Leg Rehabilitation Device for Paralysis Patients

A Major Qualifying Project Report:
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by

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Abstract

This project involved designing and manufacturing a cost efficient robot that will retrain the leg muscles of paralysis patients. This project group developed a more economic design for paralysis patients to retrain their muscles and feeling of walking in their legs at a lower cost then what's on the market today. The group was able to make the device adjustable and comfortable for the patient to use easily. The group also made the device move in a precise way to simulate the human gait walking motion.

Acknowledgements

We would like to thank Professor Yiming (Kevin) Rong of WPI for advising us during this project. In addition, we would also like to thank Professors Yang, and Professor Gao from HUST, as well as Professor Hou from WPI for assisting us with our project. We like to acknowledge all the help and contributions that were given by the HUST student members of our project group. Without their help this project would not have been possible to complete.

Authorship

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- Methodology: Tim Becker
- Results & Analysis: Tim Becker
- Conclusions & Recommendations: Tim Becker, Matthew Duplin

Table of Contents

Table of Figures

1 Introduction

According to the United States Census Bureau, as of 2002, 18.1 percent of Americans had a disability and 11.5 percent of those disabilities were severe. These severe injuries can be accredited to a multitude of causes. Paralysis, the loss of motor function of a limb or limbs, can be attributed to some of these causes such as stroke, brain trauma, and spinal cord injury.

Roughly one of every one hundred Americans has experienced a stroke. The likelihood of having a stroke doubles by the decade once reaching the age of 55. With the baby boomer era growing older, the amount of strokes in the United States will be on the rise and will therefore require more accessible rehabilitation techniques. A stroke can cause a variety of different forms of paralysis such as hemi paresis, paraplegia, quadriplegia, and tetraplegia. These types of paralysis are caused by damage to the spinal cord and nervous system. Hemi paresis is the loss of motor functions in one side of the body. Paraplegics lose the use of their legs but have complete control over their arm functions. Quadriplegic and tetraplegic refer to a patient that has lost the use of all four limbs.

A patient's rehabilitation regimen depends mainly on the severity of their disability. These exercises range from walking on a treadmill to the bending of their fingers. Sometimes however the paralysis is so severe that the patient cannot support their own body weight or lift the weight of their limbs. In the past, these cases were handled by using one or two physical therapists to hold the patients up and assist their motions manually. They also employed a technique that allowed the patients to try their movements in a pool. This was so that it weight of the limbs would seem less due to the support of the water [7]. The major problem with these standard rehabilitation techniques is that the percentage of motor function that is recovered is poor. According to the Journal of Rehabilitation Research & Development the percentage of mobility recovered is somewhere between thirty and sixty-six percent.

Research is being done so that robotics can be incorporated into the patient's treatment. These robotic rehabilitators are responsible for an increase in the overall recovery of the patents mobility in their affected limbs [6]. They are able to support the patient's weight and assist in their limb movement with minimal interaction from the therapist. An example of this would be the rehabilitation device that is being worked on at the Rehabilitation Institute of Chicago (RIC). This device is helping paralyzed patients regain their ability to walk. This robotic device could be the conventional tool in two to five years and forever change how the therapists retrain patients with paralysis to walk. The Swiss-manufactured robot, called the Lokomat, delivers power to the hip and knee joints of the patient, whose legs are strapped to the machine. The patient is hanging over a treadmill with a certain amount of their body weight supported by a harness. The Lokomat uses the power that is given to the hips and knees and allows the patient to simulate a walking motion.

Where we see a problem with these types of devices that are being developed is that they are very large and expensive machines. They seem to be only available in hospitals and not able to be used at the patient’s home or at their convenience. Our goal is to make a device or devices that will be able to retrain a patient’s motion but have them be able to use the device themselves and have it be cheap enough for them to afford without much debt.

2 Background

The following section outlines important concepts that surround and affect our project. Since there are many external issues involved, this Chapter provides the reader with a fundamental background of such issues.

Past research done on robotic rehabilitation is quite extensive. Even though today this field of study is making huge strides, its subject matter is still in the beginning stages of development. Our research was focused on the different kinds of paralysis, related projects, and current treatments. Also, research was conducted on the different types of information that will be needed for our project design to be put into realization. This information includes motion analysis on the joints as well as the technology that will be used in our design to move these joints.

2.1 Paralysis

Paralysis is defined as a loss of the motor and or sensory function of a body part due to either a muscular or neural mechanism [2].

2.1.1 Causes

There are numerous causes of paralysis. We focused our research on the stroke because it seems to be the leading cause of paralysis and a condition that is on the rise. This rise can be attributed to longer life and as stated before the aging baby boom generation [2].

2.1.2 Treatments and Rehabilitation

Massachusetts Institute of Technology and the University Of Miami School Of Medicine have made significant strides in developing treatments for paralysis patients. Engineers at MIT have announced their success with a robotic brace that helps people with paralysis retrain their muscles to regain movement in their limbs. Researchers reported an average of 23% improvement in arm function after testing the therapeutic device on patients.

Rehabilitation is another widely used form of treatment for paralysis. Repetitive task training is an effective form of rehabilitation for people suffering from debilitating injuries such as paralysis caused by a stroke [5].

2.2 *Leg Motion Parameters*

Our project calls for the study of three major joints: the hip, knee, and ankle. In order for us the manufacture a product that will work we need to know the specifics for the kinematics of these joint motions. Figure 2.1, Figure 2.2, and Figure 2.3 help show the joint angle limitations for these joints.

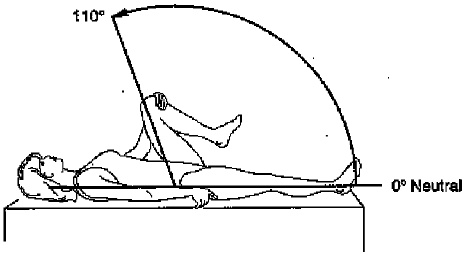

Figure 2.1 Forward Hip Joint Angle Limitation

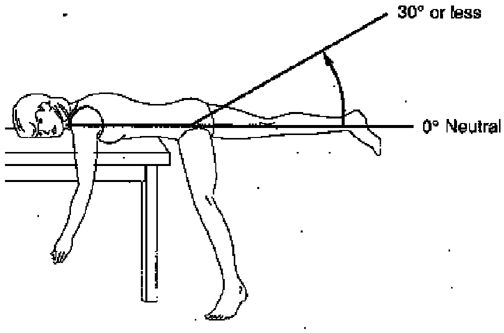

Figure 2.2 Backward Hip Joint Angle Limitation

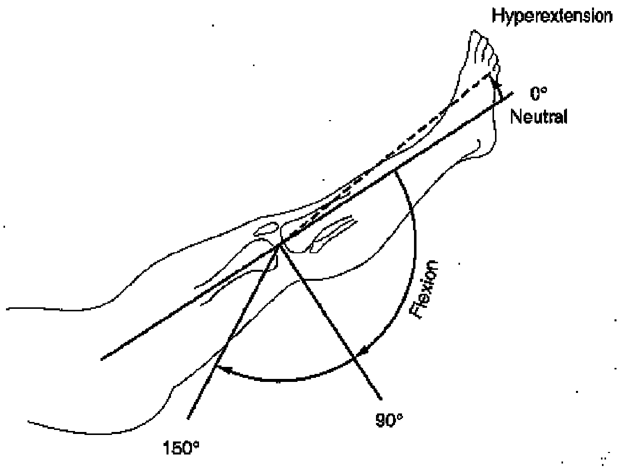

Figure 2.3 Knee Joint Angle Limitation

This information is relevant to our project because it shows the extent of what each joint can move and how far in each direction with relation to the joint. Similar devices to ours do not use these extreme angles in their mechanism design. Instead they estimated angles to simulate the walking motion.

2.2.1 Kinematics Model Research

In order to know the kinematics of the walking motion we had to know the Degrees of freedom for each joint. The kinematics structure of the leg contains six joint Degrees Of Freedom or DOF. Each hip joint contains 3 DOF, each knee joint contains 2 DOF, and the ankle can be separated into 3 DOF. When walking, the pelvis area swings the hip joint forward in the range of 8 degrees. Well the thigh shows a similar pattern of rotation, but the angle is larger, the total range is about 14 degrees. In the leg, the shank shows the same pattern, but with an even greater range of rotation, there is about 18 degrees of freedom.

These Degrees of freedom deal with the different joint angles that are involved with the gait motion of biomechanics. Biomechanics research provides evidence that "Sagittal elevation angle" may be more reusable than joint angles. Sagittal elevation angles is a new representation for motion, it exhibits less intersubject variation than joint angles during walking; therefore they form a more "canonical" data representation for gait, which can be used to drive walking animation over curved paths and uneven terrain.

This is good to know and understand but our device will not go on curved paths or uneven terrain. Although this might give more comfort to our patient when walking if the variance is lower in sagittal elevation angles then joint angles.

2.3 Forces of Walking

To every action there is an equal and opposite reaction (Newton's third Law) although some of the joint movements are produced by external forces like gravity. The easiest way to understand the forces which produce the movements of walking is to compare the joint angles, ELECTROMYOGRAPHY or (EMG) of muscles acting at that joint, and the effect of the ground reaction force on the joint. "…axial rotation of the pelvis during walking is driven by the spine rather than the limbs; walking could then be driven to some extent by the back muscles (Gracovetsky, 1985). Although there is little correlation between back muscle activity and pelvic rotation (Vink, P. & Karssemeijer, N. (1988) Anat. Embryol. 178, 455-460)." The pattern of ground reaction forces was highly speed dependent. A common observation from human studies is that the time course of the changes in muscle activity and length, joint angles and torques can be variable not only across speeds and subjects, but even from trial to trial (Pedotti, 1977; Apkarian, Naumann & Cairns, 1989; Pandy & Berme)

In order to get a better understanding of the forces on the different joints you must first understand the different ways the joints can flex. Plantar flex is when that part is fully extended out. Dorsiflex is when that part of the body is contracted. The forces on the hip at plantar flexing are the quadriceps and the forces on the hip at dorsiflexing are the hamstrings and gluteus Maximus. Even though the knee does not contribute much to the force of the walking motion, the knee is able to make walking easier by using the reaction forces from the ground and from other joints and muscles. The forces that are needed to dorsiflex the knee come from the hamstring muscle and gravity, the force needed for the knee to return to normal is the quadriceps, which is also what prevents dorsiflex in the knee and keep it in the plantar position. There are different smaller muscles in the foot that contribute to the force but the ankle (gastrocnemius muscles), calf muscle and Achilles tendon contribute the most to the movement of the ankle, although the body weight plays a major roll in the changing from plantar and dorsiflex.

When the walking motion reaches the Close packed position there is the maximum activity of the plantar flexors.

The maximal vertical forces are developed soon after heel strike and then again during push off, and reach about 125% of body weight. Note that at heel strike, the reaction force will tend to plantar flex the ankle, extend the knee, and flex the hip Mid-stance GRF orientation effect ankle in front dorsiflexion knee behind flex hip behind extension. Also the torque diminishes to zero at mid-stance. Toe off GRF orientation effect ankle in front dorsiflexion knee just behind flexion hip behind extension. The torque is the greatest at toe off and heal strike do to the distance from the hips.

Although humans can walk up to 4 m/s, the average walking speed is about 0.9m/s - 2.1m/s, they usually prefer to switch to running mode above -2-2 m s- because running becomes more economical than walking in terms of energy cost (Alexander, 1989; Minetti et al. 1994).

3 Methodology

The following section will explain our methods for completing our project. Our project's success will be contingent upon the accomplishment of the following individual objectives:

- Design a device to move in a precise human walking motion.
- Device must be adjustable to provide comfort to different sized patients.
- Manufacture the device with materials that will satisfy the needs of the design but also fall under our budget of 3000 RMB or 402 USD.

It will outline specifically what was done to achieve these objectives and fulfill the requirements set forth by the project group.

3.1 Design Process

This section will include the reasons and applications for each step in the design process that was followed by the group members to achieve the objectives. The group has laid out to the reader a detailed set of procedures that were followed.

3.1.1 Problem Definition

In this step the project group defined the problem as precisely as possible. We tried to understand and grasp the problem to the best of our ability before moving on to the next step. This step involves developing task specifications.

3.1.2 Preliminary Conceptual Designs

The project team continued their design process by coming up with early design ideas for the project based on the initial problem definition and task specifications. These designs did not have to be extremely detailed but did need to have enough information and calculations completed for the team to be able to perform a feasibility analysis of each design in order to decide which was best.

3.1.3 Model and Analysis

This step was used to model each conceptual design and analyze the feasibility of each compared to the others. This allowed the project group to use Pro-Engineer to see what type of details they missed in their initial design ideas.

3.1.4 Detail Designs

This step is used by the team to narrow the design possibilities and develop the detailed specifications for the remaining designs. In this step the team must come up with every detail needed to realize the design. In doing so, this allows the group to distinguish the most feasible of the remaining designs and enables them to move onto the next step in the design process.

3.1.5 Finalize Design

After analyzing the remaining designs and their detailed specifications and calculations, the team was able to make a final decision on which was the best to fulfill the objectives set forth in Section 3. In this step the team will finalize the design and simulation of the project. This includes the controls, electrical system and mechanism.

3.2 Manufacturing Process

This section will display the procedures that the project group followed while manufacturing their device.

3.2.1 Purchasing of Material

While purchasing material the group had to consider many different things. Some of these considerations include the following: cost, manufacturability, material properties, usefulness to project, etc. Keeping these things in mind the team purchased the necessary parts to complete the assembly of the device.

3.2.2 Manufacturing

In this stage of the Manufacturing process, the team is challenged with the task of machining the parts that are needed to assemble the device. To do this, the team must make sure that they are trained to use the machinery and use proper safety measures while using them. They must plan out in advance each machining step so that they can account for any unforeseen problems that may occur.

3.2.3 Assembly

This step should go smoothly if all of the machining and manufacturing of the parts were done correctly and without mistake. This step is where the team will assemble the device in its entirety. This step should include a detailed plan of how things should be assembled so that they will not run into obstacles later on.

4 Results and Analysis

We have designed and manufactured a cost efficient robot that will retrain the leg muscles for paralysis patients.

4.1 Design Process

This section will include the reasons and applications for each step in the design process that was followed by the group members to achieve the objectives that were just gone over above. The group has laid out to the reader a detailed set of procedures that were followed.

4.1.1 Problem Definition

The information that was gathered by the project group allowed them to formulate a problem statement that was realistic and achievable in the seven week time frame that was allowed to complete the project. The team saw a large need in both the United States and China for a device that would be able to be sold to hospitals and patients that would allow for the treatment of the paralyzed. This need, as mentioned in Chapter 1, was drawn from the increasing number of patients that were developing paralysis like conditions and the few resources available to help rehabilitate them. The team's mission was to design and manufacture a cost efficient robotic device that would retrain the leg muscles for these patients. This problem definition emphasizes that the device must be cost efficient. With a lack of monetary funds available in Chinese hospitals today the need for a cheaper alternative to rehabilitation is greatly needed.

Along with cost, the project group came up with two other important specifications that their design should follow. As mentioned before the group thought it was important that the device be comfortable to use. In the following sections you will see how the project group incorporated ideas so that their device would allow for the patients to feel comfortable while using the device.

4.1.2 Preliminary Conceptual Designs

Brainstorming sessions were conducted by the group to formulate ideas that would solve the objectives. These designs were preliminary in nature and were used to get an idea of what the team members were thinking for design concepts. The sections to follow will show the most important designs that were discussed during the brainstorming sessions.

When coming up with these preliminary designs, the project group was forced to establish a set of design specifications so that they were able to have guidelines with regards to how they should design the mechanism. A list of the most important design specifications are as follows:

- One degree of freedom for each joint (both hips and knees)
- Cycle time: 0.52-0.65s per pace
- The structure must be shaped similar to the human legs
- The trajectory of each joint must simulate the actual motion of each human joint.
- The budget must be limited within 3000RMB
- Design should fit through a standard doorway

4.1.2.1 Two-Motor Design

The teams first thought for mechanical design was a two motor design. This design would have one motor per leg. The design needed to be able to move the thigh and the shin of the patient all using one motor. This would allow for a less complicated control system. The way we would accomplish this mechanism would to use a complicated linkage system that was inspired by a past project that was done by a different HUST group. This project was the walking simulation of a horse. The linkage system that was used by them was very helpful in our design of the linkage system that would be used for a two motor design.

4.1.2.2 Four-Motor Design

Next the project group moved onto a four motor mechanical design. This would allow for each joint to be driven by its own motor. This feature came with a more complicated control system and new challenges in the mechanism design.

The mechanism would have to be separated into two main design areas. The first being the hip joint and the second being the knee joint. With a motor at each joint, the design called for a way to run both the hip and the knee in timing with each other using the controls system, not the mechanism. This allowed the mechanism team to concentrate on a design that would allow the computer program to control the legs without any interference from the physical design.

The hip design would consist of a pin joint and a four bar linkage system. Once the hip trajectory was calculated the four bar linkage could be designed to match it. This will allow for the hip to move in an accurate trajectory to that of a real human's hip motion. The knee joint becomes more complicated when adding the two additional motors to the leg. This is because it must now be able to move forward and backward separate from the hip. The motion must match that of the actual shin motion while walking. Knowing this makes it a more complicated task to keep the timing right with the hip motion.

4.1.3 Model and Analysis

Once the preliminary design concepts were thought up, the project group had to move onto the mathematical calculations that would allow them to decide which of the designs was best for their needs. Following these mathematical calculations the project group did preliminary solid models of their design concepts to see how feasible they were.

4.1.3.1 Mathematical Calculations

Using information that was found in their research, the team was able to create the desired curves for the hip and knee angles. The curves for the hip and knee, as shown in Figure 4.1 and Figure 4.2 as well as their functions in Appendix A, were calculated using a polynomial function in Matlab. Using raw data points, shown in Figure 4.1 and 4.2 and listed in Appendix B, the team was able to match a curve accurately to them. These curves were formulated so that the program that would later run the legs would have accurate equations that would simulate the leg motion of a human during its walking motion.

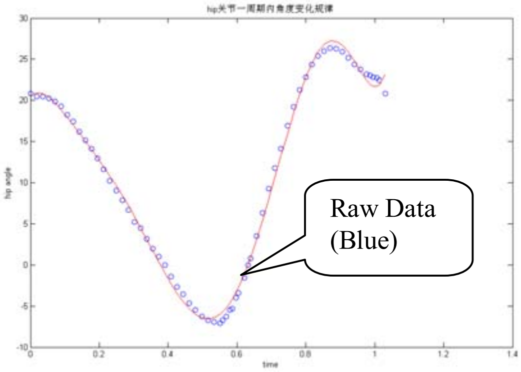

Figure 4.1 Curve Plotting Hip Angle vs. Time

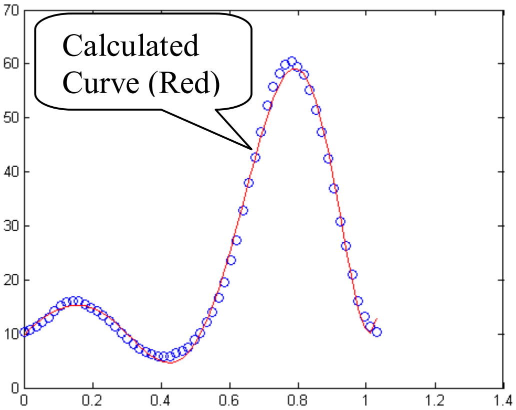

Figure 4.2 Curve Plotting Knee Angle vs. Time

Once the curves were plotted for the hip and knee angles versus time, the project group was able to formulate the trajectory of the knee motion. This trajectory, shown in Figure 4.3 and its function in Appendix A, shows the swing of the knee joint in the Y-Z plane or the side view of the leg. This allowed the project group to design a linkage system that simulates this curve for the knee motion.

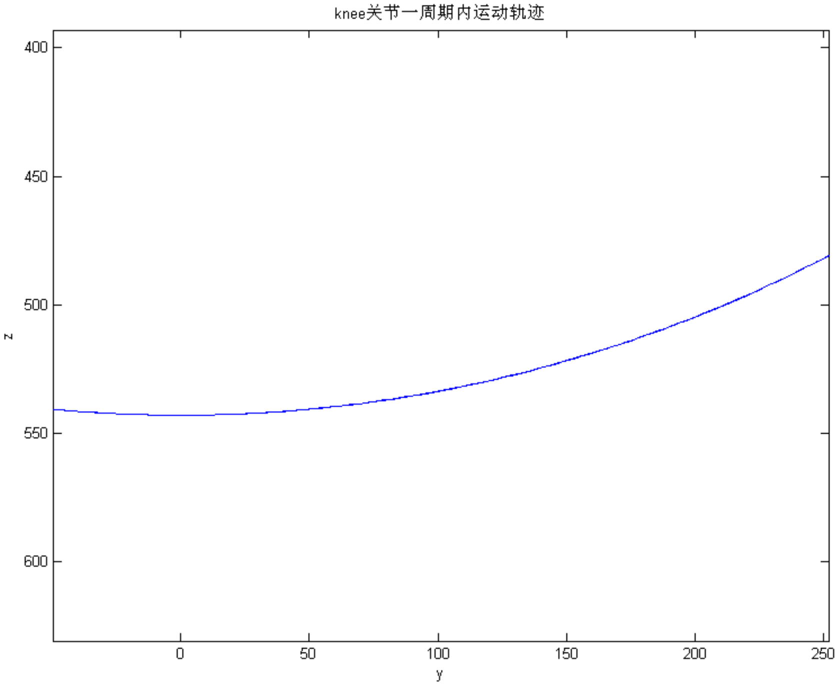

Figure 4.3 Curve of Knee Trajectory in Y-Z plane

The project group also had to calculate the torque needed to move each joint. With the equations shown in Appendix A, the design team was able to formulate that the maximum torques of the hip and knee joints were 32.25 N·m and 3.865 N·m respectively. These torque calculations were vital to the control system, since it allowed the project team to select the correct type and size motor for each joint.

4.1.3.2 Solid Modeling

Using the software Pro-Engineer, the design team was able to visualize their conceptual designs to see what was practical and what didn't actually work. The preliminary designs that were modeled were concepts of the two motor and four motor ideas.

Figure 4.4 shows a wooden model of the two-motor linkage design that the team developed. Using the Pro-Engineer software the design team was able to modify their design to simulate the walking motion of a human. It allowed them to check for interferences between the links and make sure that the motion was what they wanted. As you can see in Figure 4.5, the design team used an eight-bar linkage system, with the small green link as the crank and the red and yellow links forming the leg. An example of the usefulness of the solid modeling can be shown by the project team's assessment of the two-motor design concept. This design seemed to solve the accurate leg motion objective, but when addressing the comfort objective, this design was not useful. By using the animation software the team was able to see that the linkages would be too difficult to adjust to different sized patients. This almost completely eliminates it as a possible design option because one of the major objectives for the project was to make the device comfortable for different sized patients. This means it needed to be adjustable in some way.

Figure 4.4 Wooden Model of 2-Motor Linkage Design

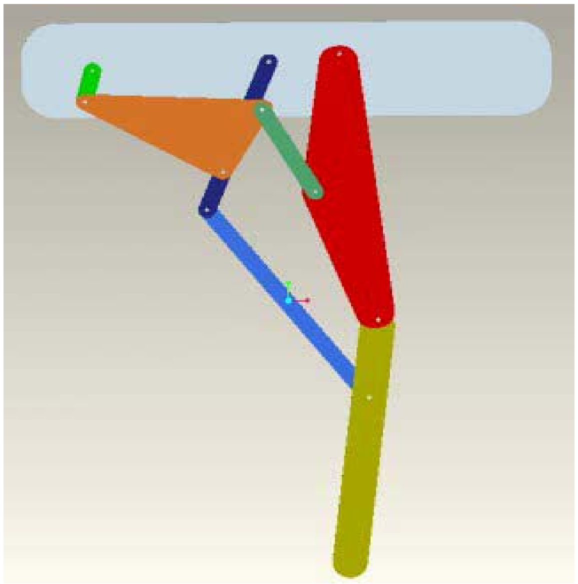

Figure 4.5 Solid Model of 2-Motor Linkage Design

4.1.4 Detailed Designs

The design team, using Pro-Engineer, was able to eliminate the two-motor design once noticing that the adjustability factor was too difficult to design. In the following section the project group will discuss their two design concepts for the four-motor design concept in detail and explain the advantages and disadvantages of each.

4.1.4.1 Initial Design

The initial design, along with the second, incorporated a four bar linkage system to control the hip motion as mentioned in Section 4.1.2.2. This linkage system was designed by using the hip trajectory that was calculated using MATLAB. Using this curve the project group was able to use a computer program that was developed by a graduate student at HUST to find the exact ratio between the four links in the system. This ratio, consisting of the crank, coupler, rocker and base links as seen in Figure 4.6, was calculated to be 5.2:13.1:26.2:19.6 respectively. This ratio had to stay constant throughout the design process to ensure that the hip motion would remain correct. The ratio became the central constraint for the design team.

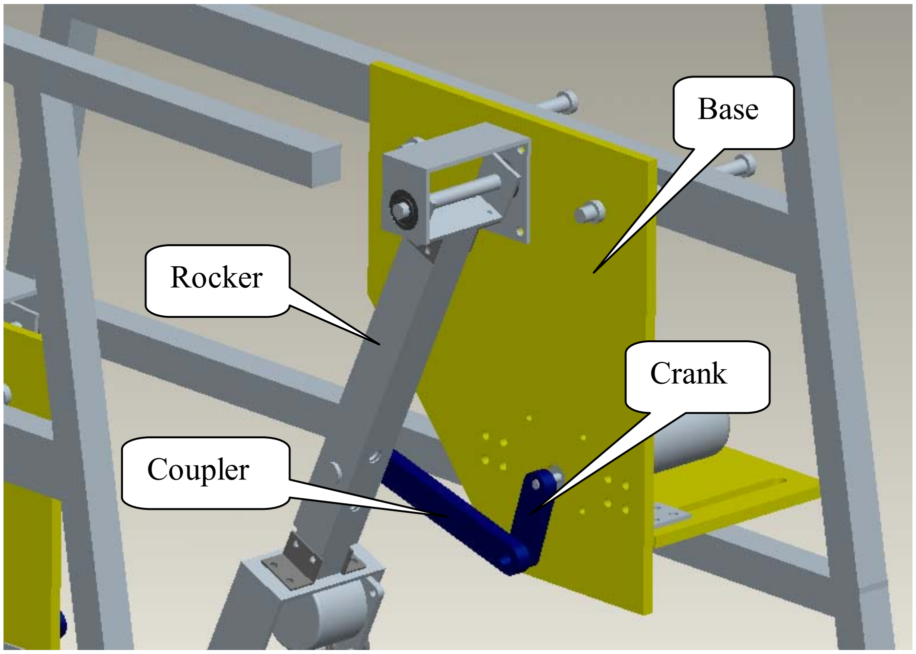

Figure 4.6 Four Bar Linkage Design

The differences between the initial design and the second design are in the knee and support structures.

The initial design for the knee joint consisted of a worm and worm gear, as seen in Figure 4.7, which would allow for the lower leg or shin to move forward and backward under control of a step motor. By controlling the step motor to rotate the worm in a clockwise direction would allow the leg to swing forward and a counter-clockwise rotation for the leg to swing backward. The design team also needed a devise that could reduce the velocity of the motor by a desired 10:1 ratio and increase the torque output from 1:10. A worm gear has the properties to do so.

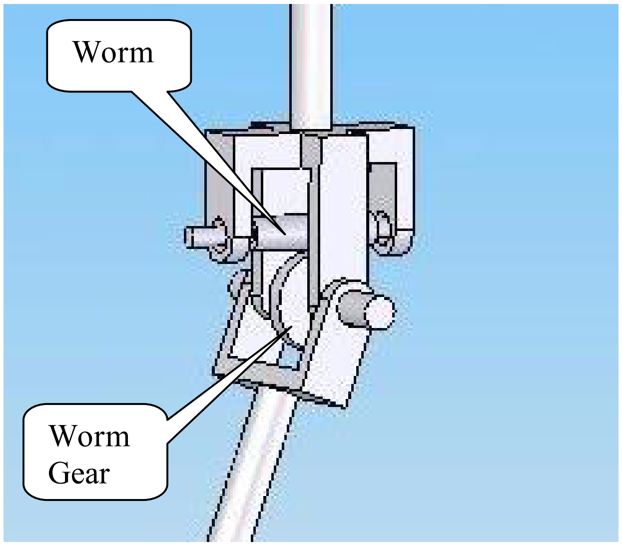

Figure 4.7 Initial Knee Mechanism Design

With the advantages of using a worm gear, the design team discovered that there were also many disadvantages that came with them. While researching more information about the properties of worm gears the design team found that they have poor efficiency ratings for this type of application. According to Norton, the sliding and thrust loads in a wormset are very high, making the worm gears fairly inefficient at 40 to 85% efficiency [9]. This is undesirable not only because of the lose in energy, but the fact that most of that energy is lost in the form of heat. Making it potentially dangerous for the patient that is going to be strapped to the device. Continuing, another problem existed with the packaging of the worm and worm gear. Knowing that a patient must be strapped to the legs of the device, the design team desired a knee that would allow for comfortable placement of the leg alongside the device. The design that was formulated in Figure 4.7 does not follow those standards. It would have been too large to allow for such comfort by the patient. The project group also had to consider the manufacturing of the device. With the proposed design as shown above in Figure 4.7, it would have been quite difficult to assemble and produce the knee with accuracy enough that the worm and worm gear would not bind or slip because of misalignment.

The design team also came up with a support structure that would allow for the patient to be hung by a harness system and be brought over the device to be strapped to the legs. This supports structure consisted of two parts, the harness stand and the mechanism stand as shown in Figure 4.8 and Figure 4.9 respectively. The mechanism stand incorporated rollers at the bottom of the structure. Originally, the project group thought that this would be used in replace of a conveyor belt system that is used in some of the devices that are on the market already. After consulting with professors, the project group decided not to include these rollers because of the potential that they may injure the patient due to the tension that the contact between the rollers and the patient's feet would place on their legs. The design team once again took in account manufacturability and cost. These designs, although feasible and not difficult to assemble and produce, would be very time and budget consuming.

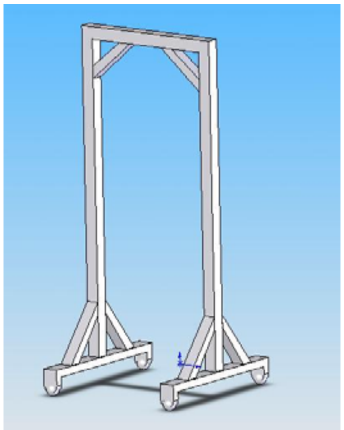

Figure 4.8 Initial Design of Harness Stand

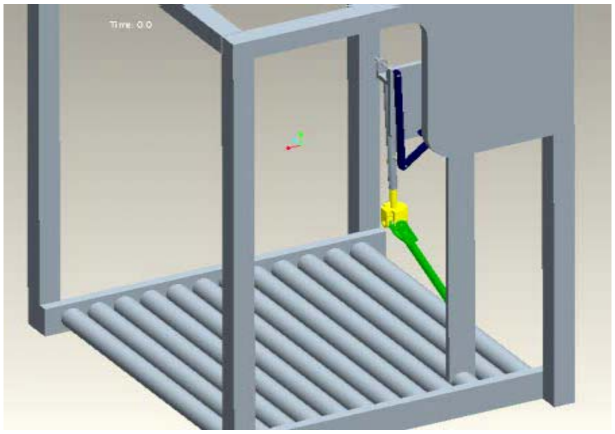

Figure 4.9 Initial Design of Mechanism Stand

4.1.4.2 Second Design

Taking in account for the disadvantages found in the initial design, the project group developed a second design that resolved those issues. Since the ratio for the four-bar linkage system did not come across any problems the design team transferred this idea over to the second design keeping the ratio of 5.2:13.1:26.2:19.6 for the crank, coupler, rocker and base links respectively.

The knee design in the initial design came across some serious problems that needed to be addressed. In place of the inefficient worm gear, the design team proposed a compound gear train in its place. This gear train would allow for the velocity reduction of the motor by the desired 10:1 ratio as well as the torque increase from 1:10. With a ratio this high the design team decided that a compound gear would be best over a simple gear train. The limited amount of space and the high train ratio made it an easy decision for the design group. Using spur gears allowed the project group to package them in a compact manor, as seen in Figure 4.10, and keep the comfort of the patient in mind. It also eliminated the efficiency problem, along with the potential to burn their patients.

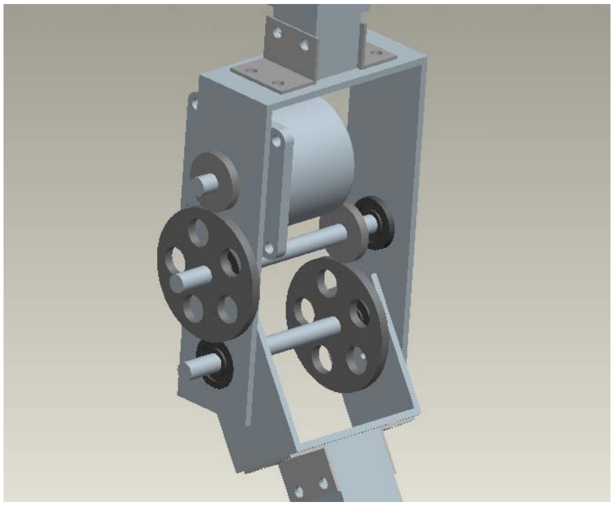

Figure 4.10 Second Knee Mechanism Design

Once realizing that the roller system and the harness stand were eliminated from the design the project group returned to the research stage to find new inspiration. What they found was two things that have assisted infants and the elderly to walk for years. The baby and adult walkers as shown in Figure 4.11 and Figure 4.12 would become the team's inspiration for their harness and support structures respectively. The baby walker allowed the design team to visualize a harness that would hang the patient from the support structure that the mechanism would also be attached to. This allowed for the elimination of the separate harness structure. The adult or elderly walker allowed the design team to envision a supporting structure that would hold the mechanism and the patient together.

Figure 4.11 Example of Baby Walker Design that Inspired Harness

Figure 4.12 Example of Adult Walker Design that Inspired the Frame

With comfort being one of the major objectives for the project group to accomplish, they designed ways for the device to be adjustable to fit the different sized patients that will ultimately be using it. To do this, the design team incorporated two design features into the mechanism that would accommodate the different sized patients.

The first feature that was incorporated was the ability to adjust the thigh length of the device's legs. As seen in Figure 4.13, the design team used two different sized stainless steel square tubes to allow for adjustability by placing pin holes on the leg. This will allow the knee joint to be adjusted up or down according to the length of the patients thigh.

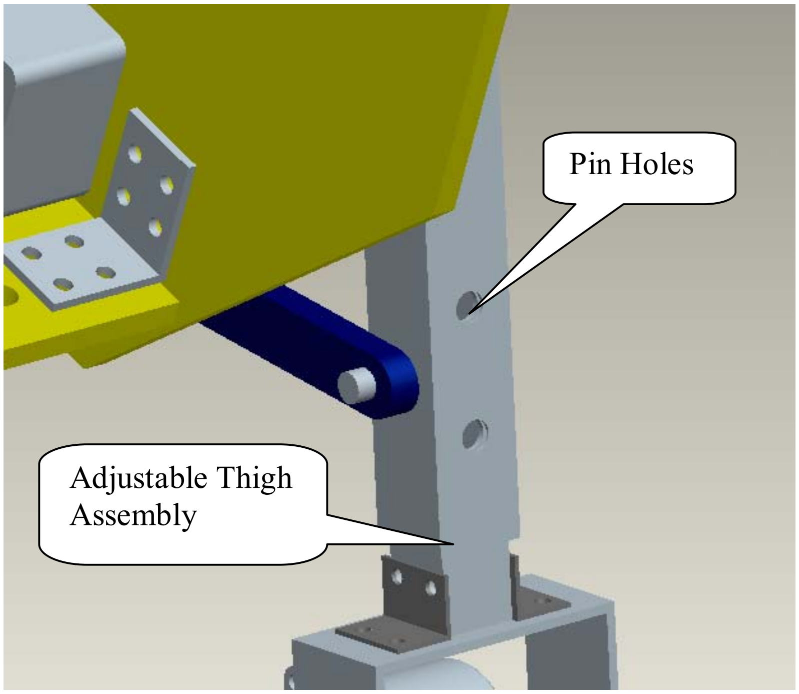

Figure 4.13 Adjustable Thigh Design

The second feature that the design team incorporated into the design was a way for the legs to be able to move closer or away from each other. This will allow the device to accommodate the different hip thicknesses of the patients. The feature will allow for the device to be securely and comfortably strapped to the patients' legs. To do this the design team, as shown in Figure 4.14, used slide pins and adjustment channels to allow for the movement of the legs. Bolts were also used to fasten the frame to the slide plates to prevent movement once the legs were separated to their desired distances.

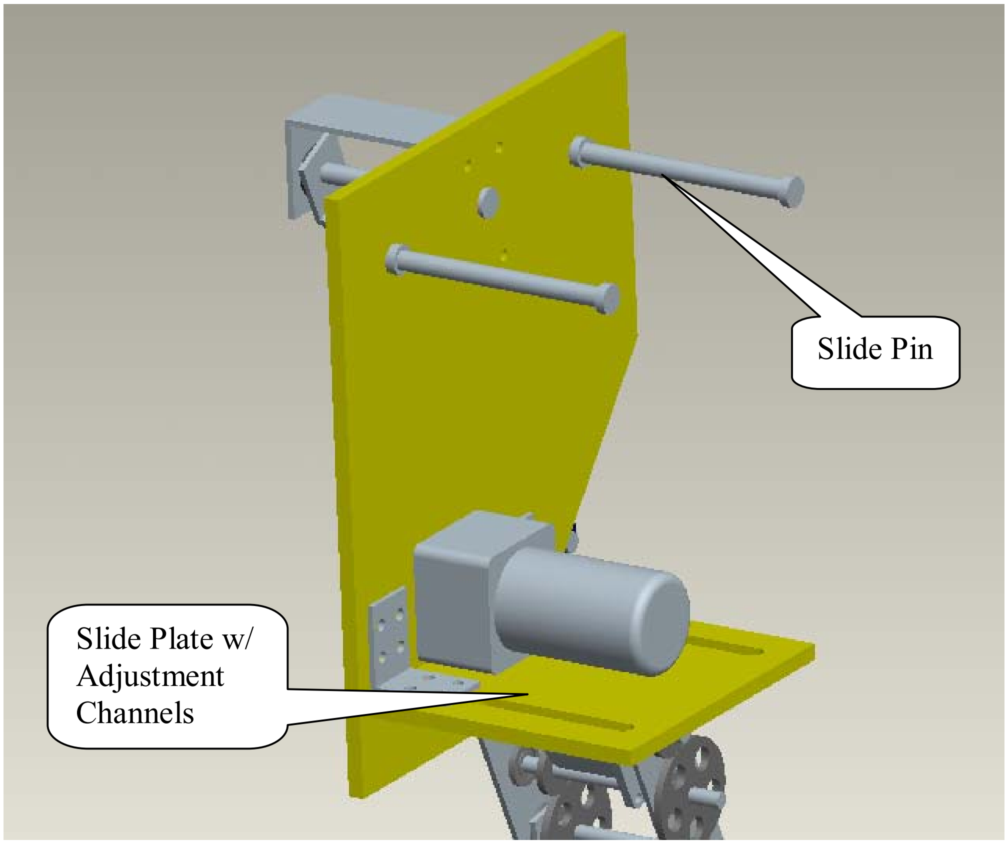

Figure 4.14 Adjustable Hip Design

4.1.5 Final Design

This section will detail the final design and show the finished product. Also, the project team will explain to the reader a basic overview of the control system used to move the device.

4.1.5.1 Mechanism

As mentioned in Section 4.1.4.1, the design team used software provided to them by HUST that allowed them to calculate the lengths of the four-bar linkage system by imputing the equation of the knee trajectory curve, which can be found in Appendix A.

The knee, as mentioned in Section 4.1.4.2, used a compound gear train to allow for the velocity of the motor to be reduced by the desired 10:1 ratio as well as increase the torque output by an inverse ratio of 1:10. This meant that the project group had to design their own gears so that they would perform according to those desired ratios. From their calculations, the design team was able to choose a small gear with fifteen teeth and a large gear with forty-nine teeth. This would allow for the compound gear train to keep its train ratio, as well as have the gears match up without binding.

Once the knee and hip joints were finished being designed, the project group was able to finish there solid modeling of the finished design assembly. The final design is as shown in Figure 4.15 and Figure 4.16.

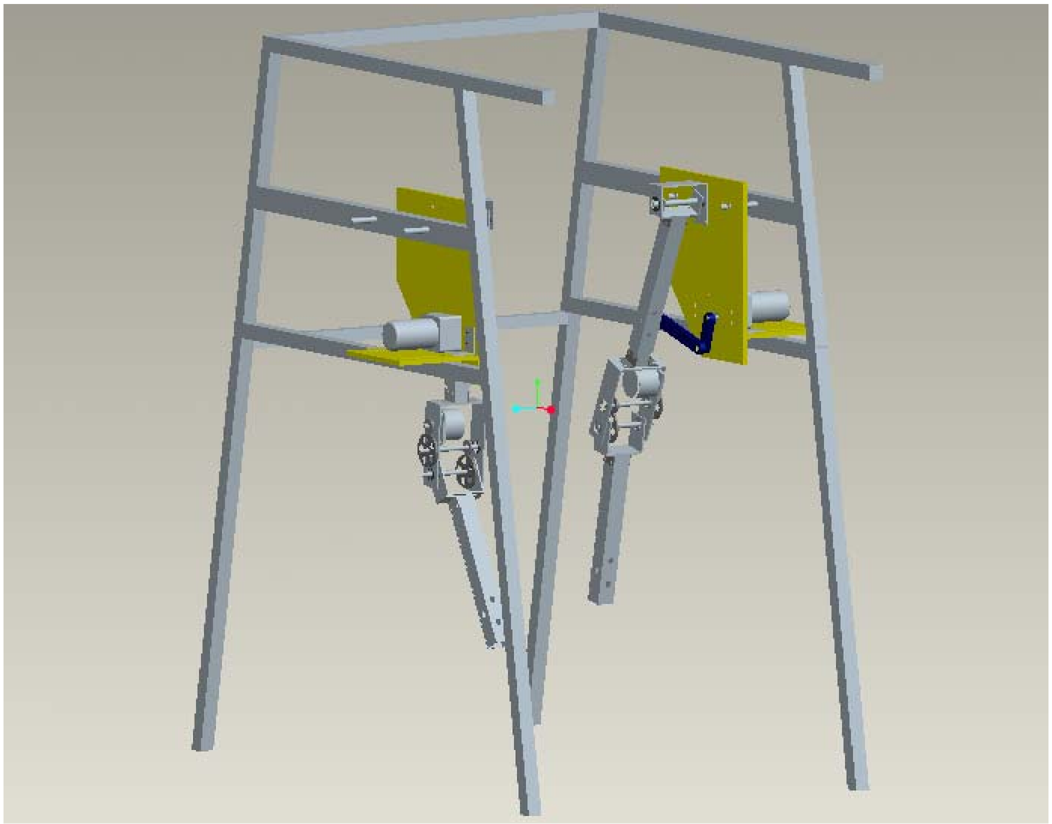

Figure 4.15 Solid Model of Final Overall Design

Figure 4.16 Final Assembly

4.1.5.2 Control System

The control system, designed by the HUST group members, had a framework made up of five main components. These components consisted of a computer, as well as a single chip control board, drive circuit, electric power source and finally a motor. A diagram of the framework can be found in Appendix C.

The controls team was able to write a C language program that would allow the hip and knee motors to run in sink with each other. This step was a vital part of the control system in that both motors had to match each other so that the motion of the legs would match precisely to that of a real human walking motion. A flow chart of this program can be found in Appendix C. As the framework shows, the computer sends this program to the single chip control board, which has its circuit diagram in Appendix C, and allows it to send pulses to the drive circuit. Receiving 24V of power from the electric power source pictured in Figure 4.17, the drive circuit is able to transfer these pulses from the control board as an electric current that is then sent to the motors to make them rotate.

Figure 4.17 Electric Power Source for Control System

The motors used by the project group were purchased so that the maximum torque rating was above that of the calculated maximum torques for both the hip and the knee joints. Since the torque of the hip joint was large and the motion was to be continuous in one direction due to the linkage system, to project group decided to chose a DC motor for each hip similar to that pictured in Figure 4.18. This provided enough torque to rotate the linkages which in turn moved the thigh. The knee joint, unlike the hip joint, needed to be able to change its direction and velocity smoothly. This called for a step motor, similar to those pictured in Figure 4.19. Step motors have very high precision because each pulse sent to it is converted into one step of the motor. The step motors that were selected by the project group had a ±0.5 degree accuracy rating.

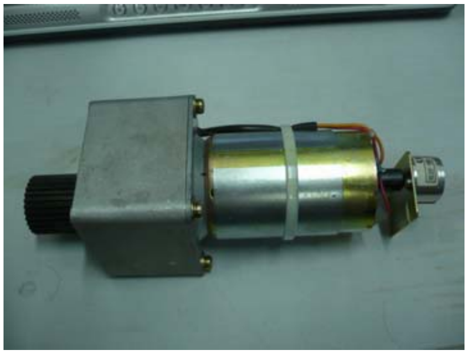

Figure 4.18 DC Motor used to drive the Hip Motion

Figure 4.19 Step Motors used to drive the Knee Motion

4.2 Manufacturing Process

This section will display the procedures that the project group followed while manufacturing their device.

4.2.1 Purchasing of Material

Attempting to design a robotic device such as this project was a difficult task with a budget of only 3000RMB or about $400. For the WPI students, the fact that they were in a foreign country made it difficult for them to figure out what was available to work with for materials. This made designing the robot especially difficult and in making sure that the materials that were purchased were in fact what the project group needed.

Taking this into account and knowing that the budget was low the project team was able to find material and parts that were cheaper and cost effective. This meant, for example, the project group purchased such things as used motors instead of new and thinner stainless steel tubing for the frame. Although still affective to demonstrate our device, it would not be capable of holding a larger sized patient such as a grown man. A cost sheet is available for viewing in Appendix D.

4.2.2 Manufacturing

Manufacturing the parts for the device was much more of a challenge for the project group than anticipated. After buying the necessary material, the manufacturing team began to use the 2-D part drawings, found in Appendix, to measure each cut and hole that was to be made. This process had to be very accurate, for if a hole in an L-bracket was cut 1mm out of spec, for instance, it would not match up with the hole on the part that it was made to mate with. Keeping this in mind, the manufacturing team took a lot of time making sure that they had each measurement correct before they cut each feature on the parts.

The manufacturing team was able to have a lot of the parts they needed machined or welded by the machinists at HUST. Not having enough time to learn how to use tools such as a welding machine and a lathe made it important for the team to outsource their work in this way.

4.2.3 Assembly

Once the parts were manufactured to the specified parameters in the drawings, the manufacturing team began assembling the robot. This step went smoothly for the most part with a few hang ups with misaligned holes. These mistakes in manufacturing were easily corrected and the robot was constructed with ease.

5 Conclusions and Recommendations

Due to the high cost of existing rehabilitation options, 85% of the paralysis patients in China are not able to get treatment for their conditions. The project group was faced with an important task to give these patients a relatively inexpensive, yet affective, alternative to help them with their recoveries.

By designing a four-bar linkage system that allowed the thigh to follow a precisely calculated knee trajectory curve, the authors were able to match the motion of a human thigh while walking. This coupled with a knee mechanism that incorporated a compound gear train and a step motor that was run by a computer program that allowed the shin to move in a precise curve that represented the actual lower leg motion of a human, allowed the authors to create a very precise mechanism that will help a patient regain their leg motion.

This design, knowing not only that the goal was to create a cheaper alternative to existing devices, but also that the projects budget was only 3000RMB, the authors were able to purchase and manufacture the parts for their mechanism amazingly 500RMB under budget (2500RMB or about $330). To do so the design team had to buy parts that were not ideally what would have been bought if they had a larger budget. Therefore the author's have a few recommendations that would allow the device to perform better and closer to their desired objectives. The first recommendation would be to use thicker stainless steel tubing for the frame. The stainless steel that was used was much too thin to be able to support a full grown man for any extended period of time. The authors also recommend that the harness system should be designed so that the patient is comfortable while being hung from the frame. Due to lack of time, the design team was unable to design and manufacture an acceptable harness. The last recommendation is to design the gears so that the gear ratio is exactly 10:1. The gears that were designed used a rounded gear ratio so that the number of teeth would be a whole number. In doing so, when the robot was run, the knee motion eventually over time became out of sink with the hip motion and made the walking motion become unrealistic. This is a problem that was not able to be adjusted due to time, but was noticed and is easy to resolve.

Overall the project team accomplished all of their objectives with few setbacks along the way. Great teamwork and communication allowed the authors to design and manufacture a robotic device that will help retrain the muscles of a paralysis patients legs.

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Appendix A Mathematical Calculations

Hip Curve Function:

$$h=10348.584 t^7 - 33338.0121 t^6 + 40396.5441 t^5 - 23224.2406 t^4 + 6899.8359 t^3 - 1122.0876 t^2 + 40.5168 t + 20.529$$

Knee Curve Function:

$$k =13825.2338 t^7 - 38392.1806 t^6 + 37203.7486 t^5 - 14867.8829 t^4 + 2553.4289 t^3 - 394.5801 t^2 + 72.9816 t + 9.7378$$

Knee Trajectory Function:

$$k_y=543*\sin((10348.584*t^7-33338.0121*t^6+40396.5441*t^5-23224.2406*t^4+6899.8359*t^3-1122.0876*t^2+37.9454*t+23.1775)*2*pi/360)$$

$$k_z=543*\cos((10348.584*t^7-33338.0121*t^6+40396.5441*t^5-23224.2406*t^4+6899.8359*t^3-1122.0876*t^2+37.9454*t+23.1775)*2*pi/360)$$

Torque Equations:

$$T_{max} = I \bullet \beta_{max}$$

$$T_{max}\, hip = I \bullet \beta_{max}\, hip = (1.238 \text{ x } 26.0438) \text{ N}\bullet\text{m} = 32.25 \text{ N}\bullet\text{m}$$

$$T_{max}\, knee = I \bullet \beta_{max}\, knee = (0.6140 \text{ x } 6.2129) \text{ N}\bullet\text{m} = 3.8647 \text{ N}\bullet\text{m}$$

Appendix B Data

Hip Curve Raw Data:

Hip Joint Angles

angle	time	angle	time	angle	time	angle	time
20.843	0	6.6854	0.28414	-6.6854	0.55762	21.236	0.78138
20.489	0.017759	5.191	0.3019	-6.2921	0.56828	22.809	0.79914
20.449	0.035517	4.4438	0.31966	-5.5056	0.57893	24.382	0.8169
20.253	0.053276	3.1461	0.33741	-5.309	0.58603	25.365	0.83466
19.86	0.071034	1.9663	0.35517	-3.9719	0.59669	25.955	0.85241
19.27	0.088793	0.98315	0.37293	-3.382	0.60379	26.388	0.87017
18.287	0.10655	0	0.39069	-1.573	0.62155	26.27	0.88793
17.461	0.12431	-1.4157	0.40845	0	0.63221	25.916	0.90569
16.202	0.14207	-2.6742	0.42621	0.78652	0.63931	25.169	0.92345
15.14	0.15983	-3.5393	0.44397	3.5393	0.65707	24.382	0.94121
14.157	0.17759	-4.6404	0.46172	6.2921	0.67483	23.792	0.95897
12.978	0.19534	-5.5056	0.47948	9.2416	0.69259	23.202	0.97672
11.601	0.2131	-6.2921	0.49724	11.798	0.71034	23.045	0.98738
10.225	0.23086	-6.7247	0.515	14.157	0.7281	22.809	0.99448
9.0449	0.24862	-6.9213	0.53276	16.91	0.74586	22.73	1.0051
7.8652	0.26638	-7.0787	0.55052	19.191	0.76362	22.416	1.0122
						20.843	1.03

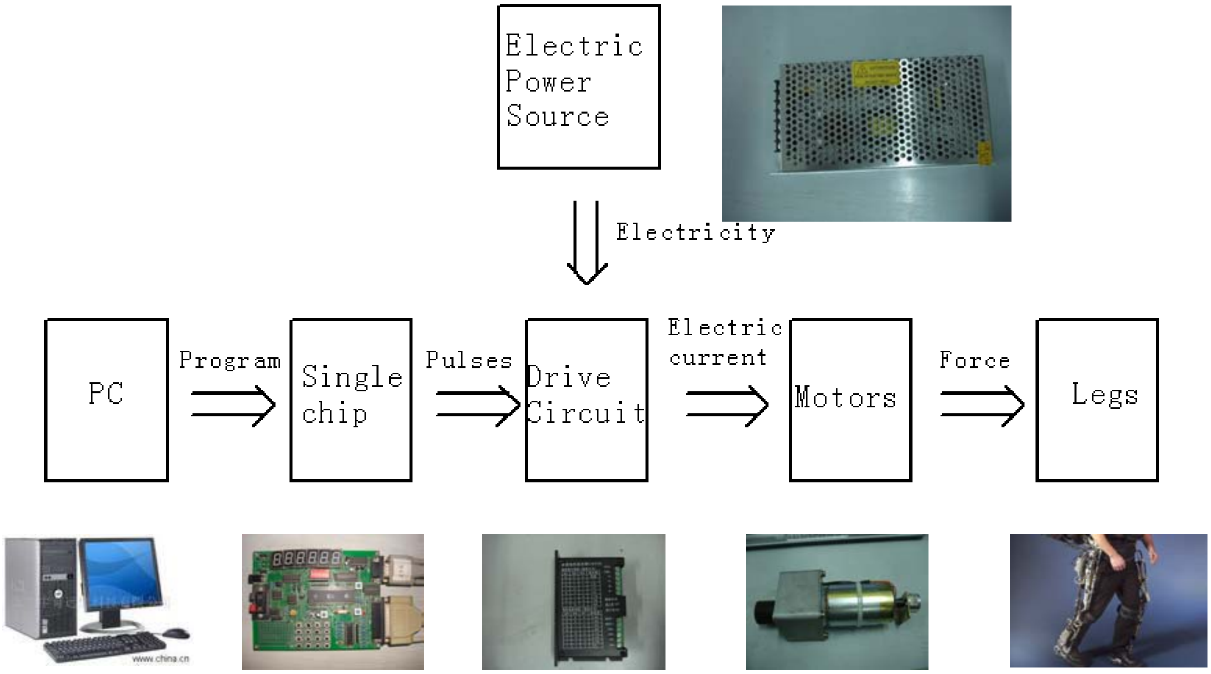
Knee Curve Raw Data:

Knee Joint Angles

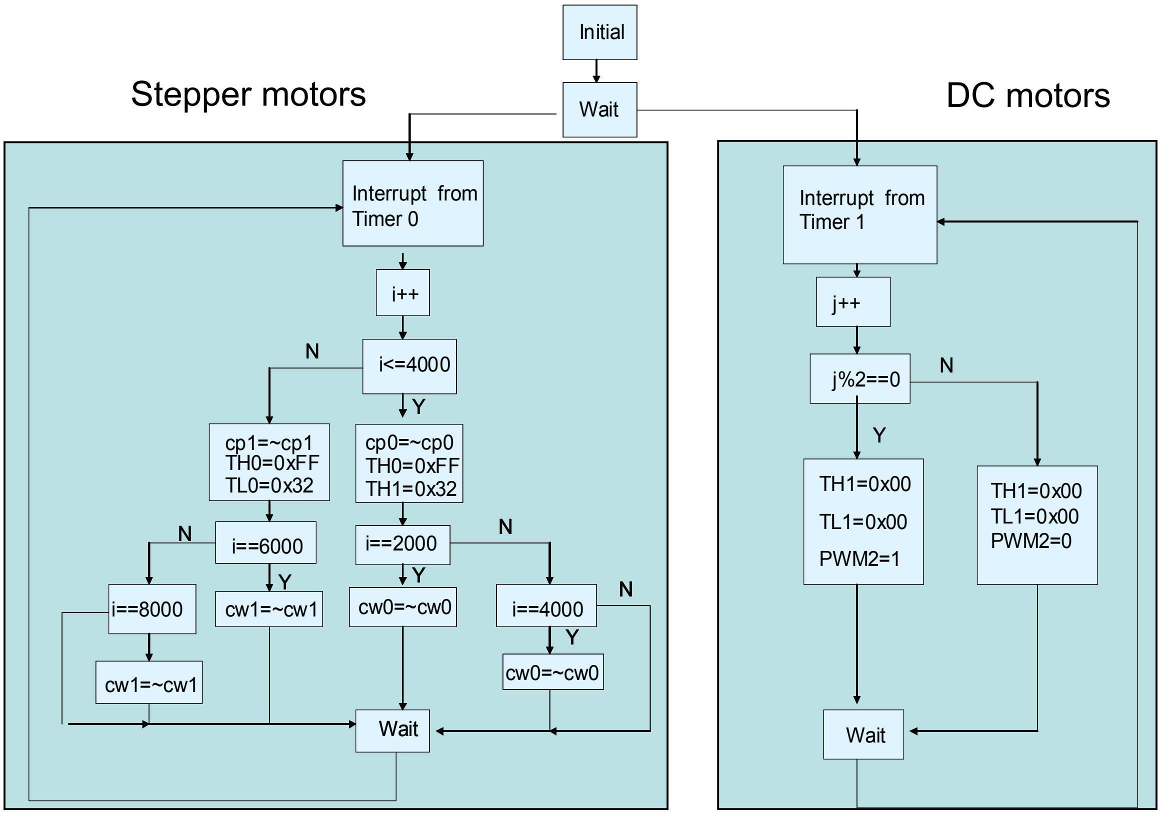
angle	time	angle	time	angle	time	angle	time
10.37	0	9.0074	0.3019	23.704	0.60379	37.037	0.90569
10.667	0.017759	8.1778	0.31966	27.319	0.62155	30.874	0.92345
11.319	0.035517	7.2889	0.33741	32.889	0.63931	26.37	0.94121
12.148	0.053276	6.637	0.35517	37.926	0.65707	20.919	0.95897
13.096	0.071034	6.2222	0.37293	42.667	0.67483	16	0.97672
14.222	0.088793	5.9259	0.39069	47.407	0.69259	13.156	0.99448
15.17	0.10655	5.9259	0.40845	52.385	0.71034	11.259	1.0122
15.881	0.12431	5.9259	0.42621	55.704	0.7281	10.37	1.03
16.119	0.14207	6.4593	0.44397	58.193	0.74586		
16	0.15983	6.9333	0.46172	59.852	0.76362		
15.526	0.17759	7.4667	0.47948	60.444	0.78138		
14.933	0.19534	8.8889	0.49724	59.378	0.79914		
14.222	0.2131	10.133	0.515	57.956	0.8169		
13.333	0.23086	12.207	0.53276	55.111	0.83466		
12.326	0.24862	13.926	0.55052	51.556	0.85241		
11.259	0.26638	16.77	0.56828	47.407	0.87017		
10.133	0.28414	19.556	0.58603	42.37	0.88793		

Appendix C Controls

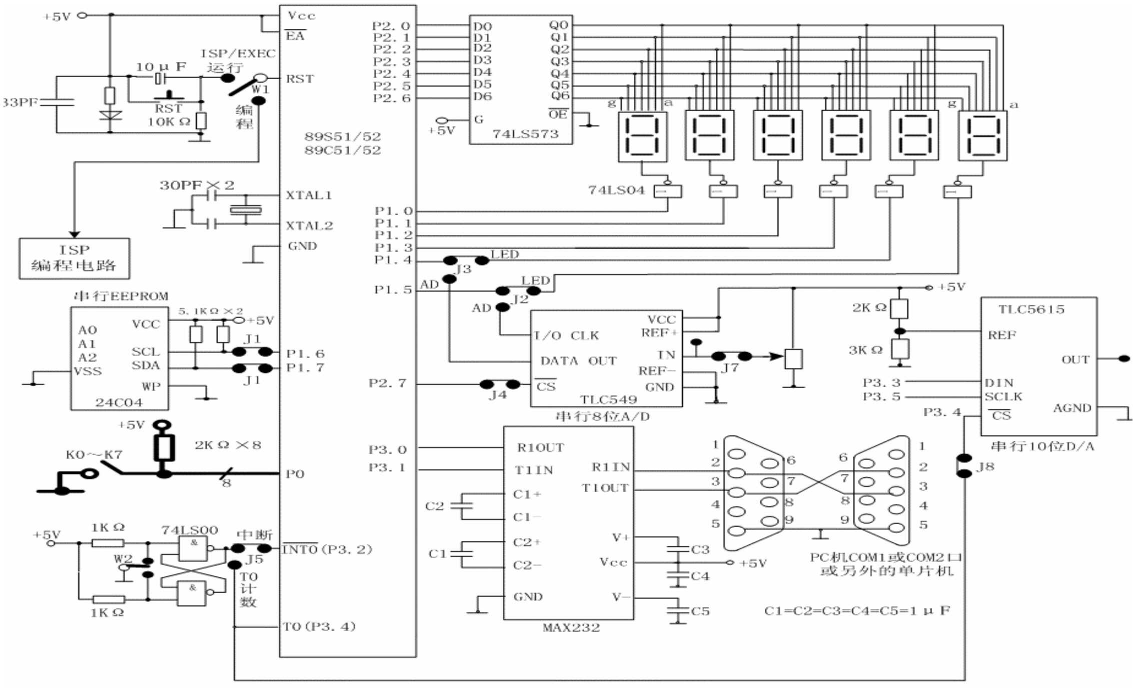
Framework of Control System:



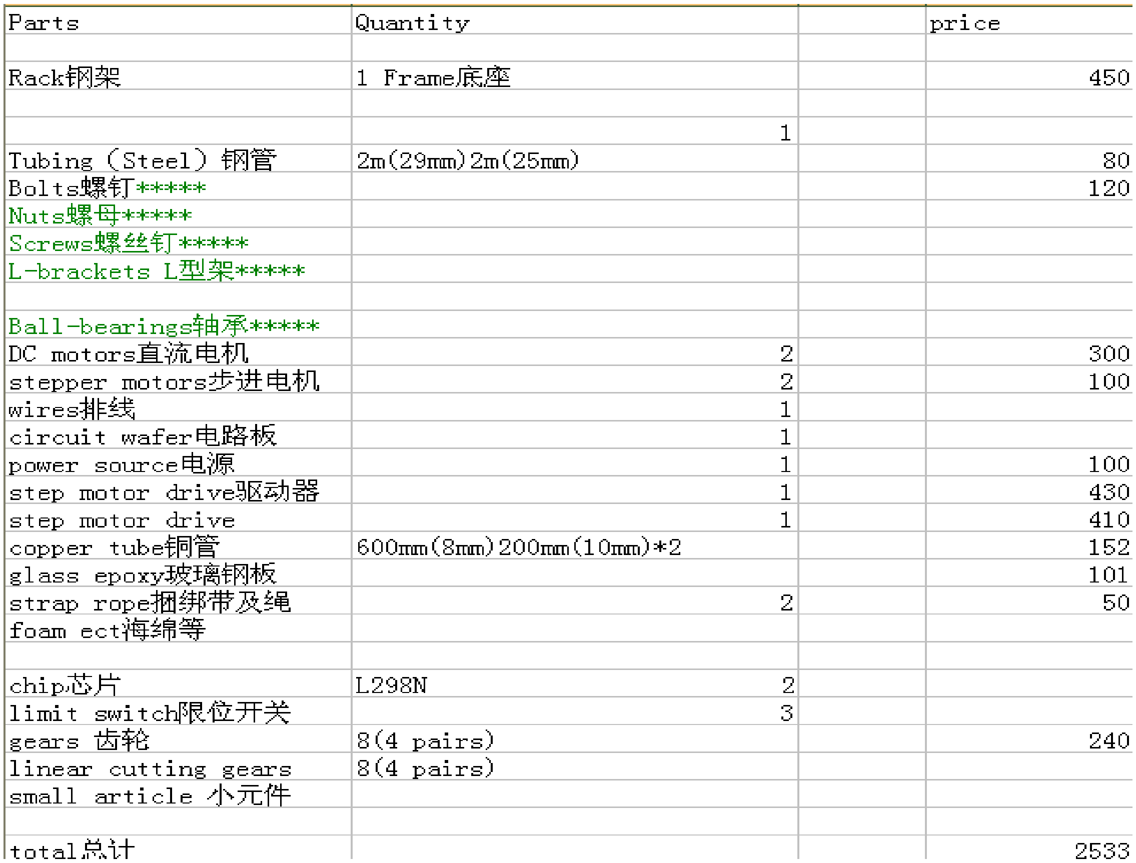
Program Flow Chart:



Single Chip Circuit Diagram:



Appendix D Cost Sheet



Parts	Quantity		price
Rack钢架	1 Frame底座		450
	1		
Tubing（Steel）钢管	2m(29mm)2m(25mm)		80
Bolts螺钉*****			120
Nuts螺母*****			
Screws螺丝钉*****			
L-brackets L型架*****			
Ball-bearings轴承*****			
DC motors直流电机	2		300
stepper motors步进电机	2		100
wires排线	1		
circuit wafer电路板	1		
power source电源	1		100
step motor drive驱动器	1		430
step motor drive	1		410
copper tube铜管	600mm(8mm)200mm(10mm)*2		152
glass epoxy玻璃钢板			101
strap rope捆绑带及绳	2		50
foam ect海绵等			
chip芯片	L298N 2		
limit switch限位开关	3		
gears 齿轮	8(4 pairs)		240
linear cutting gears	8(4 pairs)		
small article 小元件			
total总计			2533