

Figure A.1: Three Link Neutral
Figure A.4: Three Link Sad 1

Figure A.5: Three Link Sad 2
Figure A.6: Three Link Scared 1

Figure A.7: Three Link Scared 2

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Figure A.8: Three Link Angry 1

Figure A.9: Three Link Angry 2
Figure A.10: Three Link Surprised

Figure A.11: Three Link Disgusted 1
Figure A.12: Three Link Disgusted 2

Figure A.13: Three Link Interested 1
APPENDIX B. OPTIMIZATION FIGURES WITH FOUR LINKS

Optimal robot design based on four links in various poses. The green line shows the best four link robot in the optimal configuration while the red line shows the polynomial fit to the spinal motion capture data.

Figure B.1: Four Link Neutral
Figure B.2: Four Link Happy 1

Figure B.3: Four Link Happy 2
Figure B.4: Four Link Sad 1

Figure B.5: Four Link Sad 2
Figure B.6: Four Link Scared 1

Figure B.7: Four Link Scared 2

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Figure B.8: Four Link Angry 1

Figure B.9: Four Link Angry 2
Figure B.10: Four Link Surprised

Figure B.11: Four Link Disgusted 1
Figure B.12: Four Link Disgusted 2

Figure B.13: Four Link Interested 1

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Figure B.14: Four Link Interested 2
APPENDIX C. CAD DRAWINGS

This appendix presents all the parts made for the construction of the robot that were not purchased. All units are in inches and degrees unless otherwise stated.

Figure C.1: Main Robot Assembly
Figure C.2: Base Top
Figure C.3: Base Side
Figure C.5: Lower Mounting Bracket
Figure C.7: Lower Spine Link Outside
Figure C.8: Lower Spine Motor Link Inside
Figure C.9: Lower Spine Motor Link Outside
Figure C.10: Upper Spine Link Inside
Figure C.11: Upper Spine Link Outside
Upper Spine Link Motor Inside

Figure C.12: Upper Spine Motor Link Inside
Figure C.13: Upper Spine Motor Link Outside
Lower Spring
4 Copies
Stainless Steel 301 Full Hard
All Dimensions in Inches

Figure C.14: Lower Spring
Upper Spring
4 Copies Needed
Stainless Steel 301 Full Hard
All Units in Inches

Figure C.15: Upper Spring
Figure C.16: Lower Spring Bracket Part 1 View a
Figure C.17: Lower Spring Bracket Part 1 View b
Figure C.19: Lower Spring Bracket Part 2 View b
Upper Spring Bracket Part 1

Figure C.20: Upper Spring Bracket Part 1
Figure C.21: Upper Spring Bracket Part 2
Figure C.22: Pan Motor Mount
Figure C.23: Top Cap Plate
Figure C.24: Lower Back Cover Plate
Figure C.25: Lower Front Cover Plate
Figure C.26: Upper Back Cover Plate
Figure C.27: Upper Front Cover Plate
APPENDIX D. LAGRANGE EQUATIONS

Herein contains the account of the Lagrange equations used to find the torque in each robot joint. Figure D.1 shows the reference frames and variable definitions. Equations D.1 and D.2 shows Lagrange's equation [32]. Equations D.3 – D.11 show the torque experienced at each joint. The mass and inertia of the robot arms are included as part of link 2.

\[ \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\theta}_k} \right) - \frac{\partial L}{\partial \theta_k} = Q_k, k = 1, \ldots, 3 \]  

(D.1)

\[ L = \text{KineticEnergy} - \text{PotentialEnergy} \]  

(D.2)
D.1 Joint 1 Torque Equations

\[
\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\theta}_1} \right) = I_{1,\theta} \ddot{\theta}_1 + \frac{1}{2} m_2 [2L_1^2 \ddot{\theta}_1 + 2(d_2^2 + h_2^2)(\dot{\theta}_1 + \dot{\theta}_2) \\
+ 2L_1 ((-d_2 \dot{\theta}_2 \sin(\theta_2) - h_2 \dot{\theta}_2 \cos(\theta_2))(2\dot{\theta}_1 + \dot{\theta}_2) + (d_2 \cos(\theta_2) - h_2 \sin(\theta_2))(2\dot{\theta}_1 + \dot{\theta}_2))] \\
+ \frac{1}{2} m_3 [2L_1^2 \ddot{\theta}_1 + 2L_2^2 (\dot{\theta}_1 + \dot{\theta}_2) + 2L_1 L_2 (-\dot{\theta}_2 \sin(\dot{\theta}_2)(2\dot{\theta}_1 + \dot{\theta}_2) + \cos(\theta_2)(2\dot{\theta}_1 + \dot{\theta}_2)) \\
+ 2L_1 d_3 (-(\dot{\theta}_2 + \dot{\theta}_3) \sin(\theta_2 + \theta_3)(2\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3) + \cos(\theta_2 + \theta_3)(2\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3)) \\
- 2L_1 h_3 ((\dot{\theta}_2 + \dot{\theta}_3) \cos(\theta_2 + \theta_3)(2\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3) + \sin(\theta_2 + \theta_3)(2\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3)) \\
+ 2L_2 d_3 (-\dot{\theta}_3 \sin(\theta_3)(2\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3) + \cos(\theta_3)(2\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3)) \\
- 2L_2 h_3 (\dot{\theta}_3 \cos(\theta_3)(2\dot{\theta}_1 + 2\dot{\theta}_2 + \dot{\theta}_3) + \sin(\theta_3)(2\dot{\theta}_1 + 2\dot{\theta}_2 + \dot{\theta}_3)) + 2(d_3^2 + h_3^2)(\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3)]
\]  
(D.3)

\[
\frac{\partial L}{\partial \dot{\theta}_1} = m_1 g d_1 \sin(\theta_1) - m_2 g [-L_1 \sin(\theta_1) - d_2 \sin(\theta_1 + \theta_2) - h_2 \cos(\theta_1 + \theta_2)] \\
- m_3 g [-L_1 \sin(\theta_1) - L_2 \sin(\theta_1 + \theta_2) - d_3 \sin(\theta_1 + \theta_2 + \theta_3) - h_3 \cos(\theta_1 + \theta_2 + \theta_3)] 
\]  
(D.4)

\[
\tau_1 = \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\theta}_1} \right) - \frac{\partial L}{\partial \dot{\theta}_1}
\]  
(D.5)
D.2 Joint 2 Torque Equations

\[
\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_2}\right) = I_{2,c} \dot{\theta}_2 + \frac{1}{2} m_2 [2 (d_2^2 + h_2^2) (\ddot{\theta}_1 + \ddot{\theta}_2) + 2 L_1 ((-d_2 \dot{\theta}_2 \sin(\theta_2) - h_2 \dot{\theta}_2 \cos(\theta_2)) \dot{\theta}_1
+ (d_2 \cos(\theta_2) - h_2 \sin(\theta_2)) \dot{\theta}_1)] + \frac{1}{2} m_3 [2 L_2^2 (\dot{\theta}_1 + \dot{\theta}_2) + 2 L_1 L_2 (-\dot{\theta}_2 \sin(\theta_2) \dot{\theta}_1 + \cos(\theta_2) \dot{\theta}_1)
+ 2 L_1 d_3 (- (\dot{\theta}_2 + \dot{\theta}_3) \sin(\theta_2 + \theta_3) \dot{\theta}_1 + \cos(\theta_2 + \theta_3) \dot{\theta}_1) - 2 L_1 h_3 ((\dot{\theta}_2 + \dot{\theta}_3) \cos(\theta_2 + \theta_3) \dot{\theta}_1
+ \sin(\theta_2 + \theta_3) \dot{\theta}_1) + 2 L_2 d_3 (- \dot{\theta}_3 \sin(\theta_3) (2 \dot{\theta}_1 + 2 \dot{\theta}_2 + \dot{\theta}_3) + \cos(\theta_3) (2 \dot{\theta}_1 + 2 \dot{\theta}_2 + \dot{\theta}_3))
- 2 L_2 h_3 (\dot{\theta}_3 \cos(\theta_3) (2 \dot{\theta}_1 + 2 \dot{\theta}_2 + \dot{\theta}_3) + \sin(\theta_3) (2 \dot{\theta}_1 + 2 \dot{\theta}_2 + \dot{\theta}_3)) + 2 (d_2^2 + h_2^2) (\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3)]

(D.6)

D.3 Joint 3 Torque Equations

\[
\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_3}\right) = I_{3,c} \dot{\theta}_3 + \frac{1}{2} m_3 [2 L_1 d_3 (\dot{\theta}_1 \cos(\theta_2 + \theta_3) - \dot{\theta}_1 (\theta_2 + \theta_3) \sin(\theta_2 + \theta_3))
- 2 L_1 h_3 (\dot{\theta}_1 \sin(\theta_2 + \theta_3) + \dot{\theta}_1 (\theta_2 + \theta_3) \cos(\theta_2 + \theta_3))
+ 2 L_2 d_3 ((\dot{\theta}_1 + \dot{\theta}_2) \cos(\theta_3) - (\dot{\theta}_1 + \dot{\theta}_2) \dot{\theta}_3 \sin(\theta_3))
- 2 L_2 h_3 ((\dot{\theta}_1 + \dot{\theta}_2) \sin(\theta_3) + (\dot{\theta}_1 + \dot{\theta}_2) \dot{\theta}_3 \cos(\theta_3)) + 2 (d_2^2 + h_2^2) (\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3)]

(D.9)
\[
\frac{\partial L}{\partial \theta_3} = \frac{1}{2} m_3 \left[ -2L_1 d_3 (\dot{\theta}_1^2 + \dot{\theta}_1 \dot{\theta}_2 + \dot{\theta}_1 \dot{\theta}_3 \sin(\theta_2 + \theta_3)) - 2L_1 h_3 (\dot{\theta}_1^2 + \dot{\theta}_1 \dot{\theta}_2 + \dot{\theta}_1 \dot{\theta}_3 \cos(\theta_2 + \theta_3)) \\
- 2L_2 d_3 (\dot{\theta}_1 + \dot{\theta}_2) (\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3 \sin(\theta_3)) \\
- 2L_2 h_3 (\dot{\theta}_1 + \dot{\theta}_2) (\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3 \cos(\theta_3)) \right] - m_3 g \left[ -d_3 \sin(\theta_1 + \theta_2 + \theta_3) - h_3 \cos(\theta_1 + \theta_2 + \theta_3) \right]
\]

\[\tau_3 = \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\theta}_3} \right) - \frac{\partial L}{\partial \theta_3} \]  
(D.10)

(D.11)