ABSTRACT

DESIGN OF GAIT REHABILITATION SYSTEM

by
Andriy Pletenetskyy

This thesis describes the conceptual design of an innovative robotic rehabilitation machine whose purpose is to help in the recovery of people with motor function disabilities. The machine is smaller, simpler and cheaper than current solutions on the market yet it delivers same functionality.

The conceptual development of the gait rehabilitation system also features a human model with average anthropometric dimensions that allows better visualization and understanding of the actual machine operation. The human model is kinematically coupled to the machine and the whole assembly presents a complex mechanism that closely simulates gait training session.

Three-dimensional modeling and analysis techniques were extensively used throughout the study in order to achieve the best design solution. Finally, kinematic position, velocity and acceleration analyses that were performed on the machine set a direction for future research.

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by
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APPROVAL PAGE

DESIGN OF GAIT REHABILITATION SYSTEM

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LIST OF DEFINITIONS

CAD	Computer Aided Design
Gait	An individual's pattern of walking
GRS	Gait Rehabilitation System

CHAPTER 1

INTRODUCTION

1.1 Current Advances in Gait Rehabilitation

Walking ability, though important for quality of life and participation in social and economic life, can be adversely affected by neurological disorders such as spinal cord injury, stroke or traumatic brain injury. Rehabilitation of patients with such disorders should include gait training because there is evidence that the desired function or movement has to be trained in a task-specific program. One contemporary approach is body-weight supported treadmill training in which the patient is suspended over a treadmill and the patient's legs are guided by therapists (Lunenburger, 2007) as shown in Figure 1.

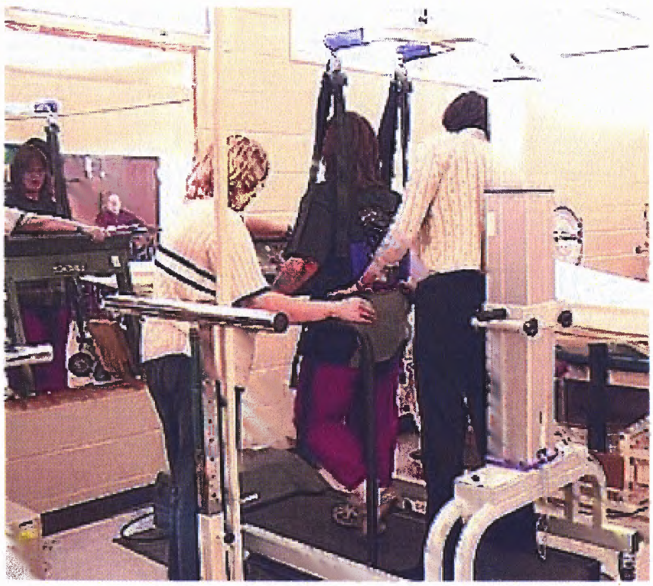

Figure 1.1 Gait Training with the Help of Therapists
(Source: Sharon, 2003)

Several studies have shown beneficial effects of this approach. There are some indications that an increased training intensity might lead to clearer results. However, the manual form of this therapy in which the patient's legs are guided by two therapists holding and moving them along a gait-like trajectory is strenuous for the therapists and labor- and cost-intensive. Depending on the patient's condition, the therapists have to assist the stance leg by extending the knee against the weight of the patient or they have to flex the knee joint, possibly against spasticity, and lift the leg through swing phase. The high physical effort for the therapists often limits the training duration, whereas the patient might benefit from a longer duration. Recently developed rehabilitation robots allow delivering continuous support for the legs in a physiological gait pattern, high repetition accuracy, and prolonged training duration compared to manual treadmill training (Lunenburger, 2007).

Many machines providing such functions are already on the market. Among most popular are: Locomat in Figure 1.2 and HapticWalker in Figure 1.3.

Figure 1.2 Locomat Training Session
(Source: Samcon, n.d.)

The basic version of the Lokomat System consists of the Lokomat (robotic gait orthosis) and the Lokobasis (body weight support system). It is used in combination with a Woodway treadmill. The orthosis is position controlled. The patient's legs are guided according to a pre-programmed physiological gait pattern. The computer controlled guidance allows individual adjustments of different gait parameters (Samcon, n.d.).

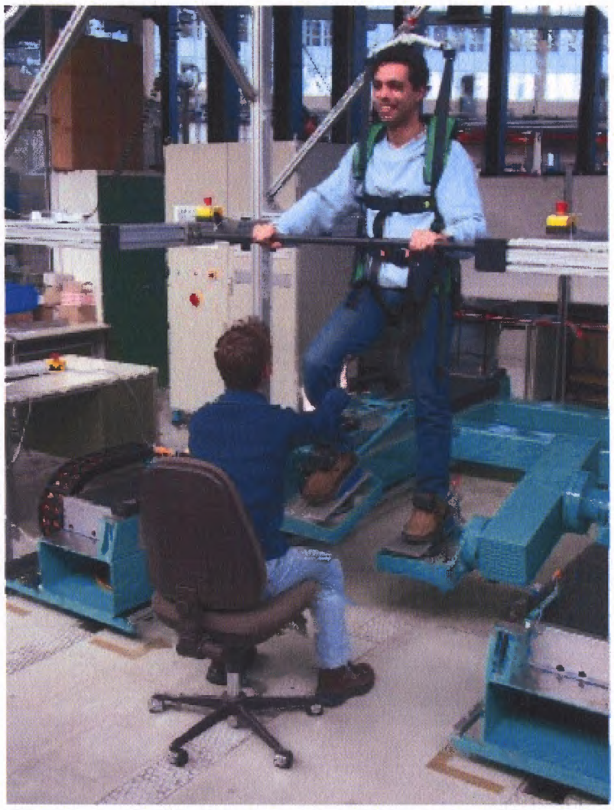

Figure 1.3 Walking upstairs during a HapticWalker gait training session
(Source: Hennig, 2002)

HapticWalker is very similar in function to the Locomat but it has a unique ability of generating any desired gait pattern by the means of computer software. Walking up or down the stairs, running, walking on irregular surface patterns can be simulated.

These devices have disadvantages. They both take up a lot of space and are very bulky. They also require presence of a computer operator throughout the session. Another concern is safety of the machine. Locomat consist of four separate devices (body weight support system, robotic gait orthosis, treadmill and computer software) which have to work synchronously and error free. This raises questions of reliability of such devices. Since they tightly interface with a human body any error could lead to major negative consequences.

Finally these machines are very expensive, and also expensive to maintain, as they require presence of a trained operator.

These deficiencies can be overcome by designing a simpler, cheaper model that would provide very similar functions. A simple model would be more appealing to the end users of the machine, and cheaper cost would make it a product of choice among institutions requiring gait function rehabilitation or research.

1.2 Objective

From the research done by Yazan A. Manna (Yazan, 2005) it was observed that, during manual gait training, the movement of therapist's hands that guide patient's legs form closed-loop, almost planar trajectories in each gait cycle. These trajectories, when produced by path-generation mechanisms, can be used to guide the legs with coordinated movement of the individual leg joints. These trajectories also limited the joint's range of motion (ROM) due to the natural kinematics constraints. By assuming that the walking gait cycle was bilaterally symmetric, the coordination between the left and right legs can be achieved with two identical, but phase shifted, mechanisms. Since the coordination of joint motion and limitation of joint range are achieved directly through the closed trajectories of the generation mechanism, safety and reliability of the training should be greatly improved when compared with a robotic system.

Hesse and Uhlenbrock used a modified crank and rocker mechanism in a mechanized gait trainer, where a planetary gear system replaced the crank to simulate 60/40 percent split of stance and swing phases. Besides the 60/40 split in phases, it is not clear what the generated gait pattern looks like during the entire gait cycle. To achieve the objective of a gait rehabilitation system based on a simple trajectory guidance mechanism, two critical issues must be addressed. One is to define the timed trajectory for entire gait cycle and the other is to find a proper mechanism to carry out the guidance function. The device should be able to operate in either passive or active modes. That is, it can be automatically controlled to manipulate affected legs in desired speed (passive mode), or be programmed to have adjustable resistance to user's own movement (active mode), according to the purpose and level of training (Yazan, 2005).

In order to define the desired trajectories for leg guidance, physiological gait patterns were studied, particularly the gait data collection available at the Clinical Gait Analysis Normative Gait Database. Similar to the development of the Lokomat and Haptic Walker, the initial study was focused on the gait in the sagittal plane. The change in orientation, or pose, of the pelvic is neglected at this stage since the variation of the three pelvic angles (pelvic tilt, pelvic obliquity, and pelvic rotation) during normal gait is relatively small. Since joint angles are more scalable, gait data is commonly presented in the form of the statistical average and standard deviation of different sets of measured values, normalized to full gait cycle in 50 equal time intervals. The relevant gait data for sagittal leg movement are angles of hip flexion and extension, knee flexion and extension, and ankle plantar flexion and dorsiflexion. Examples of hip angle and knee angle from the selected data set are shown in Figure 1.4 (Yazan, 2005).

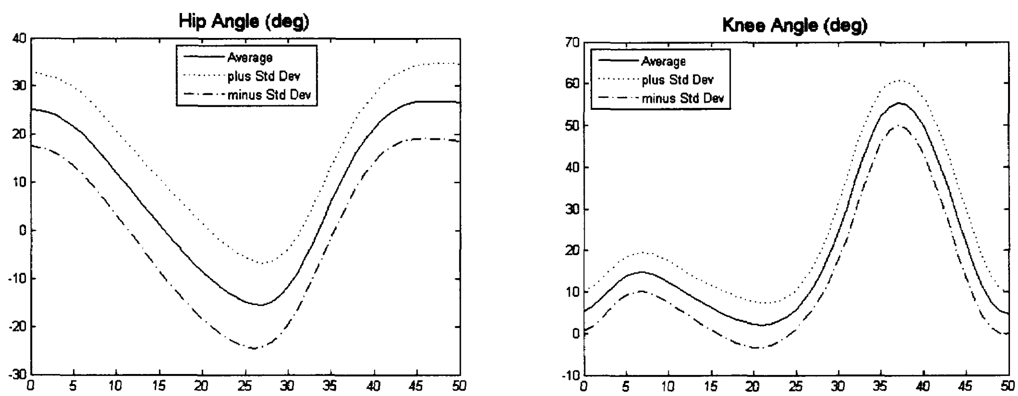

Figure 1.4 Examples of Gait Data, which is generated with data obtained from Clinical Gait from Analysis Normative Gait Database.

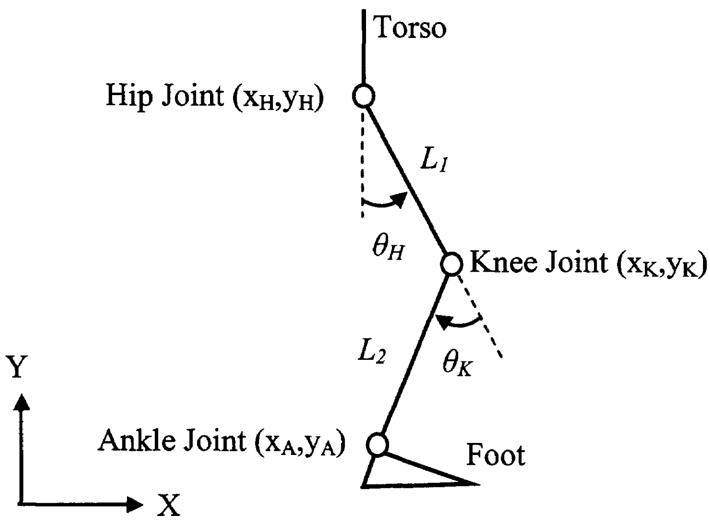

Figure 1.5 Schematics of Gait Kinematics

The position of the ankle can be obtained as

$$\begin{cases} x_A = x_H + L_1 \sin\theta_H + L_2 \sin(\theta_H - \theta_K) \\ y_A = y_H - L_1 \cos\theta_H - L_2 \cos(\theta_H - \theta_K) \end{cases} \tag{1.1}$$

Applying the average hip and knee angles, the ankle trajectory as shown in Figure 1.5 for the fraction of body height $H = 1.75m$ is obtained (here the hip joint is assumed to be fixed at an arbitrarily selected location). While human gait are continuous cycles, it is natural to see variations among gait cycles and the reported data is the result of statistical process. It can be seen from the plots in Figure 1.6 that there are small discrepancies in the starting and ending values of angle data due to the measurement and subject variability. As a result, the ankle trajectory is not closed (Yazan, 2005).

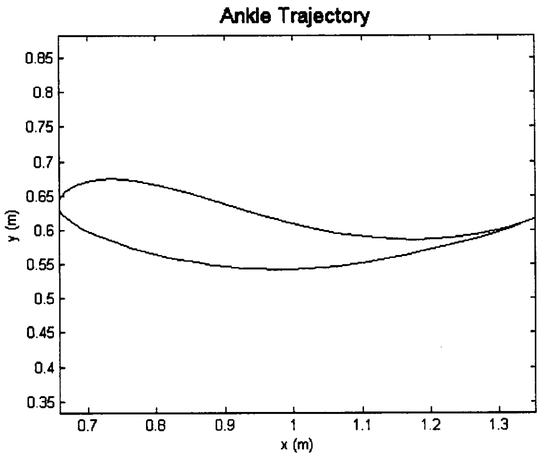

Figure 1.6 Example of an Ankle Trajectory

A mechanism needed to be synthesized to generate the obtained ankle trajectory for guiding leg movement during gait training. The focus was on the study on a four-bar linkage mechanism. A general four-bar path generating linkage is characterized by 9 independent parameters. One possible set of linkage parameters are the coordinates of one ground pivot, the frame angle of the ground link, four link lengths, and one length and one angle (or two lengths) for the coupler point, as shown in Figure 1.7 (Yazan, 2005).

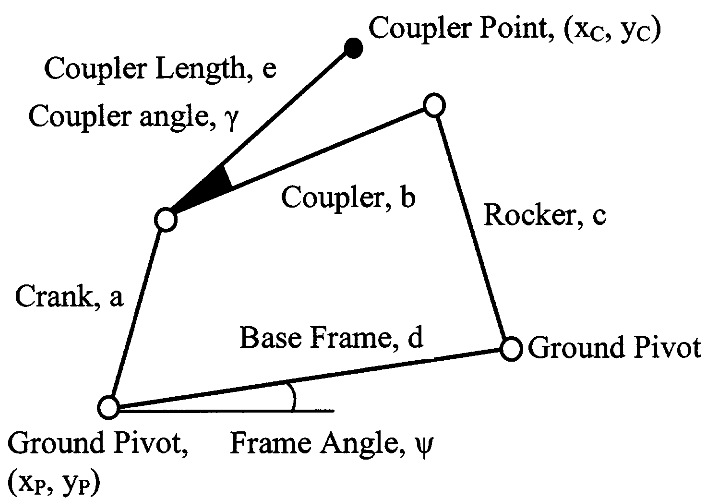

Figure 1.7 Design Parameters of a Crank-rocker Mechanism

It was determined that in order for the Coupler Point of the mechanism to follow the Ankle Trajectory specified in Figure 1.6 the four bar mechanism has to have certain dimensions for each link. These dimensions were analytically determined (Ji, 2007) and they are shown in Figure 1.8.

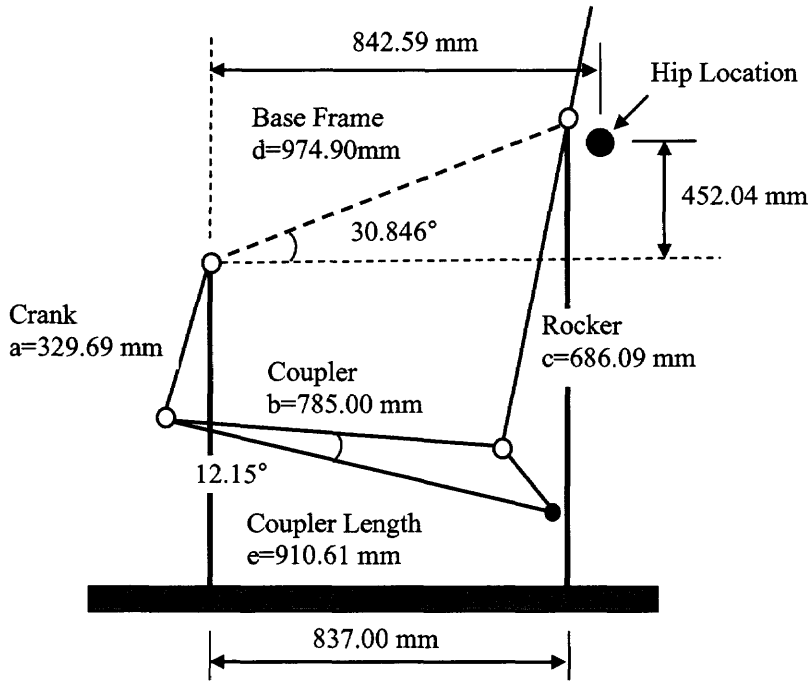

Figure 1.8 Four Bar Mechanism Dimensions for an Average 175cm Person
(Source: Ji, 2007)

Next step in the design was to conceptualize the theoretical mechanism into a three dimensional solid model in CAD software. The model allowed further investigation of the mechanism design options and various simulations involving kinematic, dynamic and structural analysis.

Multiple considerations have to be taken into account so that the final machine came out feasible and if it was to be built it would represent an accurately working model that would generate a desired output of gait rehabilitation for a patient.

The task of designing a conceptual solid model of the gait rehabilitation system lies at heart of this thesis. Process of the conceptual design and simulation as well as results of the machine output will be discussed in detail in following chapters.

CHAPTER 2

PROCESS OF THE CONCEPTUAL DESIGN

2.1 General Assembly Overview

From idea to concept to creation workflow always goes in an iterative manner. Many design options are first considered and implemented then changed back into some other variations many times over. The GRS (Gait Rehabilitation System) went through many iterations to reach its final state.

The first model was almost like a sketch and contained parts only to reflect accurate kinematics of the machine as shown in Figure 2.1.

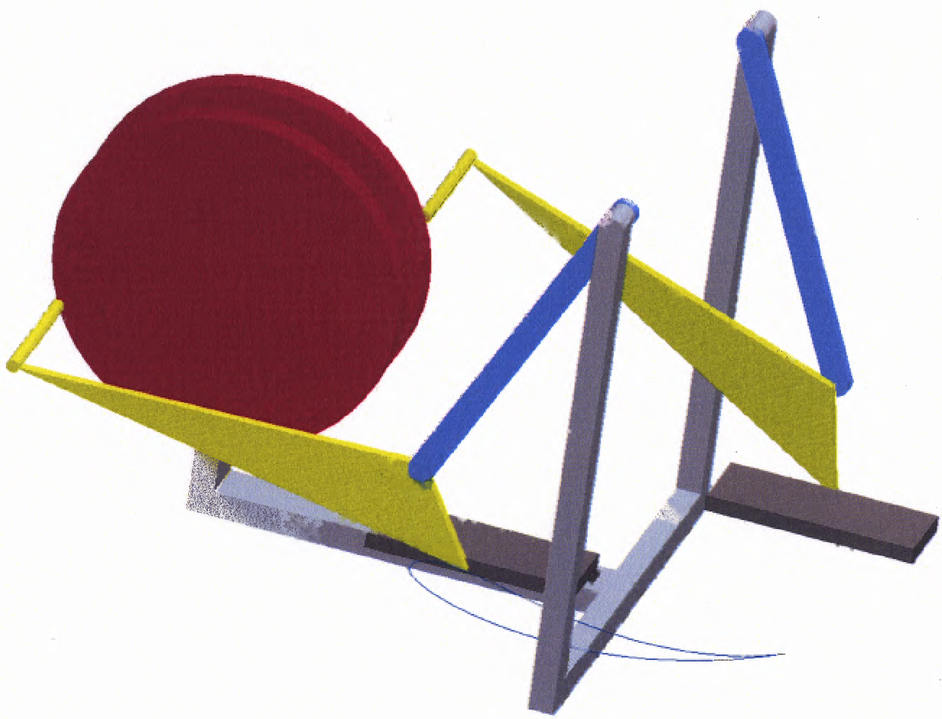

Figure 2.1 First GRS Design

Indeed, if the curve of the moving ankle joint was traced it showed an accurate gait curve like the one in Figure 1.6.

This model was purely conceptual and other modifications had to be performed to make it more realistic and feasible. Second model was created Figure 2.2.

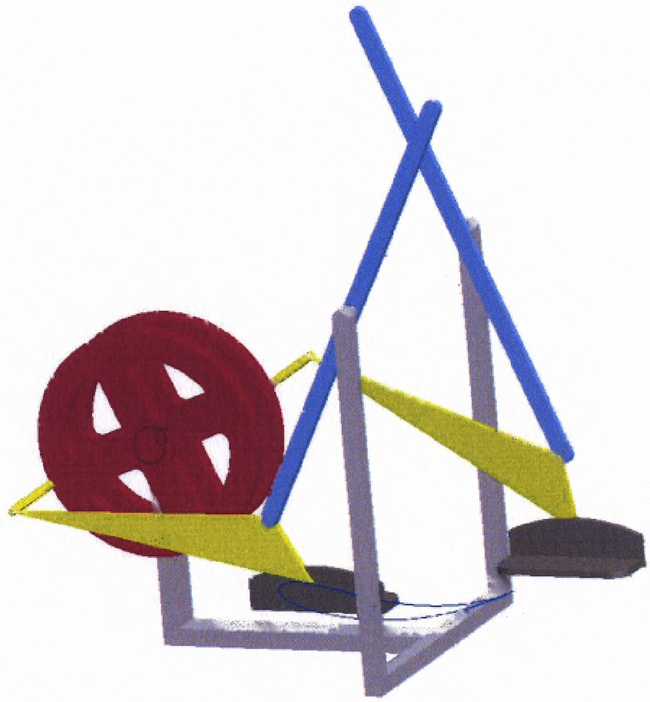

Figure 2.2 Second GRS Design

This design raised many questions as to where and how the parts should be located and spaced from each other. As well as it helped to gain insights on the final dimensions values.

In the next step all the parts were redone with great attention to the details. The result can be seen in Figure 2.3.

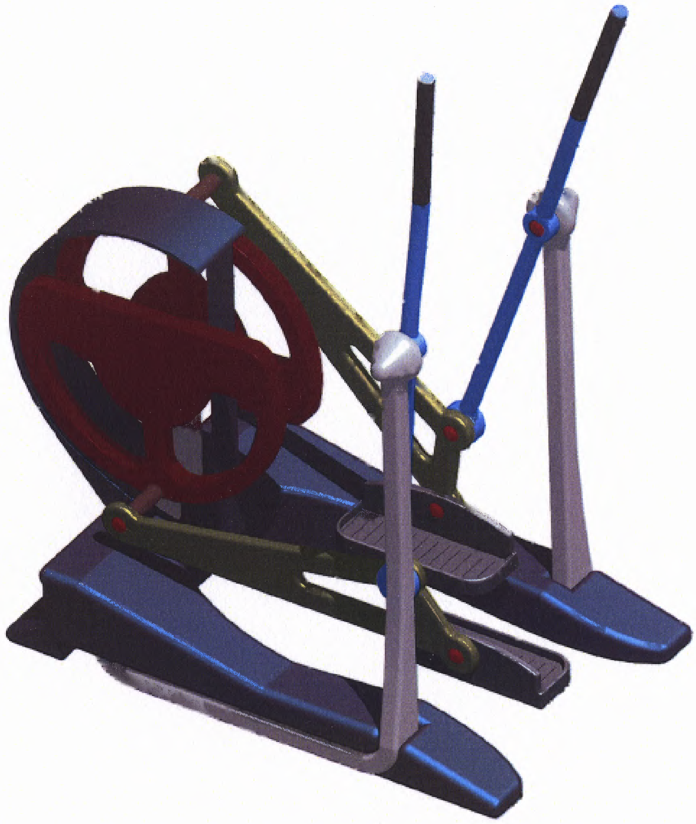

Figure 2.3 Complete Rehabilitation Machine Assembly

This version of GRS seemed like a complete model, but when it got to a design of the person's weight suspension mechanism as well as a mechanism for placing people into the machine a lot of shortcomings of the version surfaced up.

First of all, the distance between handles proved to be insufficient to comfortably move the person into the operating position. Secondly, the actual handle profile seemed to be deficient as it disallowed a natural hand movement during gait cycle. These shortcomings became apparent after creating a human model that clearly illustrated the human-machine interface.

2.2 Human Model Creation

During the design of GRS it became apparent that an actual model of a human is needed in order to make a better design and ensure its proper operation. It was hard to judge on different machine parameters and dimensions just by looking at the picture. A human model made it easy to relate all the parameters and scale of the overall machine to the actual person.

The work of David Winter (1979) on body segment length, as shown in Figure 2.4, was used in order to obtain the body parts dimensions for the human model.

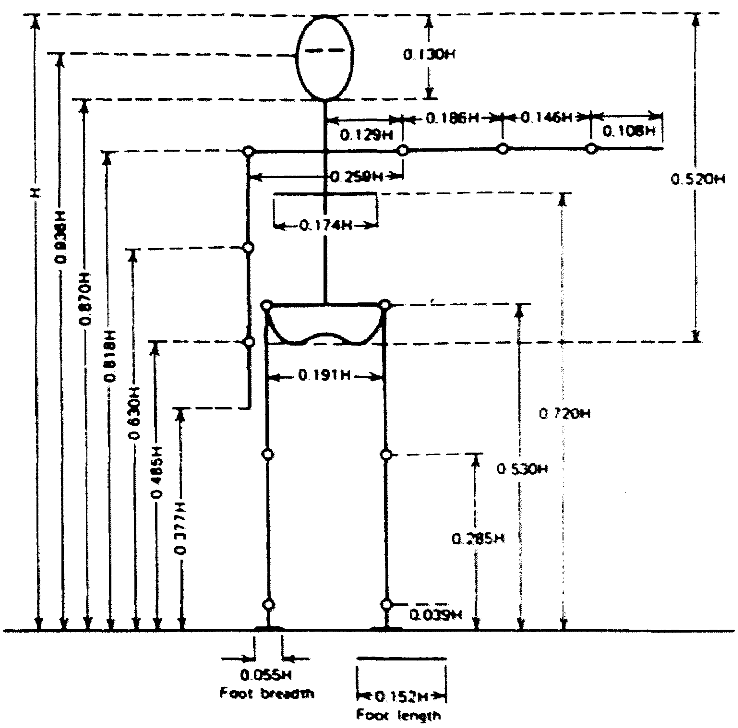

Figure 2.4 Body Segment Length Expressed as a Fraction of Body Height H
(Source: Winter, 1979)

The above model was adopted for GRS (H=175cm) with only difference in the hip joint, as it seems that legs have to be connected to pelvic bone which, in turn, gets connected to the spine. Thus a separate joint that corresponds to pelvic bone was created making the distance from the beginning of the spine to the hip axis equal 101.6mm.

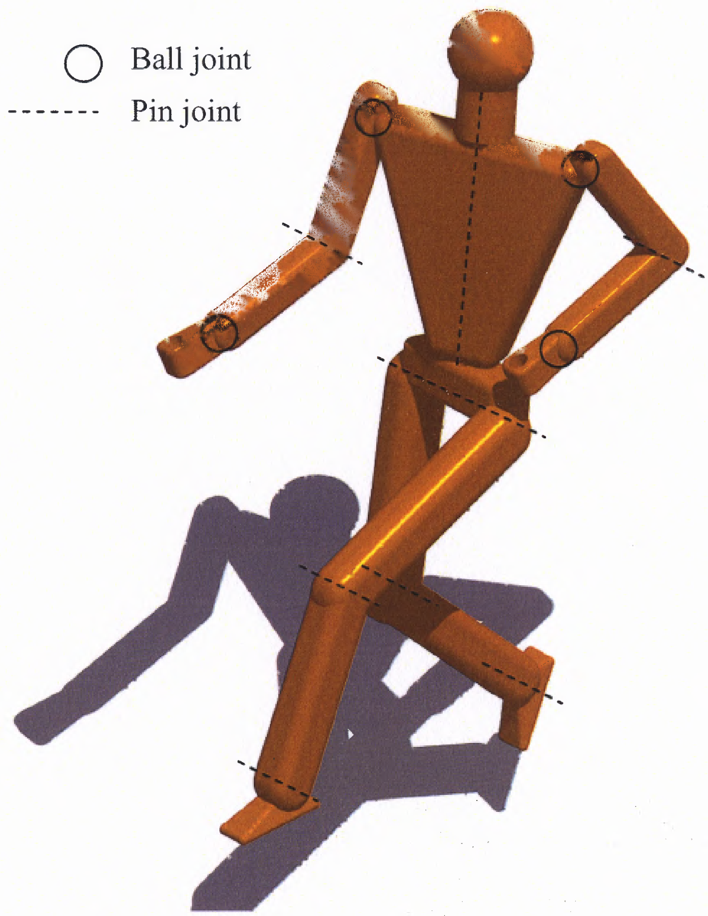

Figure 2.5 Human Model

Figure 2.5 shows the synthesized human model as well as chosen connection types at each joint. Dotted line stands for axial connections and circle for ball joints. This model is a simplification of an actual human body, but it serves sufficient purpose of illustrating the human operation in the machine.

CHAPTER 3

DISCUSSION

3.1 Machine Overview

After multiple iterations and changes to the machine, the final GRS version was synthesized Figure 3.1. A human model with suspension harness was placed inside a machine and all of the model's limbs were kinematically connected to the machine. This resulted in a coupled kinematic model between the human and the GRS. Consequently the whole human model is moving in a designated gait pattern simply by turning the driver disk which, in reality, would be powered by a motor.

The design of the machine consists of 11 major components Figure 3.1:

- Frame
- Suspension Frame
- Plastic Cover
- Driver Disk
- Triangular Link (x2)
- Handle (x2)
- Weight Support System
- Human Model
- Harness
- Suspension Cylinder
- Foot Support (x2)

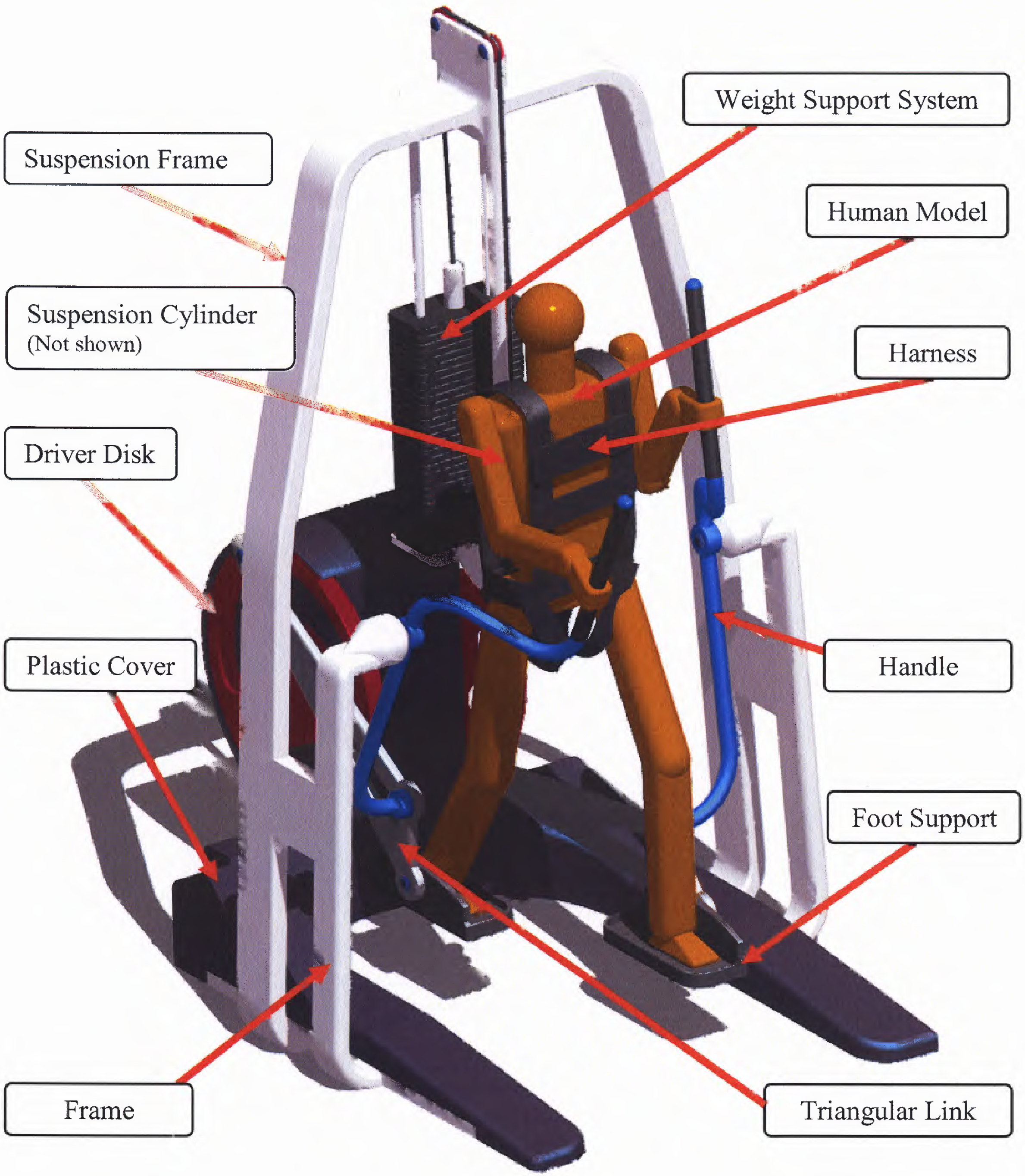

Figure 3.1 Final Gait Rehabilitation System Design

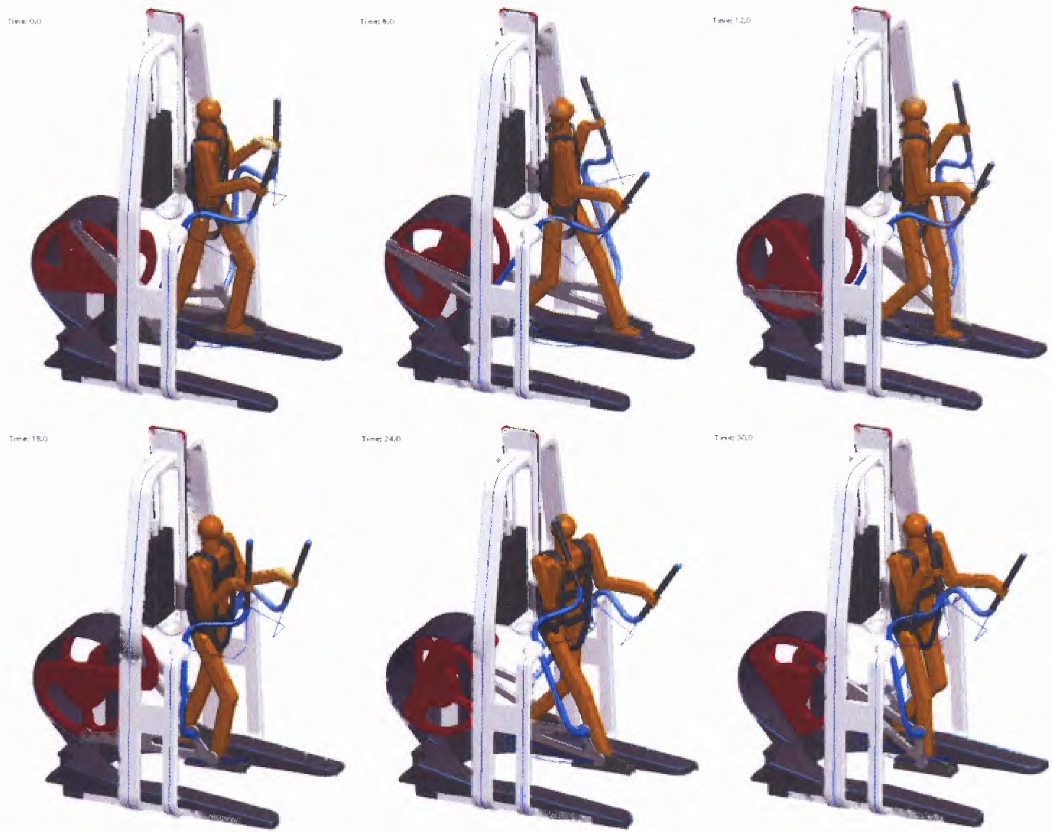

Figure 3.2 GRS with Human Model Operation Sequence

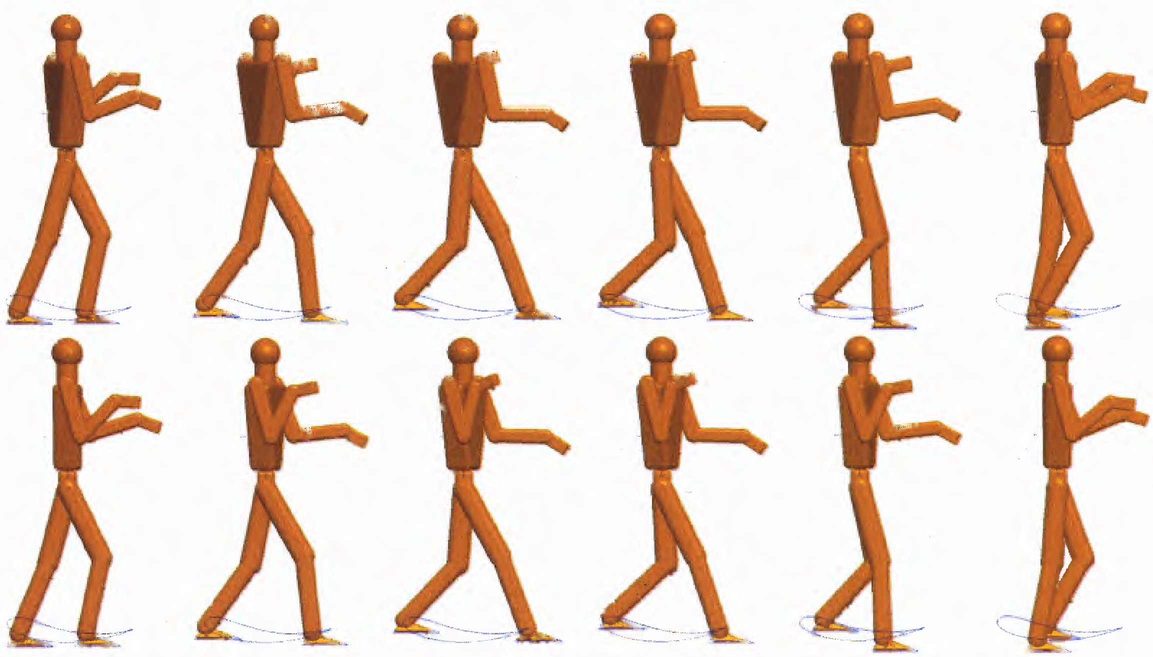

Figure 3.3 Human Model Movement Sequence with Machine Hidden

Figures 3.2 and 3.3 show the kinematic simulation of the GRS with human model operation sequence. It can be observed from the above sequence figures that the machine produces desired output. A note has to be made that this is only a simulation, and real life results will differ from computer model. Yet it is a very good approximation of the GRS's operation.

All of the key parts defining the walking kinematics (Frame, Triangular Link, Handle and Driver Disk) were created to the specification as shown in Figure 1.8 in order to meet the desired output gait function.

The dimensions of the four-bar mechanism shown in Figure 1.8 can be changed proportionally for users with different heights. Thus any modification of any key part will automatically result in an overall modification of the entire machine. In other words that gives the flexibility of adjusting the machine to different people by making simple changes to basic dimensions.

Dimensions other then basic were chosen using best judgment so that the machine range of motion is suitable and natural to the average person. These dimensions are shown and described with the following figures.

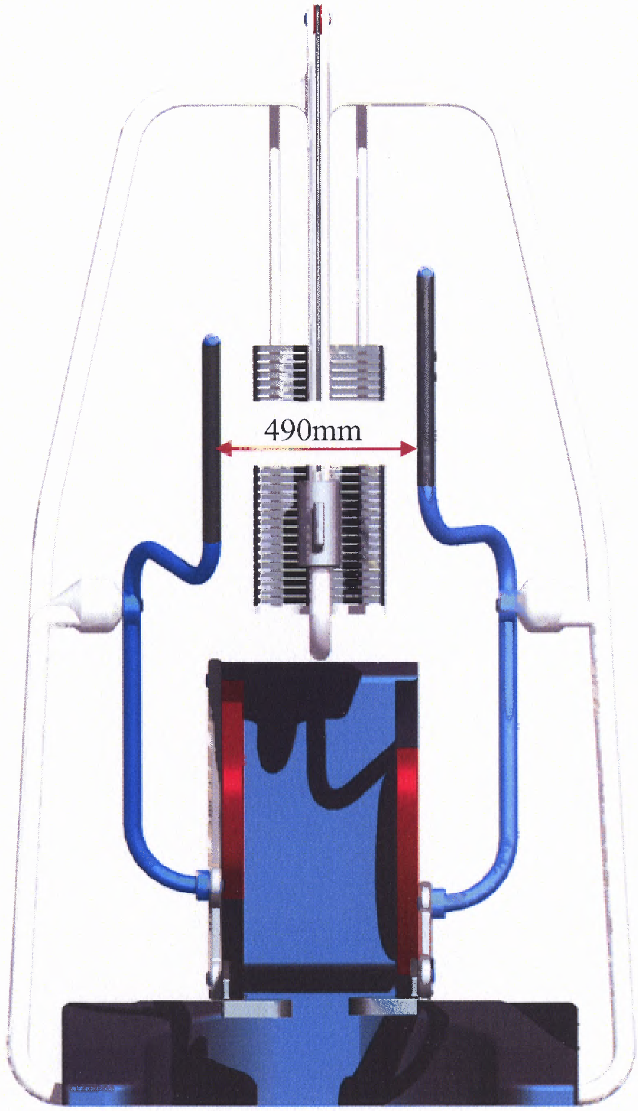

Figure 3.4 GRS Front View

The distance between the handles is 490mm, as shown in Figure 3.4, which is about a shoulder width of an average man. The natural extension of the hands forward would be at the same distance apart.

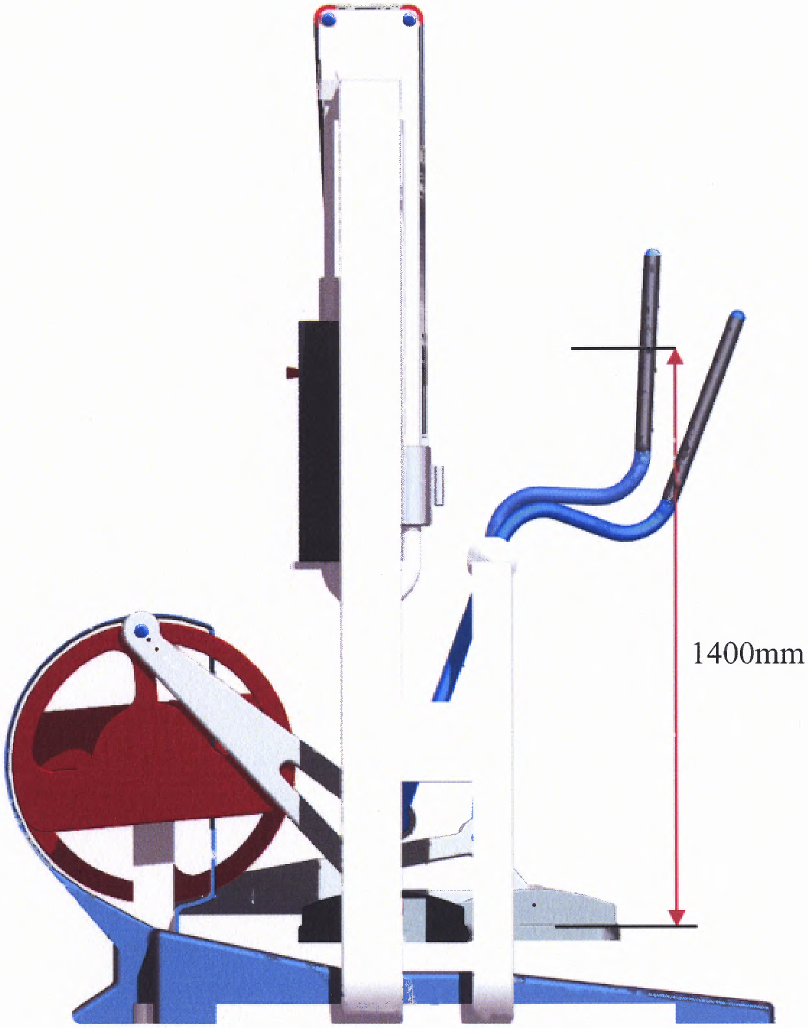

Figure 3.5 GRS Left View

The distance from the foot support ground to the place where a person would hold the handle is about 1400mm as shown in Figure 3.5. The measurement was obtained from the person standing on the ground extending the hand forward parallel to the floor. It seems to be a natural distance to hold something in front of one's self and also a position where the most pulling force can be naturally applied by the means of arm contraction. The black grip area on the handle is 450mm long and is sufficient to account for a lower stance during walking and also different people's preferences due to habit and comfort.

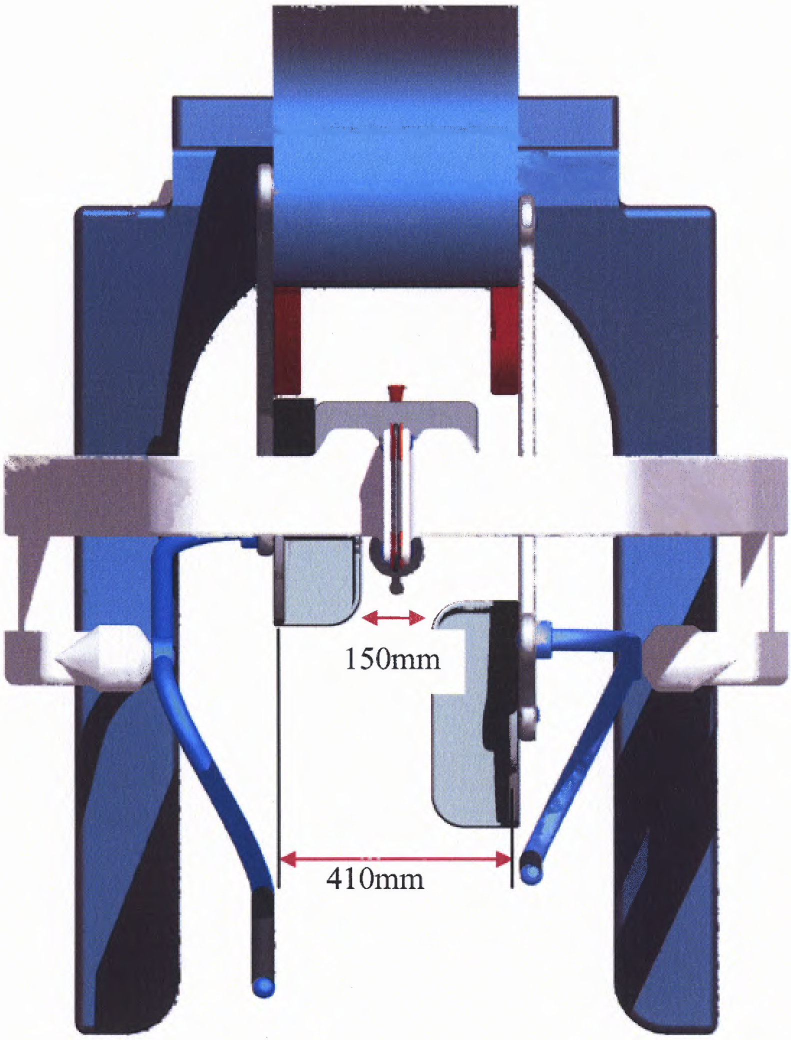

Figure 3.6 GRS Top View

The smallest distance between the feet is 150mm and the largest is 410mm as indicated in Figure 3.6. The area that these dimensions generate should be sufficient for any desirable feet placement. Such separation of feet is common during walking or running.

Additional back and bottom views of the design are available in Appendix A.

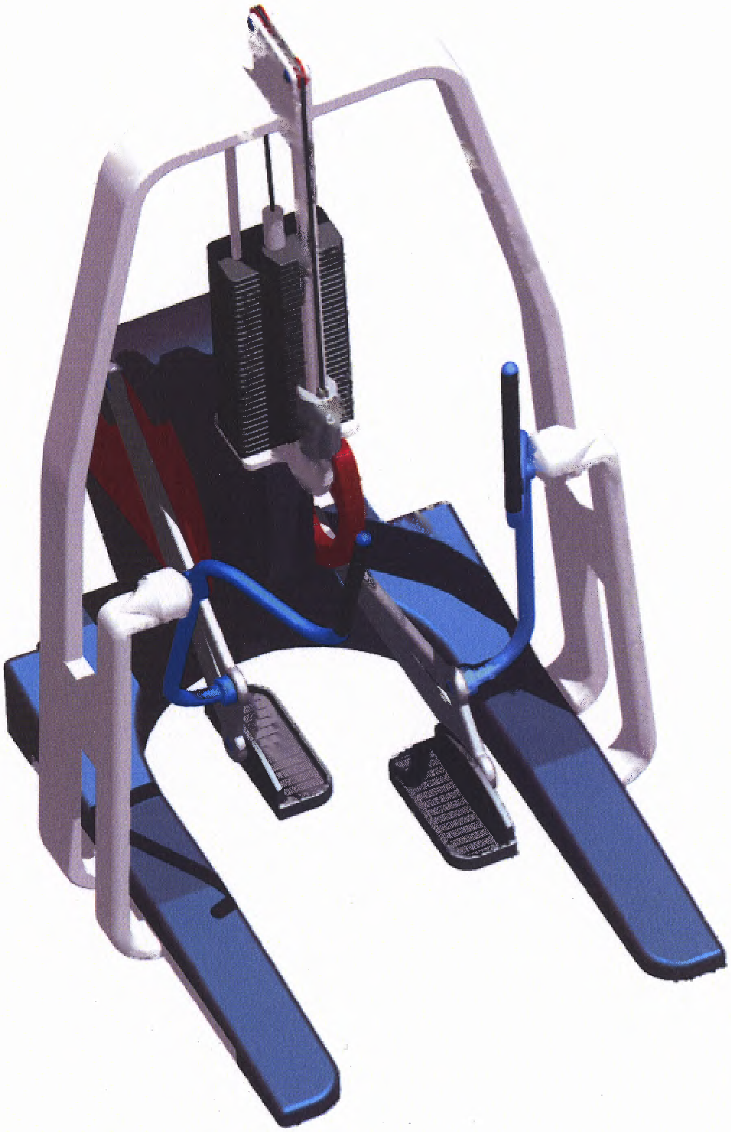

Figure 3.7 GRS Perspective View without Human

A perspective view of the GRS without human is shown in Figure 3.7. The color scheme of the machine was also deliberately chosen to resemble medical equipment. White, blue and light-grey colors breathe calmness into the machine look and may appear inviting to people who are to use the GRS.

The next section focuses on features specific to each part of the assembly.

3.2 Parts Features

Initially, a general three dimensional model outline and all links were pictured. The frame that would support all the links as shown in Figure 3.8 was considered first. Unlike in regular commercially available elliptical machines the driver disk in GRS is quite large. It calls for a different approach for frame design which also requires devising a non-standard way for people to engage the machine.

The frame also had to support the handles on the sides as opposed to the support in the middle.

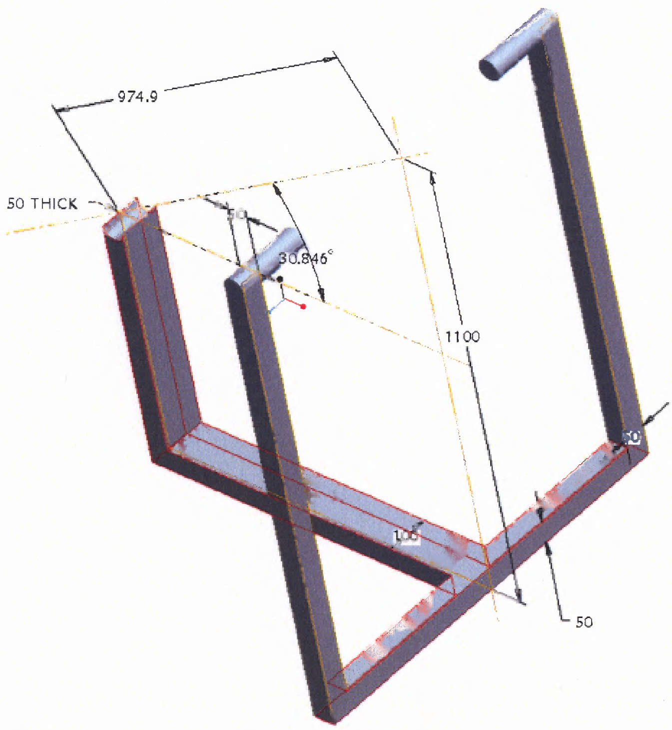

Figure 3.8 Initial Frame Concept

After making improvements and changing dimensions, the final form of the frame is presented in Figure 3.9 (detailed line drawing Figure C.1).

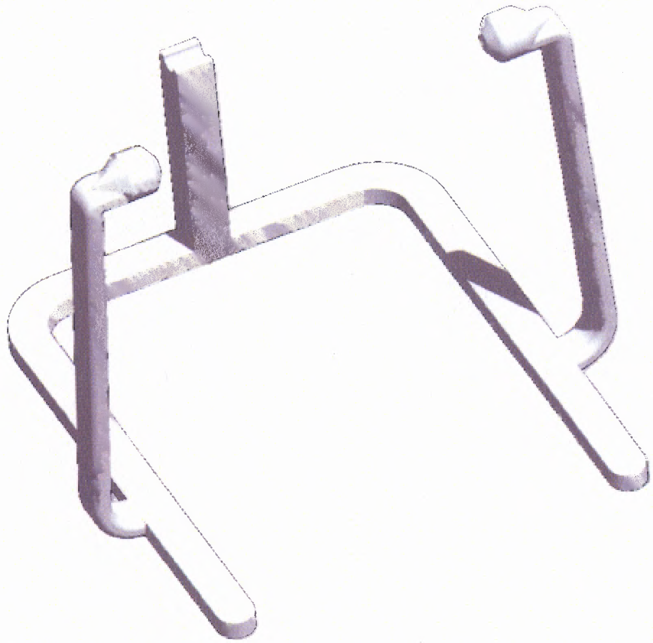

Figure 3.9 Final Frame Concept

One may notice that the frame does not feature a motor support. This is not considered at this conceptual design stage and will be addressed in the future design considerations.

Next part to consider was the driver disk. Cylinder seemed like the best option for the link as it generates a solid look and occupies the same area that a single revolving link would occupy. It was placed in the center of the frame as the whole machine is symmetric along the middle plain.

It was observed that during the driver disk movement it might generate instances where the operator of the machine will be subjected to coming in contact with it. Therefore it was decided to cut out a segment of the disk that interferes with the operator motion. The resultant modification can be seen in Figure 3.10 (detailed line drawing Figure C.2). Such modification creates an opening for the leg moving to its backwardmost position. An illustration of the concept can be seen on Figure 3.2 at time 12 seconds (the third picture in the sequence).

Figure 3.10 Driver Disk Interference Cut out Feature

The Driver Disk was modified a lot of times. The final version had cutouts to reduce weight and a circular segment cutout for legs. Figure 3.11 shows different instances of the disk up to the final version.

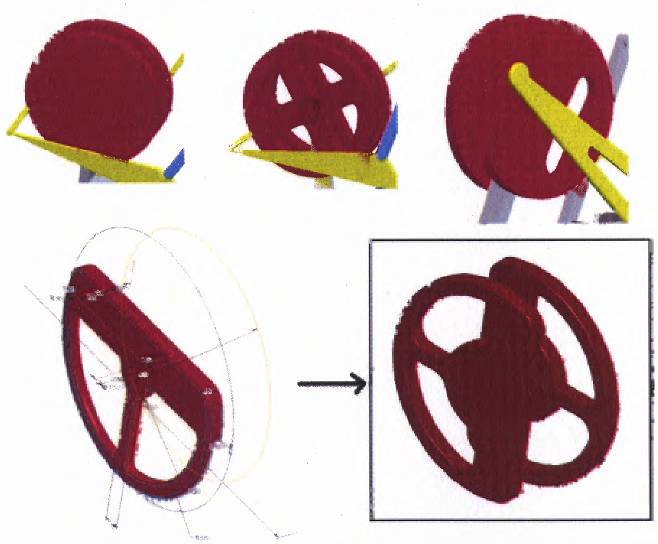

Figure 3.11 Driver Disk Design Iterations

Another key part is the Triangular Coupler Link Figure 3.12 (detailed line drawing Figure C.3).

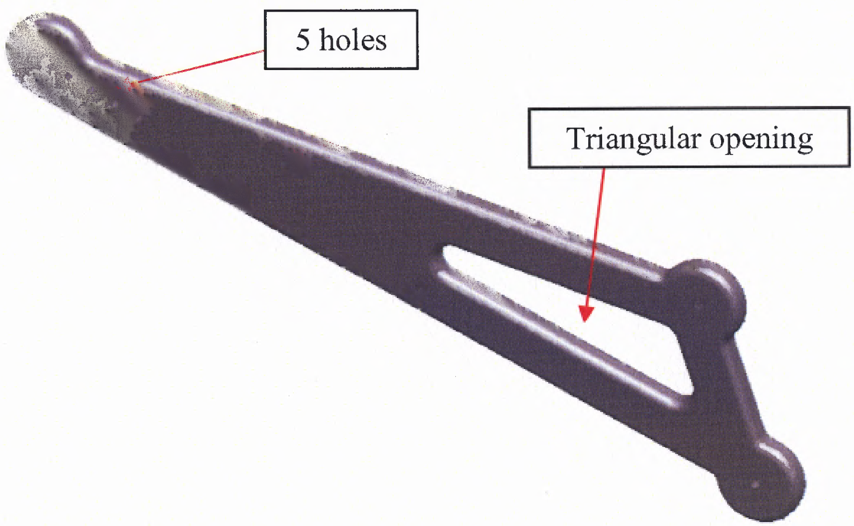

Figure 3.12 Triangular Coupler Link

It was made smooth throughout for the operator's safety as it might come in contact with patient's legs during training. A triangular opening was cut out from inside of the part to reduce weight. Five holes were created 30 mm apart along the line that goes to the coupler point which allow snap on modification that changes the output gait pattern of the machine. As a result it makes the machine easily adjustable for different people.

The Foot Support shown in Figure 3.13 (detailed line drawing Figure C.4) was also made smooth because it comes in direct contact with patient's boots and pants. Little grooves were added along the foot support so that the foot doesn't slip and stay in position. Little walls along the outer curve of the part were raised 2cm high to further keep the foot in place. Firm placement of foot is required because the ankle has to be always situated on the ankle axis for the machine to deliver accurate gait pattern.

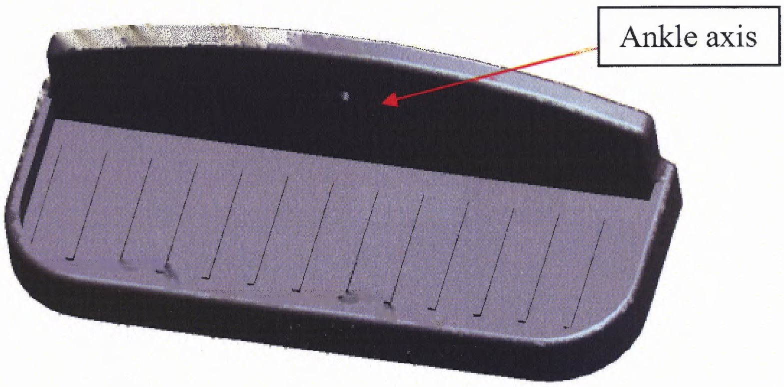

Figure 3.13 Foot Support

Great attention was paid to the Handle (Figures 3.14 and C.5). It was made straight in the bottom portion and smoothly convergent to the ideal grip position at the top. Even though the handle's profile is optimal for the current kinematic model, further improvements can be made and they are discussed in Future Design Considerations section.

Figure 3.14 Handle

Final major part that gives the machine finalized look and also plays an important role in overall safety of the machine is the Cover, which is shown in Figures 3.15 and C.6

Figure 3.15 Cover

The main purpose of the part is to cover as many moving parts as possible thus reducing the risk of injury and any possible interfere with the motion. Motion envelope of the assembly was created, as shown in Figure 3.16, in order to obtain general dimensions for the cover.

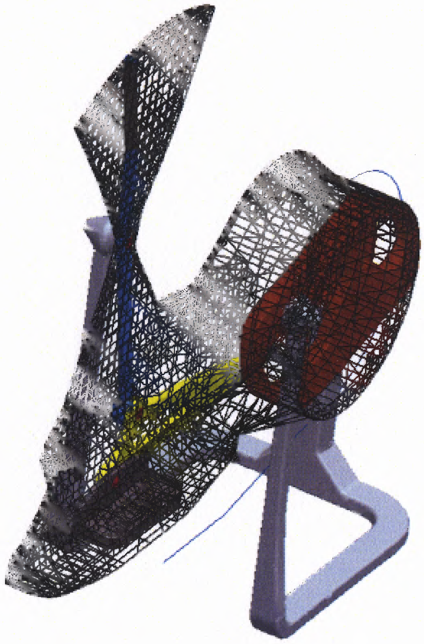

Figure 3.16 Motion Packet of the Assembly

It allowed getting the height of the cover as well as the opening size in between the ground extensions. Circular section of the cover protects the Driver Disk and its mechanism.

All of the above features were designed concurrently with the overall spatial requirements for a general user discussed in objective section.

3.3 Weight Suspension System

Since the machine is designed with disabled people in mind, a system that would support person's weight had to be implemented. That way, depending on a patient's condition, one could either have partially or fully supported body weight by counter balanced weights shown in Figure 3.17.

Figure 3.17 Weight Suspension System

The nature of the machine requires the hips of the person to be relatively stationary with respect to the ground plane. Therefore it was decided to create a support system that would allow vertical movement and some rotation about the spine axis but would restrict movement in the ground plane. A rod and a cylinder connection was chosen to carry out such function. Another important aspect of the weight suspension system is that a harness that would fit tightly around the person and connect to the cylinder is required. Keeping it all in mind a Suspension Frame part was created as shown in Figures 3.18 and C.7. It holds a sliding cylinder, weights, pulleys and a cable that connects the weights to the cylinder.

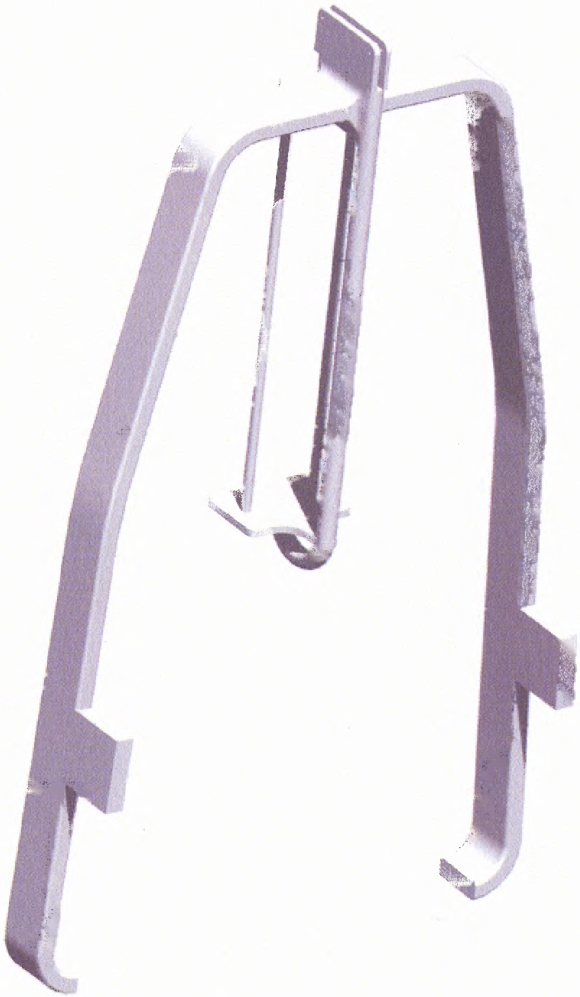

Figure 3.18 Suspension Frame

The weight suspension system was implemented in a location right behind and above the person with the purpose of minimizing cable length – thus reducing the stretch of the cable, and increasing the counterbalancing weight responsiveness.

The suspension cylinder shown in Figures 3.19 and C.8 features a connection for the cable and a connection for the harness shown in Figure 3.20. A commercial harness is to be modified with a connection which is yet to be designed.

Figure 3.19 Suspension Cylinder

Harness itself presents belts of strong fabric interconnected and tailored to fit an average patient. Also various harness belts should be made adjustable in order for harness to fit different people. A distinct feature of the harness is that it has to have a rigid protrusion in the back which would allow connection to the suspension cylinder. Figures 3.20 and C.9 show an illustration of the harness with connection.

Figure 3.20 Harness

The total weight counterbalance amasses 150kg and is achieved by stacking thirty weight plates 5kg each. The particular counterbalancing weight is selected by moving the weight adjuster into the desired hole on the weights rod, which is aligned with a corresponding number of weight plates shown in Figure 3.21 (and Appendix Figures C10, C.11 and C.12). Same system is employed in general weight training machines.

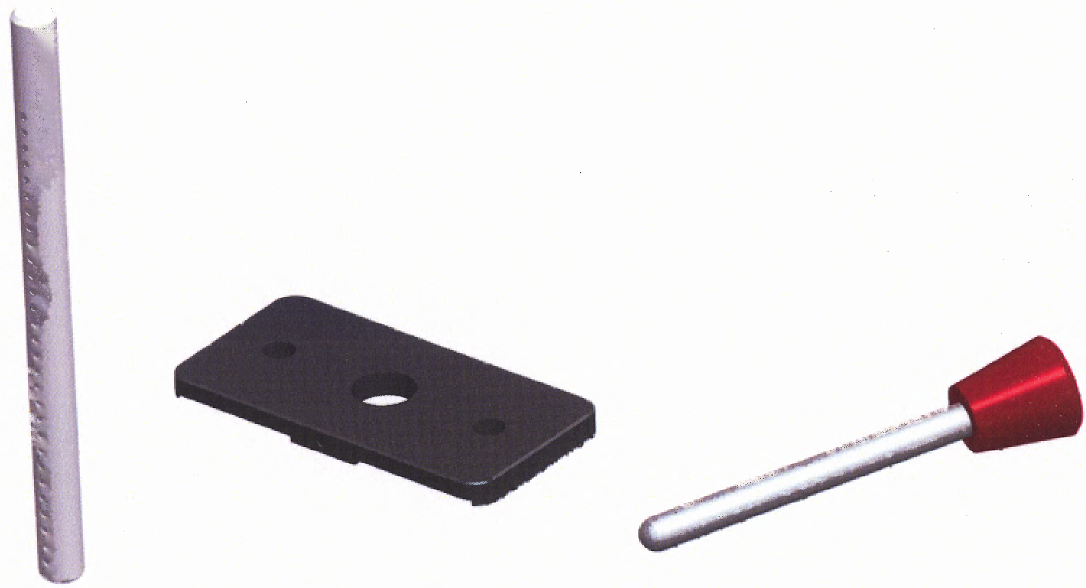

Figure 3.21 Weights Rod, Weight Plate and Weight Selector

3.4 Position, Velocity and Acceleration Kinematic Analyses

Once the assembly with all accurate basic dimensions was complete, various analyses on the machine were performed. The main point of concern is concentrated on the movement of the ankle axis relative to stationary point on the ground. All the obtained analyses are in two-dimensional plane due to two-dimensional nature of the four bar mechanism. To make results detailed and scalable 360 points were created for every analysis. The fist study performed was the position analysis.

The plots shown in Figure 3.22 and Figure B.1 represent two gait curves. Thick curve is the theoretical and thin curve is the one obtained from the position analysis in Pro-Engineer software. They look very similar with only minor discrepancies. The discrepancies are due to inability of the four bar mechanism to exactly match the desired path.

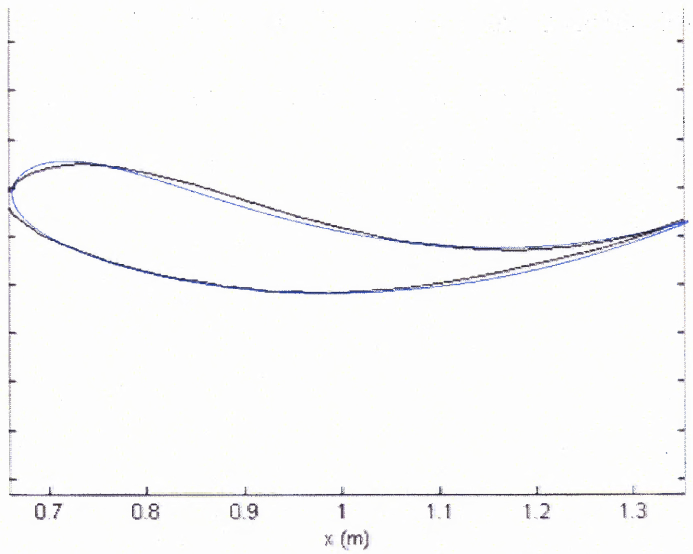

Figure 3.22 Superimposed Ankle Trajectories: Theoretical (thick) vs. Actual (thin)

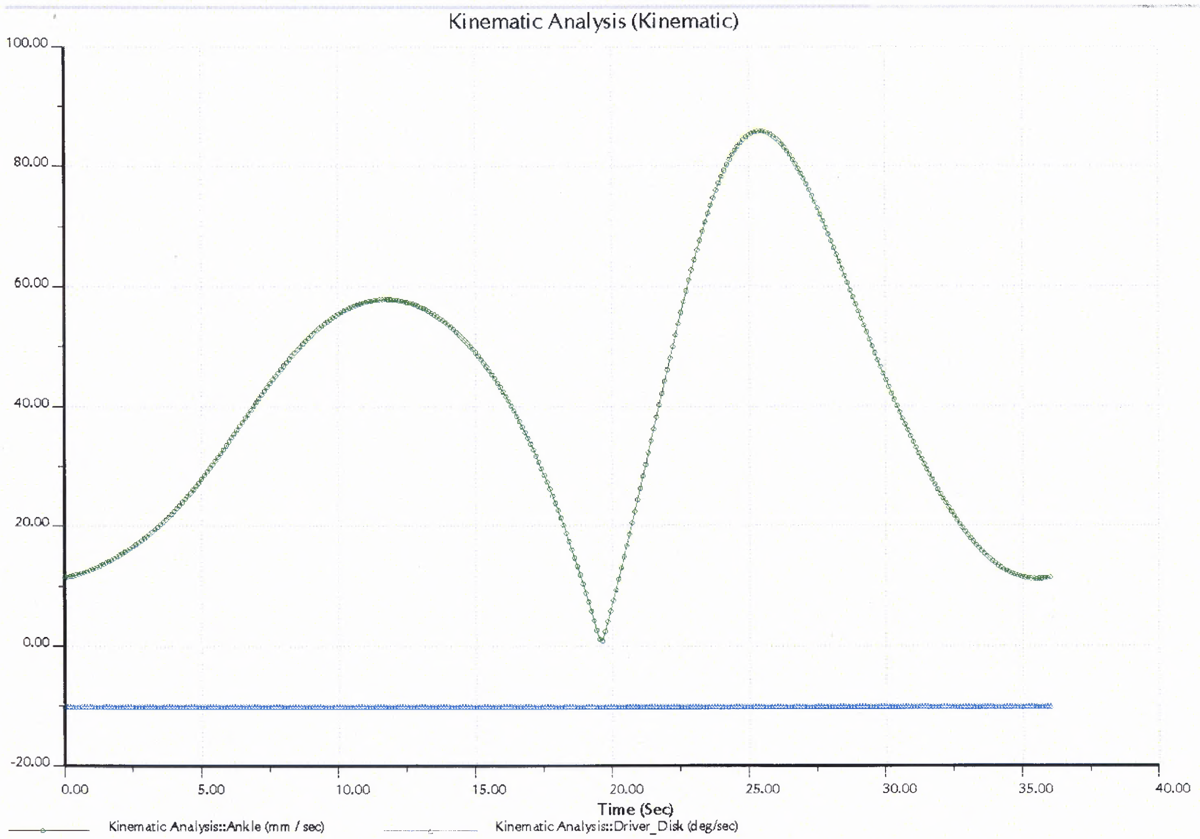

Figure 3.23 Velocity Magnitude Analysis of the Ankle (single cycle)

Velocity analysis was performed on the Driver Disk and the ankle axis relative to stationary ground frame vs. time. As it is shown in Figure 3.23 (and appendix Figure B.3 continuous cycle), when the driver disk rotates at a 10 [deg/sec] angular velocity the ankle moves according to the curve above ranging from 0 [mm/sec] at the sharp tip of the curve, to approximately 87 [mm/sec] at the bottom area of the gait curve where velocity magnitude is maximum. Since two of the velocities (Driver Disk angular velocity and Ankle's Velocity Magnitude) are superimposed on the same graph, the values for the ankle axis velocity can be easily scaled based on the driver disk input deg/sec or RPM.

This plot can be verified by theoretical kinematic analysis of the four bar mechanism with the coupler point on the coupler link (corresponding to the ankle axis).

Pro-Engineer software proved to be very reliable at many instances of the design and the results it yields are very accurate and precise. The data points obtained from three analyses Table B.1 can be exported into excel spread sheet or MatLab for further curve fitting and future determination of the required motor rotation profile.

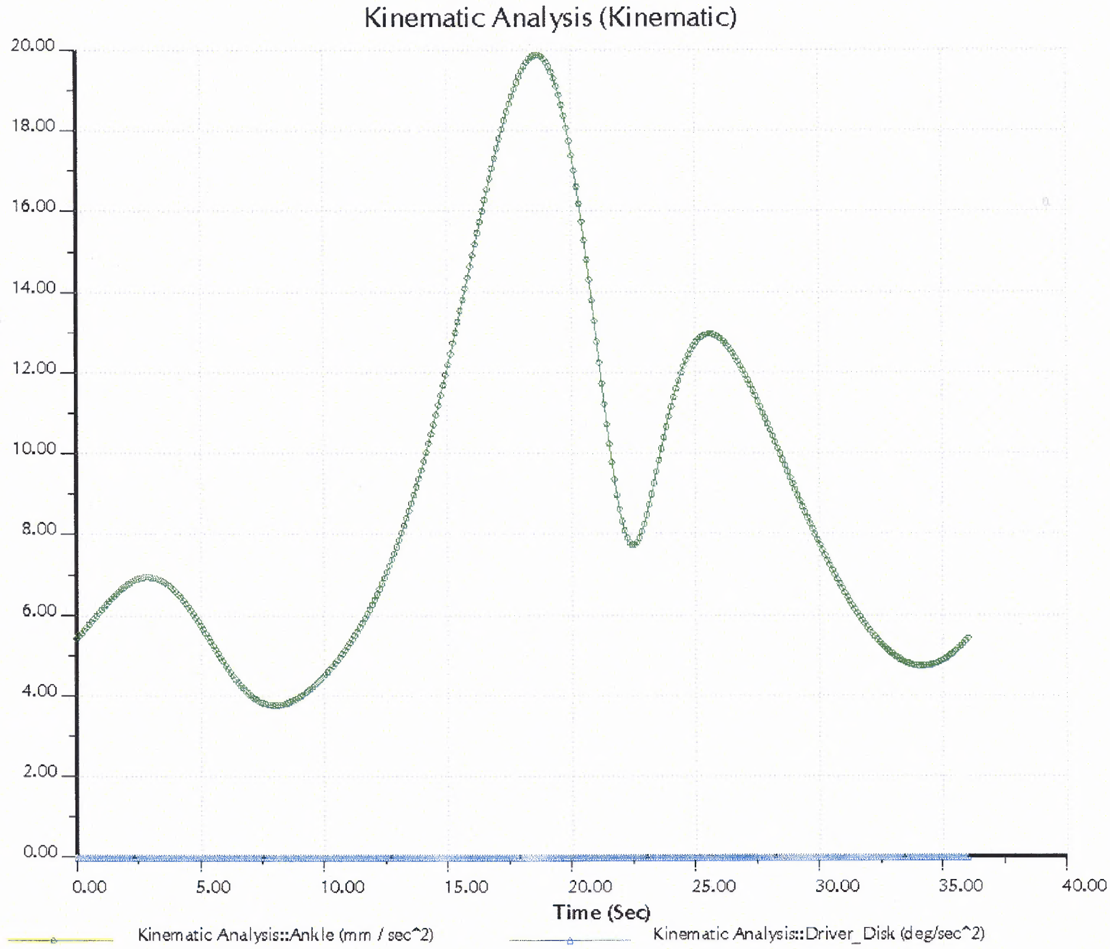

Figure 3.24 Acceleration Magnitude Analysis of the Ankle (single cycle)

Finally acceleration analysis was performed Figure 3.24 in the same manner as the velocity analysis. It represents Driver Disk and the Foot Support ankle axis acceleration magnitude relative to the stationary base frame vs. time. Actual data points can be found in the Appendix Table B.1. With the knowledge of the system's acceleration profile it is possible to make predictions of motor torque requirements. The required torque that a motor has to generate can be determined by taking reaction forces from person's weight applied at the point of the largest acceleration.

Three kinematic analyses performed set the direction for future analysis.

CHAPTER 4

FUTURE DESIGN CONSIDERATIONS

The GRS design presented in this thesis is only at the beginning stage of the product development. The proposed design does not account for many details that are required in order for the machine to be operational in reality.

First of all the machine should implement some mechanism that would allow placement of disabled people into the machine. Its current operation requires the person to approach the machine and be engaged into it with the help of therapists. In order to make this step easier, another subsystem has to be designed that would allow a person to get out of the wheelchair and be placed into the machine.

Also attention has to be paid to the Foot Support part connection to the overall assembly Figure 4.1. It was set to be always oriented horizontally thought the operating cycle by allowing the Foot Support part to freely spin along the ankle axis, which might prove beneficial as it will allow the foot of the user to be in the natural walking angle through the cycle.

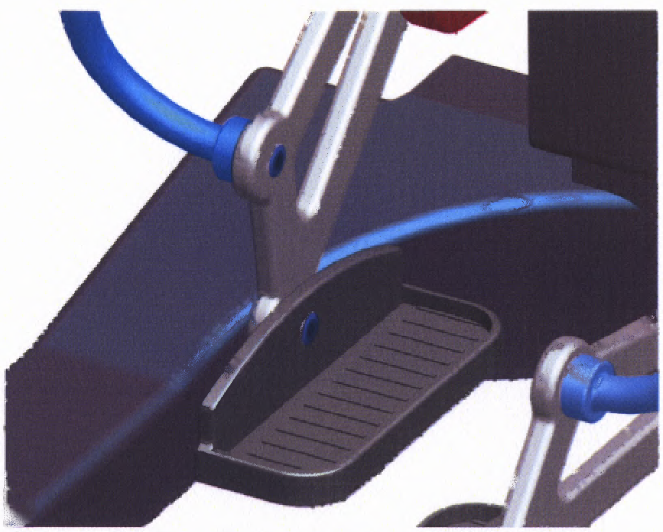

Figure 4.1 Foot Support Part Connection to the Assembly

Another note is that the machine's connection axes are all connected conditionally throughout the design. In order for all the links to be connected, actual bearing systems have to be designed for each interconnection.

The cylinder suspension (that supports the person) rotates around the axis located on the suspension frame and not around the spine axis. This type of connection would constrain entire upper body movement of the simulated human model, but it should work during actual operation because the computer simulation does not account for person slightly shifting weight from right to left foot during operation in which case the axis of rotation shifts towards the suspension frame rod (where the suspension cylinder is located).

Handles of the GRS might have to be redone completely in order to provide a more natural movement pattern for arms. Such modification would involve making the handle into three parts (instead of one) but that might make machine a more complex system which would defeat an initial purpose of making the machine simple.

The GRS is developed with an idea of having a motor to power it. The analysis for the right motor selection has yet to be performed. Once the exact dimensions of the motor and the type of needed control system are determined, easy modifications to the overall assembly can be performed to include it in the design.

When considering a motor, the required velocity and torque outputs have to be determined. The motion of the machine will have to be carefully controlled throughout the operating cycle in order to generate the perfect gait vs. time function for the patient. This can be done by varying RPM over time. The maximum required torque can be determined by making use of the acceleration analysis Figure 3.24. And the velocity function can be obtained from the velocity analysis Figure 3.23. This function will have to be analyzed together with the natural gait function (pace of walking throughout the cycle) of a human. Then two can be subtracted and the ideal velocity function for the motor can be obtained. Pro-Engineer can be further used to simulate the variable input velocity taking into the account a downward weight of the person acting on the Foot Supports as well as torques applied to spin the Driver Disk.

Another consideration is making a variable motor output settings so that the work can be distributed between the person using legs and hands and the actual motor spinning the Driver Disk (active and passive modes).

All of the above topics come together as tasks and directions for the future design of the GRS.

CHAPTER 5

CONCLUSION

The conceptual design of the Gait Rehabilitation System presented in this thesis was able to tie down on paper analytical results to a visual solid model. A human model was created during the design that greatly helped and speeded up the design process. The system showed a sound kinematic model and suitability for human use since the final design was able to generate the desired complex movement patterns simply by inputting a rotational motion. Such simplicity gives an edge to the proposed design versus other models currently available.

Position, velocity and acceleration analyses of the ankle relative to the ground were performed and show strong correlation between actual and theoretical results. Many of the obtained results can be further used in the research on the topic.

There is a definite market potential for the proposed gait rehabilitation system, and this thesis have brought it closer to realization. Nevertheless much more work is still required to get it there.

APPENDIX A

ADDITIONAL VIEWS OF THE DESIGN

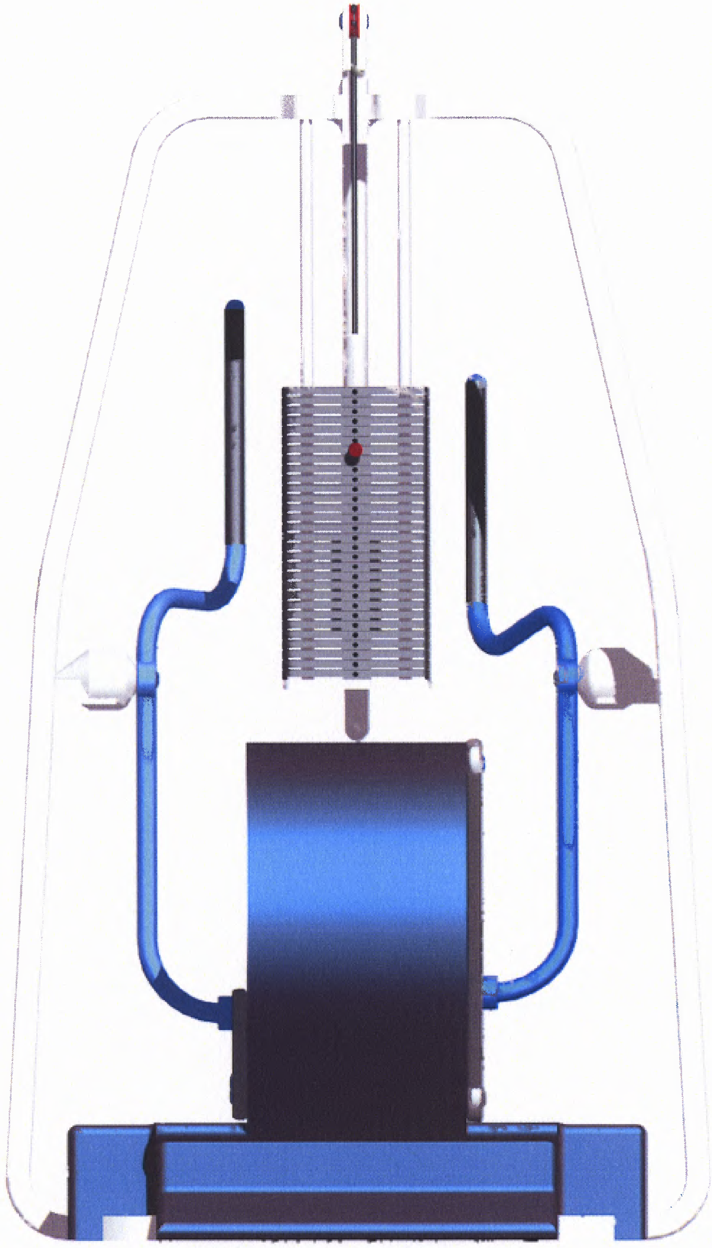

Figure A.1 GRS Back View

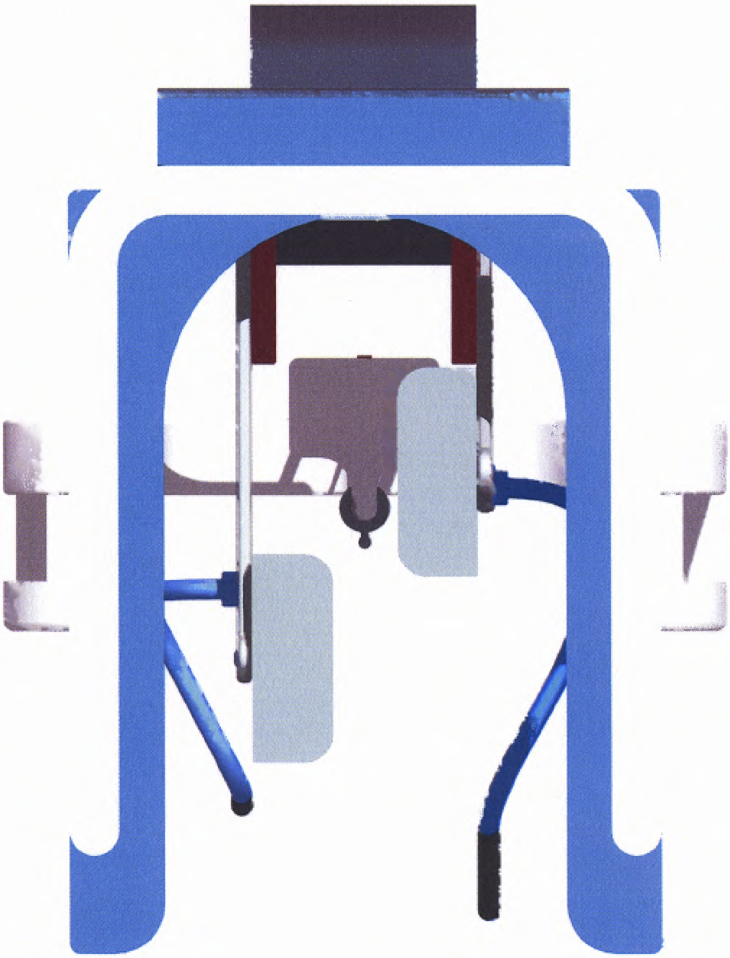

Figure A.2 GRS Bottom View

APPENDIX B

KINEMATIC ANALYSIS DATA

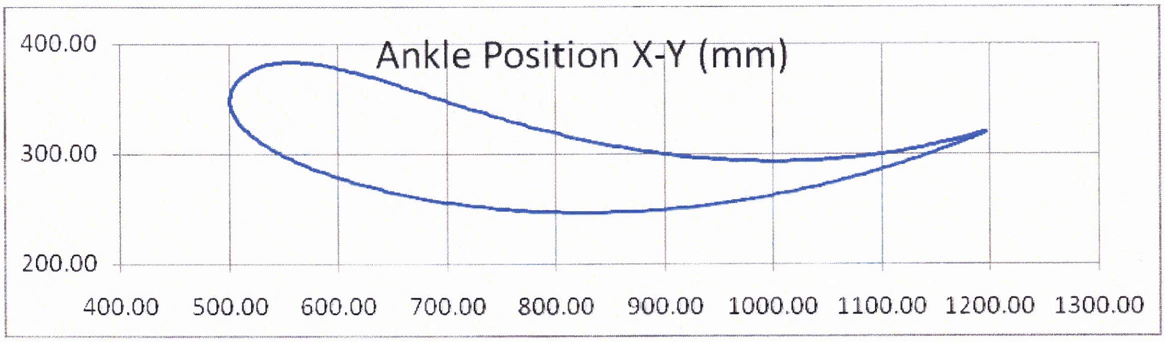

Figure B.1 Position Analysis of the Ankle

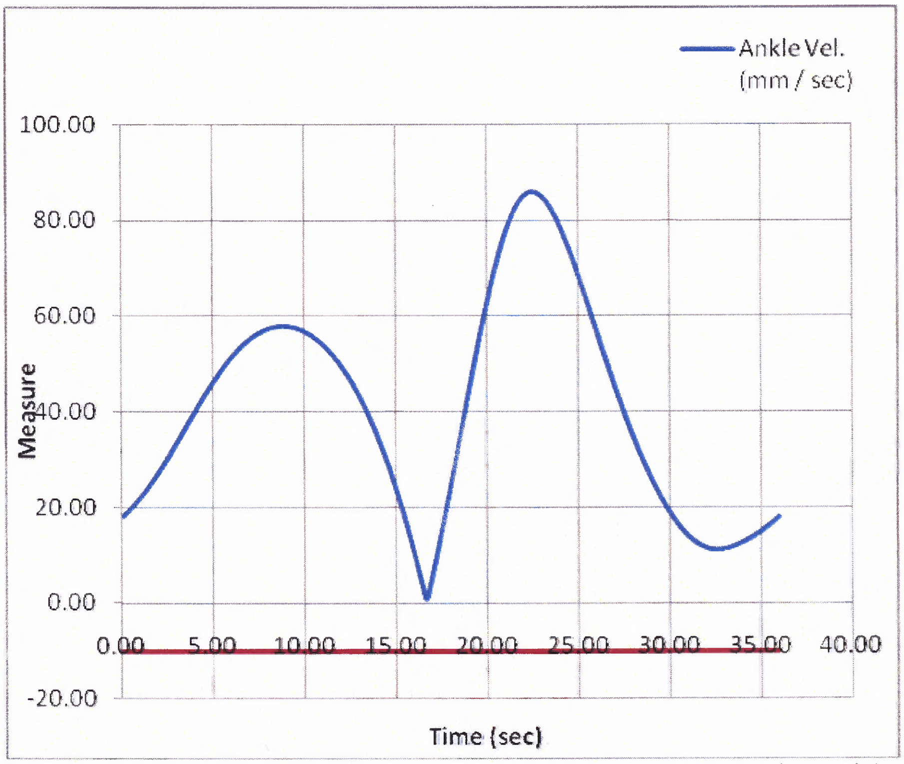

Figure B.2 Velocity Magnitude Analysis of the Ankle (single cycle)

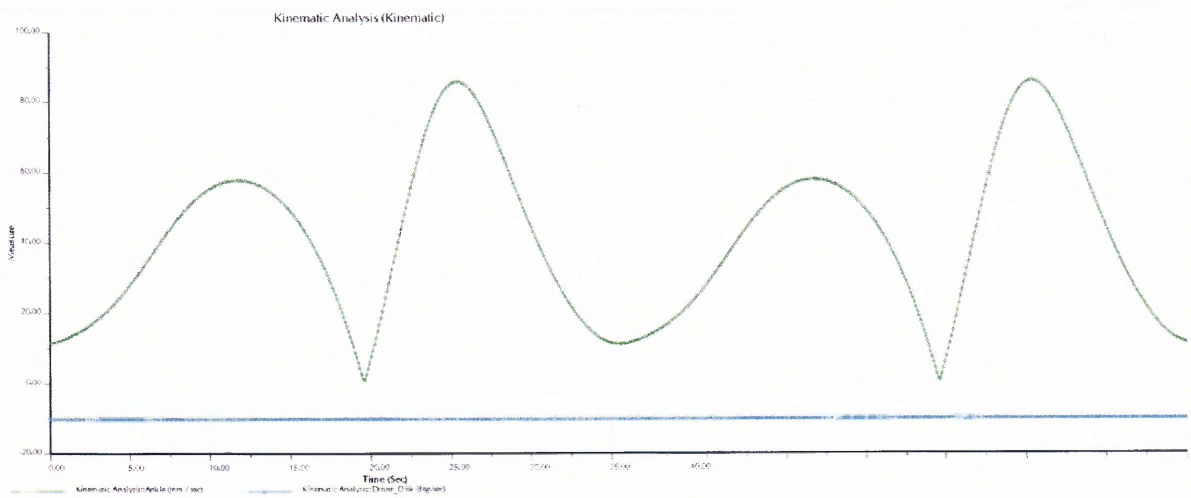

Figure B.3 Velocity Magnitude Analysis of the Ankle (continuous cycle)

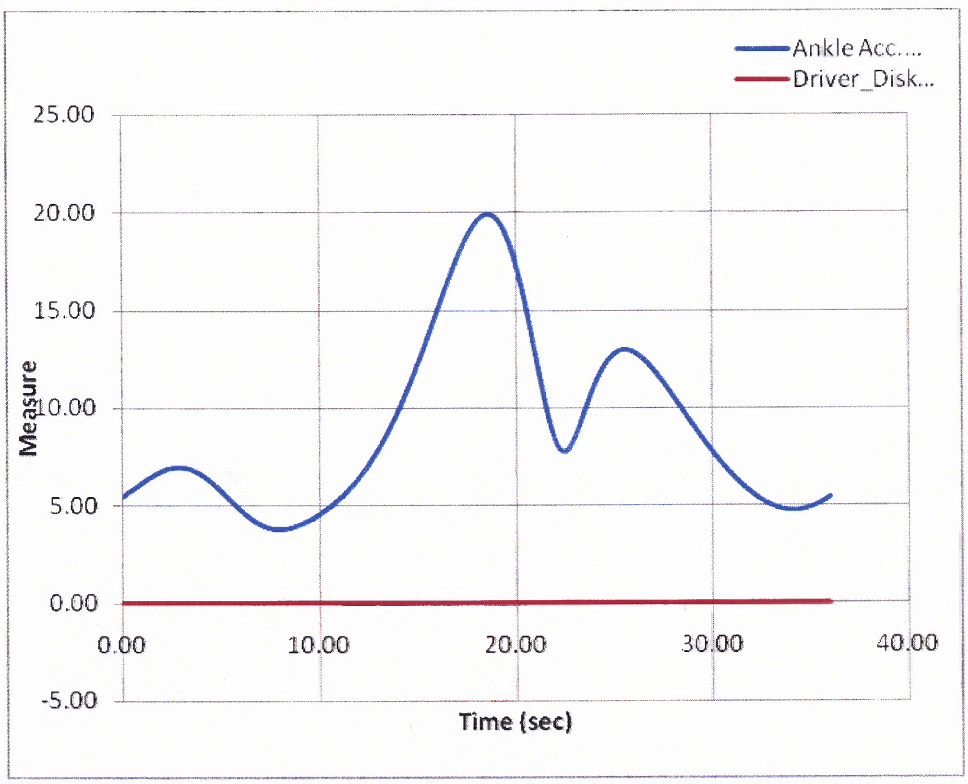

Figure B.4 Acceleration Analysis of the Ankle

Table B.1 Position (X,Y), Velocity and Acceleration vs. Time Data Points

Time	Ankle Position X (mm)	Ankle Position Y (mm)	Ankle Vel. (mm / sec)	Driver_Disk (deg/sec)	Ankle Acc. (mm / sec^2)	Driver_Disk (deg/sec^2)
0.00	540.49	381.81	18.87	-10.00	5.57	0.00
0.10	542.35	382.10	19.25	-10.00	5.65	0.00
0.20	544.28	382.34	19.65	-10.00	5.72	0.00
0.30	546.25	382.54	20.06	-10.00	5.79	0.00
0.40	548.27	382.71	20.47	-10.00	5.86	0.00
0.50	550.34	382.84	20.90	-10.00	5.93	0.00
0.60	552.45	382.93	21.35	-10.00	6.01	0.00
0.70	554.61	382.98	21.80	-10.00	6.08	0.00
0.80	556.81	382.99	22.27	-10.00	6.15	0.00
0.90	559.06	382.97	22.74	-10.00	6.22	0.00
1.00	561.36	382.90	23.23	-10.00	6.29	0.00
1.10	563.70	382.80	23.73	-10.00	6.36	0.00
1.20	566.10	382.65	24.25	-10.00	6.42	0.00
1.30	568.54	382.46	24.77	-10.00	6.49	0.00
1.40	571.03	382.23	25.30	-10.00	6.55	0.00
1.50	573.57	381.96	25.85	-10.00	6.60	0.00
1.60	576.17	381.64	26.41	-10.00	6.66	0.00
1.70	578.81	381.28	26.97	-10.00	6.71	0.00
1.80	581.51	380.88	27.55	-10.00	6.75	0.00
1.90	584.26	380.44	28.14	-10.00	6.79	0.00
2.00	587.06	379.95	28.73	-10.00	6.83	0.00
2.10	589.91	379.42	29.34	-10.00	6.86	0.00
2.20	592.82	378.85	29.95	-10.00	6.89	0.00
2.30	595.78	378.24	30.57	-10.00	6.91	0.00
2.40	598.80	377.58	31.19	-10.00	6.93	0.00
2.50	601.87	376.88	31.83	-10.00	6.94	0.00
2.60	605.00	376.14	32.46	-10.00	6.95	0.00
2.70	608.19	375.36	33.11	-10.00	6.95	0.00
2.80	611.43	374.54	33.75	-10.00	6.94	0.00
2.90	614.72	373.68	34.40	-10.00	6.93	0.00
3.00	618.08	372.77	35.06	-10.00	6.91	0.00
3.10	621.49	371.83	35.71	-10.00	6.89	0.00
3.20	624.96	370.86	36.37	-10.00	6.86	0.00
3.30	628.49	369.84	37.03	-10.00	6.83	0.00
3.40	632.07	368.79	37.69	-10.00	6.79	0.00
3.50	635.72	367.71	38.34	-10.00	6.74	0.00
3.60	639.42	366.59	39.00	-10.00	6.69	0.00
3.70	643.18	365.43	39.65	-10.00	6.63	0.00
3.80	647.00	364.25	40.30	-10.00	6.57	0.00
3.90	650.87	363.04	40.94	-10.00	6.51	0.00
4.00	654.81	361.79	41.58	-10.00	6.44	0.00
4.10	658.80	360.52	42.22	-10.00	6.36	0.00
4.20	662.85	359.23	42.85	-10.00	6.28	0.00

Table B.1 (Continued)

Time	Ankle Position X (mm)	Ankle Position Y (mm)	Ankle Vel. (mm / sec)	Driver_Disk (deg/sec)	Ankle Acc. (mm / sec^2)	Driver_Disk (deg/sec^2)
4.30	666.96	357.90	43.47	-10.00	6.20	0.00
4.40	671.13	356.56	44.08	-10.00	6.11	0.00
4.50	675.35	355.19	44.69	-10.00	6.02	0.00
4.60	679.63	353.81	45.29	-10.00	5.93	0.00
4.70	683.97	352.40	45.88	-10.00	5.83	0.00
4.80	688.36	350.98	46.45	-10.00	5.74	0.00
4.90	692.81	349.55	47.02	-10.00	5.64	0.00
5.00	697.31	348.10	47.58	-10.00	5.54	0.00
5.10	701.87	346.64	48.12	-10.00	5.44	0.00
5.20	706.48	345.17	48.66	-10.00	5.34	0.00
5.30	711.15	343.69	49.18	-10.00	5.24	0.00
5.40	715.86	342.20	49.68	-10.00	5.14	0.00
5.50	720.63	340.72	50.18	-10.00	5.04	0.00
5.60	725.45	339.22	50.66	-10.00	4.94	0.00
5.70	730.31	337.73	51.13	-10.00	4.85	0.00
5.80	735.23	336.24	51.58	-10.00	4.75	0.00
5.90	740.19	334.75	52.02	-10.00	4.66	0.00
6.00	745.20	333.27	52.44	-10.00	4.57	0.00
6.10	750.25	331.79	52.85	-10.00	4.49	0.00
6.20	755.35	330.32	53.25	-10.00	4.41	0.00
6.30	760.50	328.87	53.63	-10.00	4.33	0.00
6.40	765.68	327.42	53.99	-10.00	4.26	0.00
6.50	770.90	325.98	54.34	-10.00	4.19	0.00
6.60	776.17	324.56	54.67	-10.00	4.12	0.00
6.70	781.47	323.16	54.99	-10.00	4.06	0.00
6.80	786.80	321.77	55.29	-10.00	4.01	0.00
6.90	792.18	320.41	55.57	-10.00	3.96	0.00
7.00	797.58	319.06	55.84	-10.00	3.92	0.00
7.10	803.02	317.74	56.09	-10.00	3.88	0.00
7.20	808.49	316.44	56.32	-10.00	3.85	0.00
7.30	813.99	315.16	56.54	-10.00	3.82	0.00
7.40	819.52	313.92	56.75	-10.00	3.80	0.00
7.50	825.07	312.69	56.93	-10.00	3.79	0.00
7.60	830.64	311.50	57.10	-10.00	3.78	0.00
7.70	836.24	310.34	57.25	-10.00	3.77	0.00
7.80	841.87	309.21	57.39	-10.00	3.77	0.00
7.90	847.51	308.11	57.51	-10.00	3.78	0.00
8.00	853.16	307.05	57.62	-10.00	3.79	0.00
8.10	858.84	306.02	57.71	-10.00	3.80	0.00
8.20	864.53	305.02	57.78	-10.00	3.82	0.00
8.30	870.23	304.06	57.83	-10.00	3.84	0.00

Table B.1 (Continued)

Time	Ankle Position X (mm)	Ankle Position Y (mm)	Ankle Vel. (mm / sec)	Driver_Disk (deg/sec)	Ankle Acc. (mm / sec^2)	Driver_Disk (deg/sec^2)
8.40	875.94	303.14	57.87	-10.00	3.87	0.00
8.50	881.66	302.26	57.90	-10.00	3.90	0.00
8.60	887.39	301.41	57.90	-10.00	3.93	0.00
8.70	893.13	300.60	57.89	-10.00	3.96	0.00
8.80	898.86	299.84	57.87	-10.00	4.00	0.00
8.90	904.60	299.11	57.83	-10.00	4.05	0.00
9.00	910.34	298.42	57.77	-10.00	4.09	0.00
9.10	916.08	297.77	57.69	-10.00	4.14	0.00
9.20	921.81	297.17	57.60	-10.00	4.19	0.00
9.30	927.54	296.61	57.49	-10.00	4.24	0.00
9.40	933.26	296.08	57.37	-10.00	4.30	0.00
9.50	938.97	295.60	57.23	-10.00	4.36	0.00
9.60	944.67	295.17	57.08	-10.00	4.42	0.00
9.70	950.36	294.77	56.90	-10.00	4.48	0.00
9.80	956.03	294.42	56.72	-10.00	4.55	0.00
9.90	961.69	294.10	56.51	-10.00	4.61	0.00
10.00	967.32	293.84	56.29	-10.00	4.68	0.00
10.10	972.93	293.61	56.05	-10.00	4.76	0.00
10.20	978.52	293.42	55.80	-10.00	4.83	0.00
10.30	984.09	293.28	55.53	-10.00	4.91	0.00
10.40	989.63	293.17	55.24	-10.00	4.99	0.00
10.50	995.14	293.11	54.93	-10.00	5.07	0.00
10.60	1000.61	293.09	54.61	-10.00	5.15	0.00
10.70	1006.06	293.10	54.27	-10.00	5.24	0.00
10.80	1011.47	293.16	53.92	-10.00	5.33	0.00
10.90	1016.84	293.25	53.55	-10.00	5.43	0.00
11.00	1022.18	293.38	53.16	-10.00	5.52	0.00
11.10	1027.47	293.55	52.75	-10.00	5.62	0.00
11.20	1032.72	293.76	52.32	-10.00	5.72	0.00
11.30	1037.93	294.00	51.88	-10.00	5.83	0.00
11.40	1043.09	294.27	51.42	-10.00	5.94	0.00
11.50	1048.20	294.58	50.94	-10.00	6.05	0.00
11.60	1053.26	294.93	50.44	-10.00	6.17	0.00
11.70	1058.26	295.30	49.93	-10.00	6.29	0.00
11.80	1063.21	295.70	49.39	-10.00	6.42	0.00
11.90	1068.11	296.13	48.84	-10.00	6.54	0.00
12.00	1072.94	296.60	48.27	-10.00	6.68	0.00
12.10	1077.71	297.08	47.68	-10.00	6.81	0.00
12.20	1082.42	297.60	47.07	-10.00	6.95	0.00
12.30	1087.07	298.14	46.44	-10.00	7.10	0.00
12.40	1091.65	298.70	45.78	-10.00	7.25	0.00
12.50	1096.16	299.28	45.11	-10.00	7.40	0.00

Table B.1 (Continued)

Time	Ankle Position X (mm)	Ankle Position Y (mm)	Ankle Vel. (mm / sec)	Driver_Disk (deg/seC)	Ankle Acc. (mm / sec^2)	Driver_Disk (deg/sec^2)
12.60	1100.59	299.88	44.42	-10.00	7.56	0.00
12.70	1104.96	300.50	43.71	-10.00	7.73	0.00
12.80	1109.25	301.14	42.98	-10.00	7.90	0.00
12.90	1113.46	301.79	42.23	-10.00	8.07	0.00
13.00	1117.59	302.46	41.45	-10.00	8.25	0.00
13.10	1121.64	303.14	40.65	-10.00	8.43	0.00
13.20	1125.60	303.83	39.84	-10.00	8.62	0.00
13.30	1129.48	304.52	38.99	-10.00	8.81	0.00
13.40	1133.28	305.23	38.13	-10.00	9.01	0.00
13.50	1136.98	305.94	37.24	-10.00	9.21	0.00
13.60	1140.59	306.65	36.34	-10.00	9.42	0.00
13.70	1144.11	307.36	35.40	-10.00	9.63	0.00
13.80	1147.53	308.07	34.45	-10.00	9.84	0.00
13.90	1150.85	308.78	33.46	-10.00	10.07	0.00
14.00	1154.07	309.49	32.46	-10.00	10.29	0.00
14.10	1157.19	310.19	31.43	-10.00	10.52	0.00
14.20	1160.20	310.87	30.37	-10.00	10.76	0.00
14.30	1163.11	311.55	29.29	-10.00	11.00	0.00
14.40	1165.91	312.22	28.19	-10.00	11.24	0.00
14.50	1168.59	312.87	27.06	-10.00	11.49	0.00
14.60	1171.17	313.50	25.90	-10.00	11.74	0.00
14.70	1173.62	314.11	24.72	-10.00	11.99	0.00
14.80	1175.96	314.70	23.51	-10.00	12.25	0.00
14.90	1178.18	315.27	22.27	-10.00	12.51	0.00
15.00	1180.28	315.81	21.01	-10.00	12.78	0.00
15.10	1182.25	316.33	19.72	-10.00	13.04	0.00
15.20	1184.09	316.81	18.40	-10.00	13.31	0.00
15.30	1185.81	317.27	17.05	-10.00	13.59	0.00
15.40	1187.39	317.68	15.68	-10.00	13.86	0.00
15.50	1188.84	318.07	14.28	-10.00	14.13	0.00
15.60	1190.15	318.41	12.86	-10.00	14.41	0.00
15.70	1191.33	318.72	11.40	-10.00	14.69	0.00
15.80	1192.36	318.98	9.92	-10.00	14.96	0.00
15.90	1193.26	319.20	8.41	-10.00	15.24	0.00
16.00	1194.00	319.37	6.88	-10.00	15.52	0.00
16.10	1194.60	319.50	5.32	-10.00	15.79	0.00
16.20	1195.05	319.57	3.75	-10.00	16.06	0.00
16.30	1195.34	319.60	2.18	-10.00	16.33	0.00
16.40	1195.49	319.57	0.82	-10.00	16.60	0.00
16.50	1195.47	319.49	1.45	-10.00	16.86	0.00
16.60	1195.29	319.36	3.04	-10.00	17.11	0.00
16.70	1194.96	319.16	4.74	-10.00	17.36	0.00

Table B.1 (Continued)

Time	Ankle Position X (mm)	Ankle Position Y (mm)	Ankle Vel. (mm / sec)	Driver_Disk (deg/sec)	Ankle Acc. (mm / sec^2)	Driver_Disk (deg/sec^2)
16.80	1194.46	318.91	6.47	-10.00	17.61	0.00
16.90	1193.79	318.60	8.24	-10.00	17.85	0.00
17.00	1192.96	318.24	10.03	-10.00	18.08	0.00
17.10	1191.95	317.81	11.84	-10.00	18.30	0.00
17.20	1190.78	317.31	13.68	-10.00	18.51	0.00
17.30	1189.42	316.76	15.54	-10.00	18.71	0.00
17.40	1187.90	316.14	17.42	-10.00	18.89	0.00
17.50	1186.19	315.47	19.32	-10.00	19.07	0.00
17.60	1184.30	314.72	21.23	-10.00	19.23	0.00
17.70	1182.24	313.92	23.16	-10.00	19.37	0.00
17.80	1179.98	313.05	25.10	-10.00	19.50	0.00
17.90	1177.55	312.13	27.05	-10.00	19.61	0.00
18.00	1174.93	311.14	29.02	-10.00	19.71	0.00
18.10	1172.11	310.09	30.99	-10.00	19.78	0.00
18.20	1169.12	308.98	32.97	-10.00	19.83	0.00
18.30	1165.93	307.81	34.95	-10.00	19.87	0.00
18.40	1162.55	306.59	36.93	-10.00	19.88	0.00
18.50	1158.98	305.31	38.92	-10.00	19.87	0.00
18.60	1155.21	303.98	40.90	-10.00	19.83	0.00
18.70	1151.26	302.60	42.87	-10.00	19.77	0.00
18.80	1147.11	301.17	44.83	-10.00	19.68	0.00
18.90	1142.77	299.69	46.79	-10.00	19.57	0.00
19.00	1138.25	298.17	48.72	-10.00	19.43	0.00
19.10	1133.53	296.61	50.65	-10.00	19.26	0.00
19.20	1128.62	295.02	52.55	-10.00	19.07	0.00
19.30	1123.52	293.39	54.42	-10.00	18.84	0.00
19.40	1118.24	291.73	56.27	-10.00	18.59	0.00
19.50	1112.78	290.05	58.09	-10.00	18.32	0.00
19.60	1107.13	288.34	59.88	-10.00	18.01	0.00
19.70	1101.30	286.62	61.63	-10.00	17.68	0.00
19.80	1095.30	284.88	63.34	-10.00	17.33	0.00
19.90	1089.12	283.13	65.01	-10.00	16.95	0.00
20.00	1082.77	281.38	66.63	-10.00	16.54	0.00
20.10	1076.26	279.63	68.20	-10.00	16.11	0.00
20.20	1069.59	277.88	69.72	-10.00	15.67	0.00
20.30	1062.76	276.14	71.19	-10.00	15.20	0.00
20.40	1055.78	274.41	72.59	-10.00	14.72	0.00
20.50	1048.65	272.70	73.94	-10.00	14.22	0.00
20.60	1041.38	271.01	75.23	-10.00	13.71	0.00
20.70	1033.98	269.35	76.44	-10.00	13.19	0.00
20.80	1026.45	267.72	77.59	-10.00	12.67	0.00
20.90	1018.79	266.13	78.68	-10.00	12.15	0.00

Table B.1 (Continued)

Time	Ankle Position X (mm)	Ankle Position Y (mm)	Ankle Vel. (mm / sec)	Driver_Disk (deg/sec)	Ankle Acc. (mm / sec^2)	Driver_Disk (deg/sec^2)
21.00	1011.03	264.57	79.68	-10.00	11.64	0.00
21.10	1003.15	263.06	80.62	-10.00	11.13	0.00
21.20	995.17	261.60	81.48	-10.00	10.63	0.00
21.30	987.11	260.19	82.27	-10.00	10.16	0.00
21.40	978.95	258.83	82.98	-10.00	9.71	0.00
21.50	970.72	257.54	83.61	-10.00	9.29	0.00
21.60	962.42	256.30	84.17	-10.00	8.91	0.00
21.70	954.05	255.13	84.64	-10.00	8.57	0.00
21.80	945.64	254.03	85.04	-10.00	8.29	0.00
21.90	937.18	252.99	85.37	-10.00	8.06	0.00
22.00	928.68	252.03	85.61	-10.00	7.89	0.00
22.10	920.15	251.14	85.78	-10.00	7.78	0.00
22.20	911.60	250.33	85.87	-10.00	7.73	0.00
22.30	903.04	249.59	85.89	-10.00	7.74	0.00
22.40	894.48	248.93	85.84	-10.00	7.81	0.00
22.50	885.92	248.35	85.71	-10.00	7.93	0.00
22.60	877.37	247.85	85.52	-10.00	8.10	0.00
22.70	868.84	247.42	85.25	-10.00	8.30	0.00
22.80	860.33	247.08	84.93	-10.00	8.52	0.00
22.90	851.86	246.81	84.53	-10.00	8.77	0.00
23.00	843.43	246.62	84.08	-10.00	9.04	0.00
23.10	835.04	246.51	83.57	-10.00	9.32	0.00
23.20	826.71	246.48	83.00	-10.00	9.60	0.00
23.30	818.44	246.52	82.38	-10.00	9.88	0.00
23.40	810.23	246.63	81.70	-10.00	10.16	0.00
23.50	802.10	246.82	80.98	-10.00	10.44	0.00
23.60	794.04	247.08	80.21	-10.00	10.70	0.00
23.70	786.06	247.41	79.40	-10.00	10.96	0.00
23.80	778.17	247.80	78.55	-10.00	11.20	0.00
23.90	770.38	248.26	77.66	-10.00	11.43	0.00
24.00	762.67	248.79	76.73	-10.00	11.64	0.00
24.10	755.07	249.37	75.77	-10.00	11.84	0.00
24.20	747.57	250.01	74.78	-10.00	12.02	0.00
24.30	740.17	250.71	73.76	-10.00	12.18	0.00
24.40	732.88	251.47	72.72	-10.00	12.33	0.00
24.50	725.71	252.28	71.65	-10.00	12.46	0.00
24.60	718.65	253.13	70.56	-10.00	12.58	0.00
24.70	711.70	254.04	69.46	-10.00	12.68	0.00
24.80	704.88	254.99	68.34	-10.00	12.76	0.00
24.90	698.17	255.98	67.20	-10.00	12.83	0.00
25.00	691.59	257.01	66.05	-10.00	12.88	0.00
25.10	685.13	258.08	64.89	-10.00	12.92	0.00

Table B.1 (Continued)

Time	Ankle Position X (mm)	Ankle Position Y (mm)	Ankle Vel. (mm / sec)	Driver_Disk (deg/sec)	Ankle Acc. (mm / sec^2)	Driver_Disk (deg/sec^2)
25.20	678.80	259.19	63.72	-10.00	12.95	0.00
25.30	672.59	260.33	62.55	-10.00	12.96	0.00
25.40	666.50	261.50	61.37	-10.00	12.95	0.00
25.50	660.54	262.70	60.19	-10.00	12.94	0.00
25.60	654.71	263.93	59.01	-10.00	12.91	0.00
25.70	649.00	265.18	57.82	-10.00	12.88	0.00
25.80	643.43	266.46	56.64	-10.00	12.83	0.00
25.90	637.97	267.76	55.46	-10.00	12.77	0.00
26.00	632.65	269.08	54.28	-10.00	12.71	0.00
26.10	627.45	270.42	53.11	-10.00	12.63	0.00
26.20	622.37	271.77	51.94	-10.00	12.55	0.00
26.30	617.42	273.14	50.78	-10.00	12.46	0.00
26.40	612.59	274.53	49.63	-10.00	12.36	0.00
26.50	607.89	275.92	48.49	-10.00	12.26	0.00
26.60	603.31	277.33	47.35	-10.00	12.15	0.00
26.70	598.85	278.74	46.23	-10.00	12.04	0.00
26.80	594.51	280.16	45.12	-10.00	11.92	0.00
26.90	590.29	281.59	44.02	-10.00	11.79	0.00
27.00	586.18	283.03	42.93	-10.00	11.67	0.00
27.10	582.20	284.47	41.85	-10.00	11.53	0.00
27.20	578.33	285.91	40.79	-10.00	11.40	0.00
27.30	574.57	287.36	39.74	-10.00	11.26	0.00
27.40	570.92	288.81	38.71	-10.00	11.12	0.00
27.50	567.39	290.26	37.69	-10.00	10.98	0.00
27.60	563.97	291.71	36.68	-10.00	10.84	0.00
27.70	560.65	293.16	35.70	-10.00	10.70	0.00
27.80	557.44	294.61	34.72	-10.00	10.55	0.00
27.90	554.34	296.06	33.76	-10.00	10.40	0.00
28.00	551.34	297.50	32.82	-10.00	10.26	0.00
28.10	548.44	298.94	31.90	-10.00	10.11	0.00
28.20	545.65	300.38	30.99	-10.00	9.96	0.00
28.30	542.95	301.82	30.10	-10.00	9.81	0.00
28.40	540.35	303.25	29.23	-10.00	9.67	0.00
28.50	537.85	304.68	28.37	-10.00	9.52	0.00
28.60	535.45	306.10	27.54	-10.00	9.37	0.00
28.70	533.13	307.52	26.72	-10.00	9.23	0.00
28.80	530.91	308.93	25.91	-10.00	9.08	0.00
28.90	528.78	310.33	25.13	-10.00	8.94	0.00
29.00	526.74	311.73	24.37	-10.00	8.80	0.00

Table B.1 (Continued)

Time	Ankle Position X (mm)	Ankle Position Y (mm)	Ankle Vel. (mm / sec)	Driver_Disk (deg/sec)	Ankle Acc. (mm / sec^2)	Driver_Disk (deg/sec^2)
29.10	524.79	313.12	23.62	-10.00	8.66	0.00
29.20	522.92	314.51	22.89	-10.00	8.52	0.00
29.30	521.14	315.89	22.19	-10.00	8.38	0.00
29.40	519.44	317.26	21.50	-10.00	8.24	0.00
29.50	517.83	318.63	20.83	-10.00	8.11	0.00
29.60	516.29	319.99	20.18	-10.00	7.97	0.00
29.70	514.84	321.34	19.55	-10.00	7.84	0.00
29.80	513.46	322.68	18.95	-10.00	7.71	0.00
29.90	512.16	324.02	18.36	-10.00	7.58	0.00
30.00	510.93	325.35	17.80	-10.00	7.46	0.00
30.10	509.78	326.67	17.25	-10.00	7.34	0.00
30.20	508.70	327.98	16.73	-10.00	7.22	0.00
30.30	507.69	329.28	16.23	-10.00	7.10	0.00
30.40	506.76	330.58	15.75	-10.00	6.98	0.00
30.50	505.89	331.87	15.30	-10.00	6.87	0.00
30.60	505.09	333.15	14.87	-10.00	6.75	0.00
30.70	504.36	334.42	14.46	-10.00	6.64	0.00
30.80	503.69	335.68	14.08	-10.00	6.54	0.00
30.90	503.09	336.93	13.72	-10.00	6.43	0.00
31.00	502.55	338.17	13.38	-10.00	6.33	0.00
31.10	502.08	339.41	13.07	-10.00	6.23	0.00
31.20	501.66	340.63	12.79	-10.00	6.13	0.00
31.30	501.31	341.85	12.53	-10.00	6.04	0.00
31.40	501.02	343.05	12.29	-10.00	5.95	0.00
31.50	500.78	344.25	12.08	-10.00	5.86	0.00
31.60	500.60	345.43	11.89	-10.00	5.77	0.00
31.70	500.48	346.61	11.73	-10.00	5.69	0.00
31.80	500.42	347.77	11.60	-10.00	5.61	0.00
31.90	500.41	348.93	11.48	-10.00	5.54	0.00
32.00	500.45	350.07	11.39	-10.00	5.46	0.00
32.10	500.55	351.20	11.32	-10.00	5.39	0.00
32.20	500.70	352.32	11.28	-10.00	5.32	0.00
32.30	500.91	353.43	11.25	-10.00	5.26	0.00
32.40	501.16	354.52	11.24	-10.00	5.20	0.00
32.50	501.46	355.61	11.26	-10.00	5.14	0.00
32.60	501.82	356.68	11.29	-10.00	5.09	0.00
32.70	502.22	357.73	11.34	-10.00	5.04	0.00
32.80	502.67	358.78	11.40	-10.00	4.99	0.00

Table B.1 (Continued)

Time	Ankle Position X (mm)	Ankle Position Y (mm)	Ankle Vel. (mm / sec)	Driver_Disk (deg/sec)	Ankle Acc. (mm / sec^2)	Driver_Disk (deg/sec^2)
32.90	503.17	359.81	11.48	-10.00	4.95	0.00
33.00	503.72	360.82	11.58	-10.00	4.91	0.00
33.10	504.31	361.82	11.69	-10.00	4.87	0.00
33.20	504.95	362.81	11.81	-10.00	4.84	0.00
33.30	505.64	363.78	11.94	-10.00	4.82	0.00
33.40	506.37	364.73	12.08	-10.00	4.79	0.00
33.50	507.15	365.67	12.24	-10.00	4.77	0.00
33.60	507.97	366.59	12.40	-10.00	4.76	0.00
33.70	508.83	367.49	12.57	-10.00	4.75	0.00
33.80	509.74	368.37	12.76	-10.00	4.74	0.00
33.90	510.69	369.23	12.95	-10.00	4.74	0.00
34.00	511.69	370.08	13.15	-10.00	4.74	0.00
34.10	512.73	370.90	13.36	-10.00	4.75	0.00
34.20	513.81	371.71	13.57	-10.00	4.76	0.00
34.30	514.93	372.49	13.80	-10.00	4.77	0.00
34.40	516.10	373.25	14.03	-10.00	4.79	0.00
34.50	517.30	373.98	14.27	-10.00	4.81	0.00
34.60	518.55	374.70	14.51	-10.00	4.84	0.00
34.70	519.84	375.39	14.77	-10.00	4.87	0.00
34.80	521.18	376.05	15.03	-10.00	4.91	0.00
34.90	522.55	376.69	15.30	-10.00	4.94	0.00
35.00	523.97	377.30	15.58	-10.00	4.99	0.00
35.10	525.43	377.89	15.86	-10.00	5.03	0.00
35.20	526.93	378.45	16.16	-10.00	5.08	0.00
35.30	528.47	378.98	16.47	-10.00	5.14	0.00
35.40	530.06	379.48	16.78	-10.00	5.19	0.00
35.50	531.68	379.95	17.10	-10.00	5.25	0.00
35.60	533.35	380.39	17.43	-10.00	5.31	0.00
35.70	535.07	380.80	17.78	-10.00	5.37	0.00
35.80	536.82	381.17	18.13	-10.00	5.44	0.00
35.90	538.62	381.51	18.49	-10.00	5.51	0.00
36.00	540.46	381.82	18.87	-10.00	5.58	0.00

APPENDIX C

PARTS DETAIL LINE DRAWINGS

All the detailed line drawings dimensions are in units of millimeters.

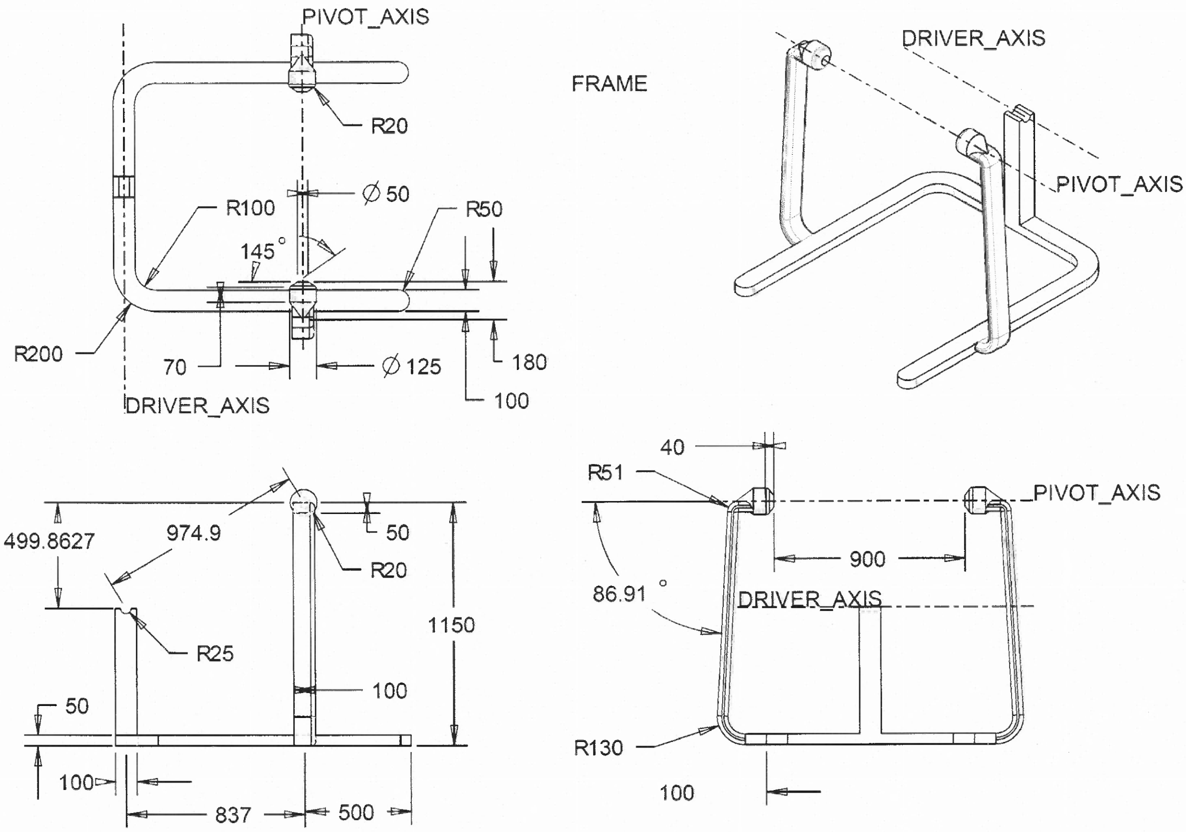

Figure C.1 Frame Detailed Line Drawing

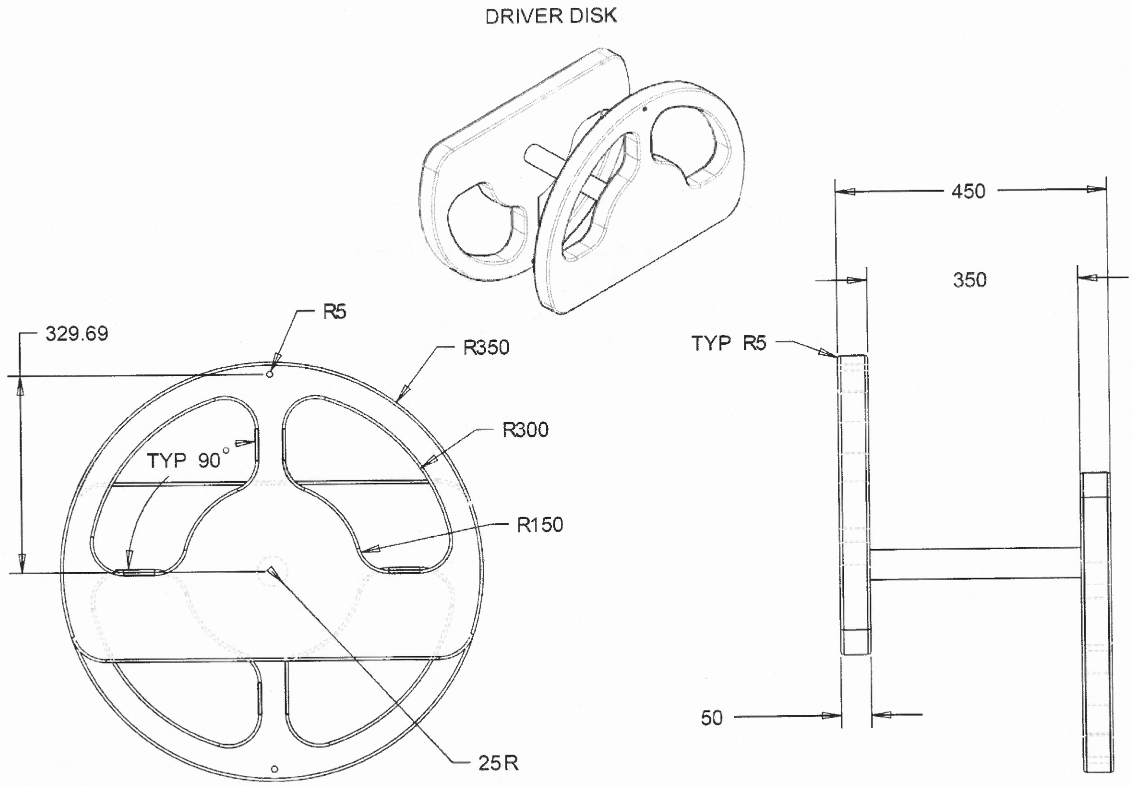

Figure C.2 Driver Disk Detailed Line Drawing

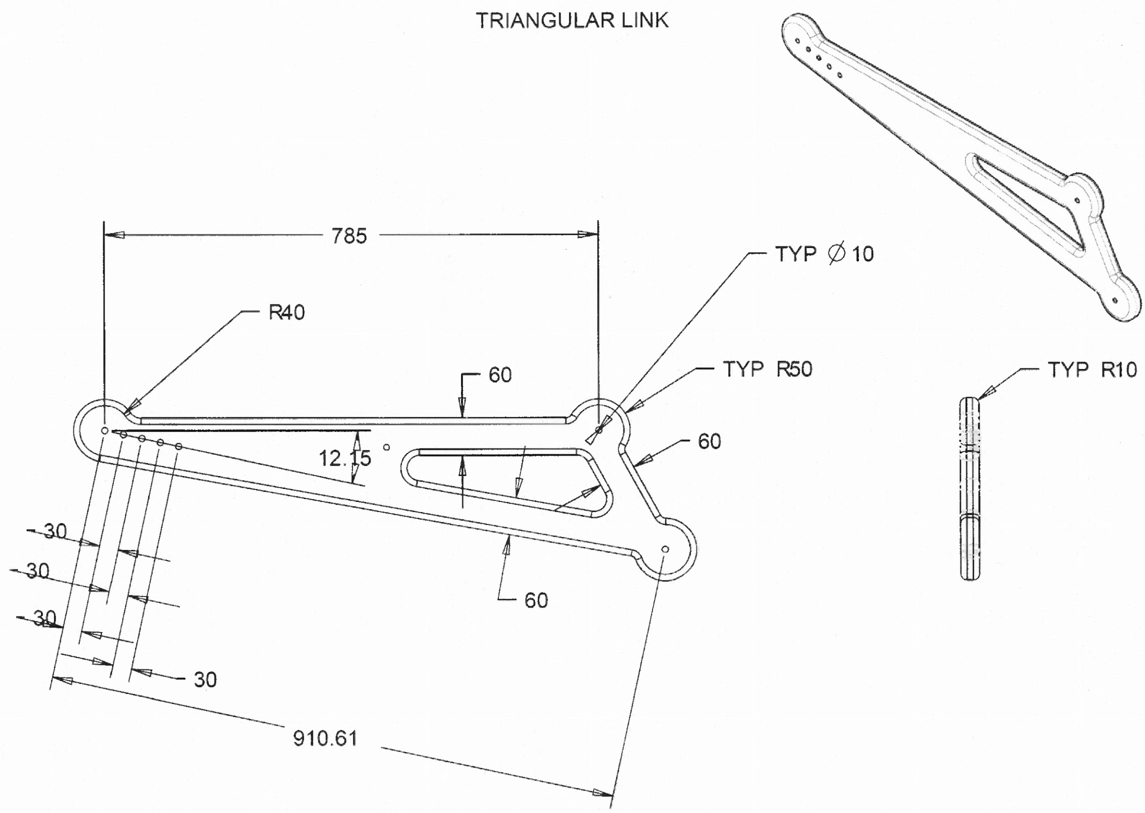

Figure C.3 Triangular Link Detailed Line Drawing

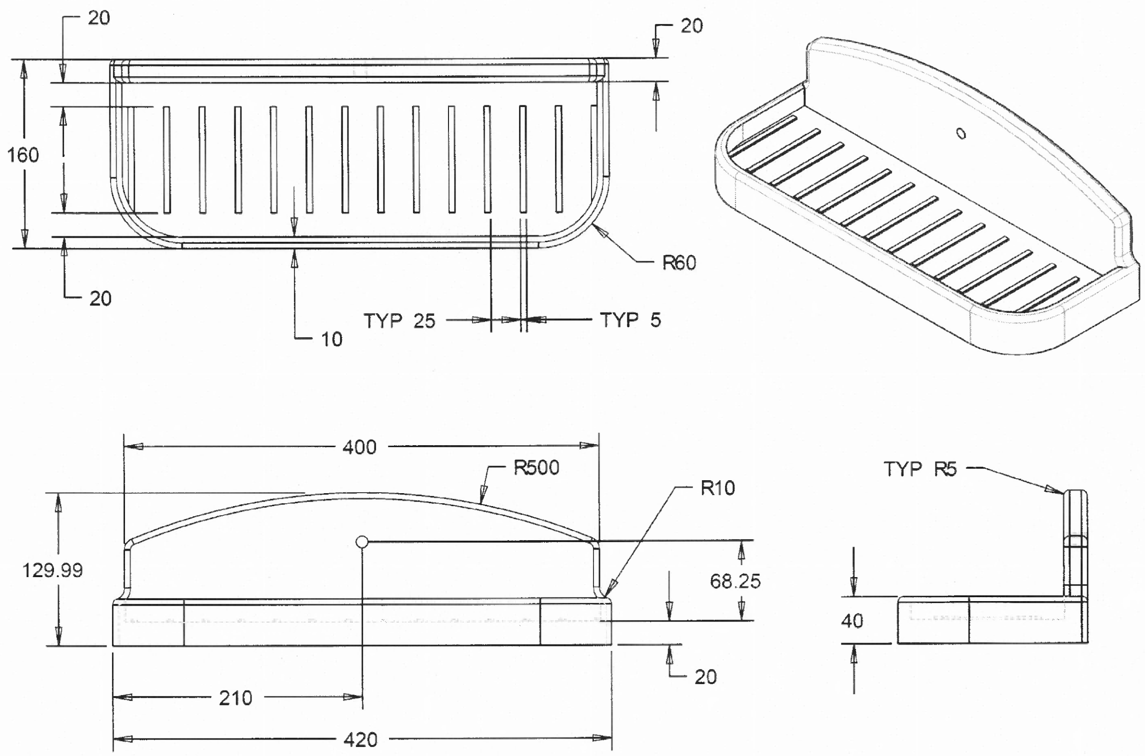

Figure C.4 Foot Support Detailed Line Drawing

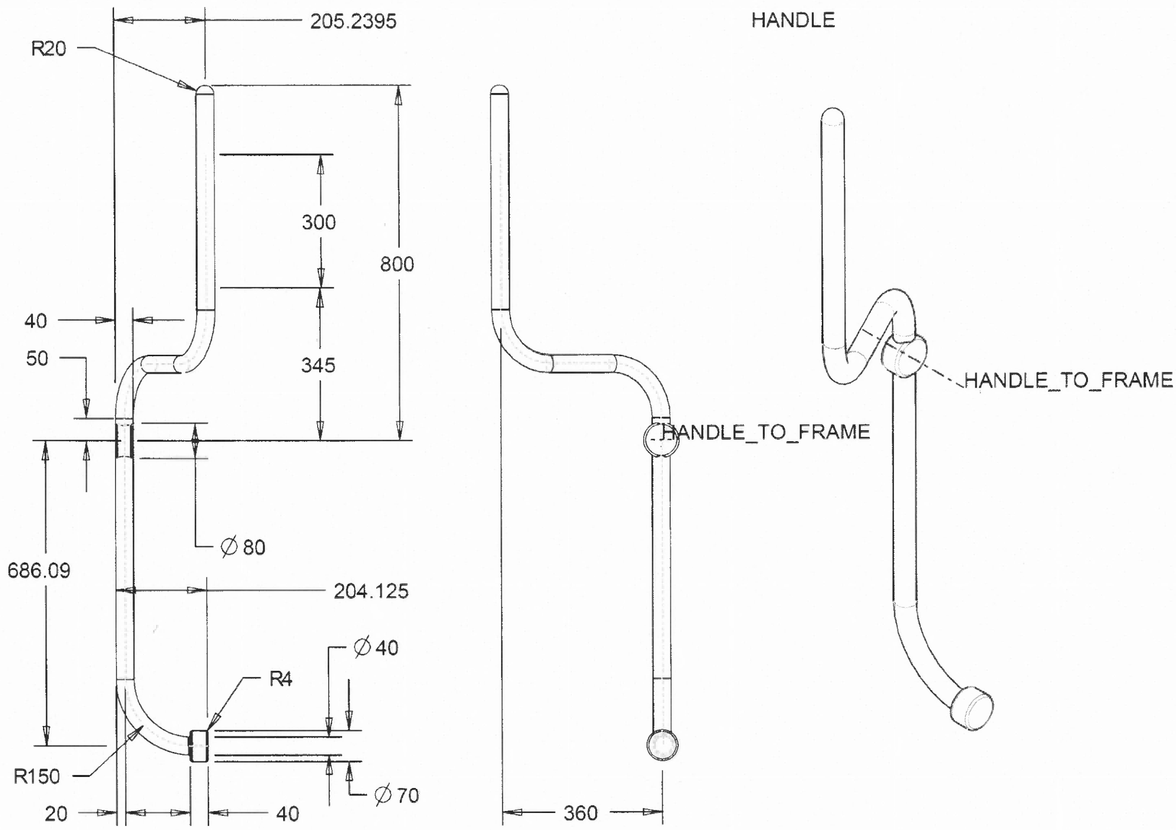

Figure C.5 Handle Detailed Line Drawing

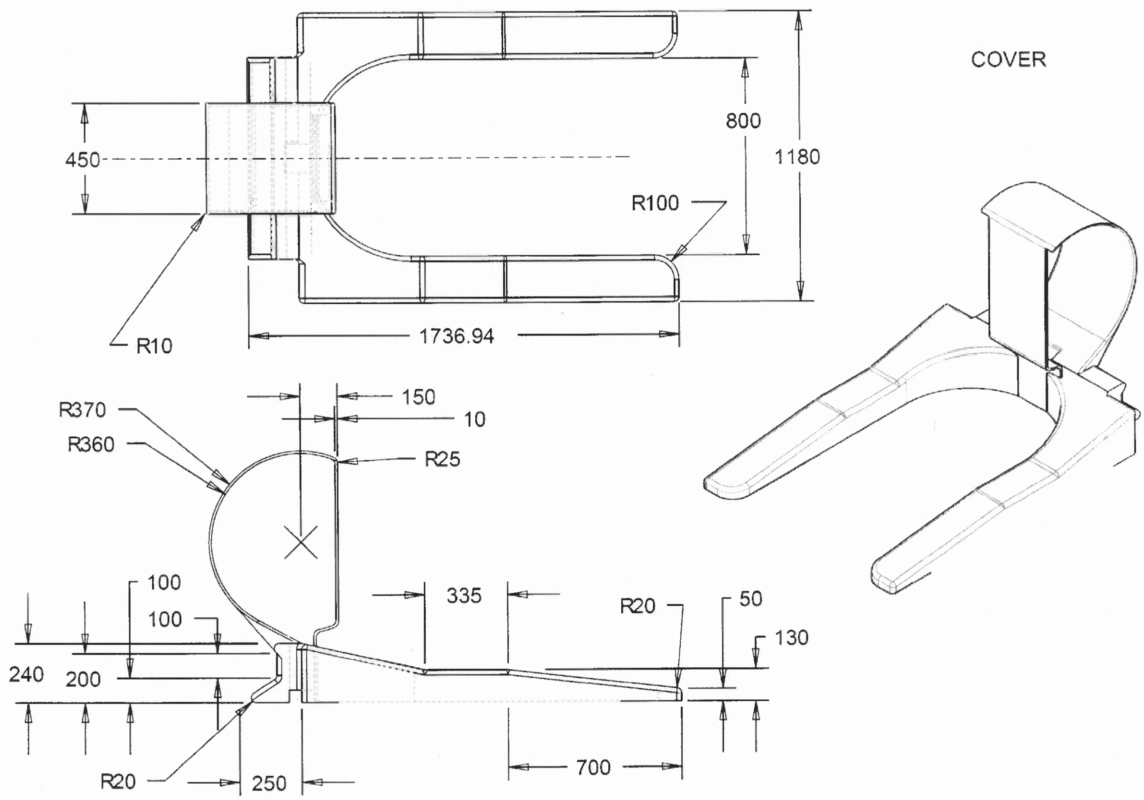

Figure C.6 Cover Detailed Line Drawing

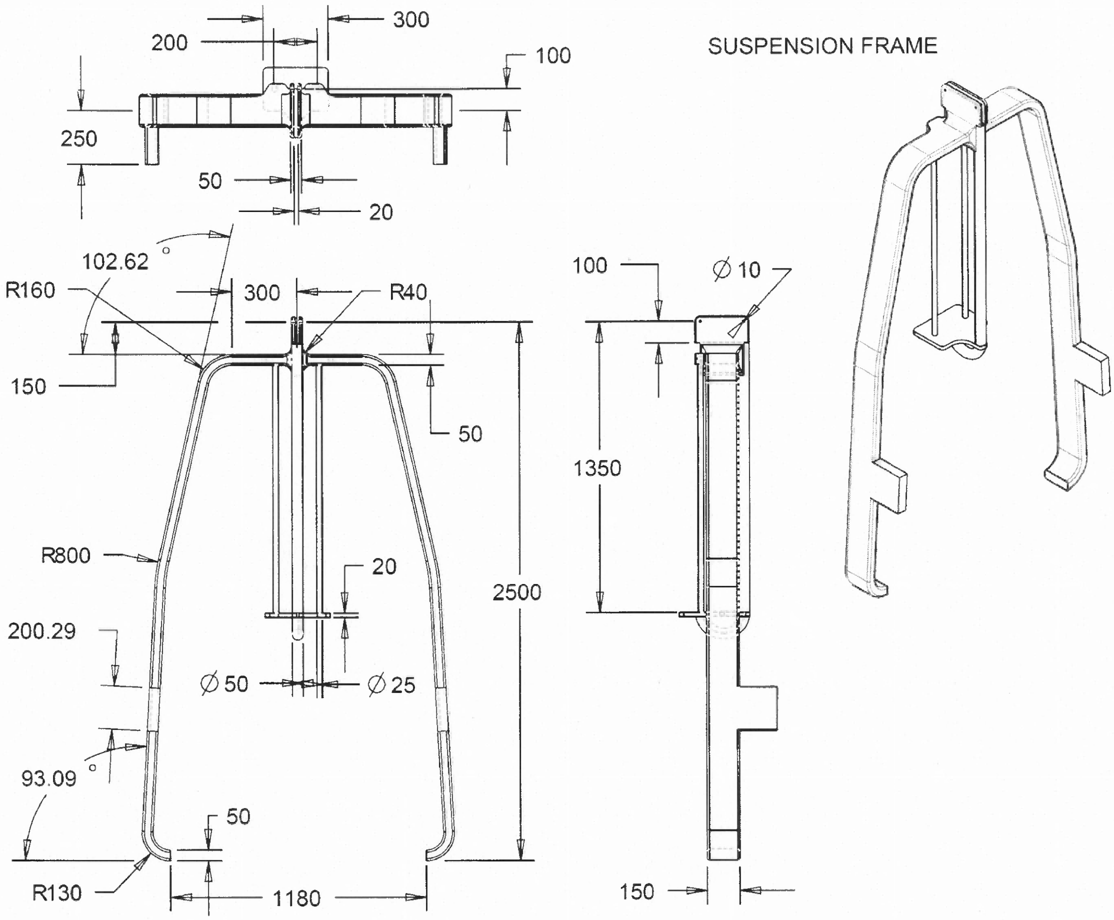

Figure C.7 Suspension Frame Detailed Line Drawing

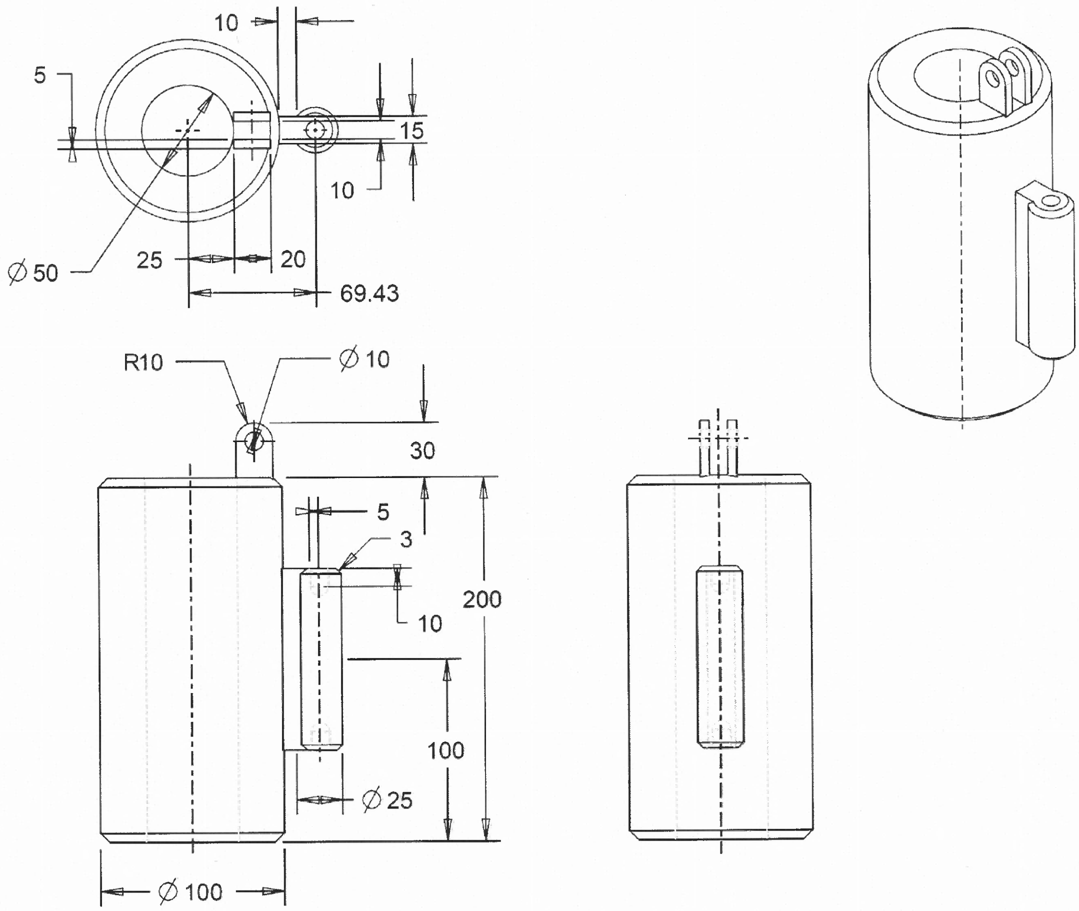

Figure C.8 Suspension Cylinder Detailed Line Drawing

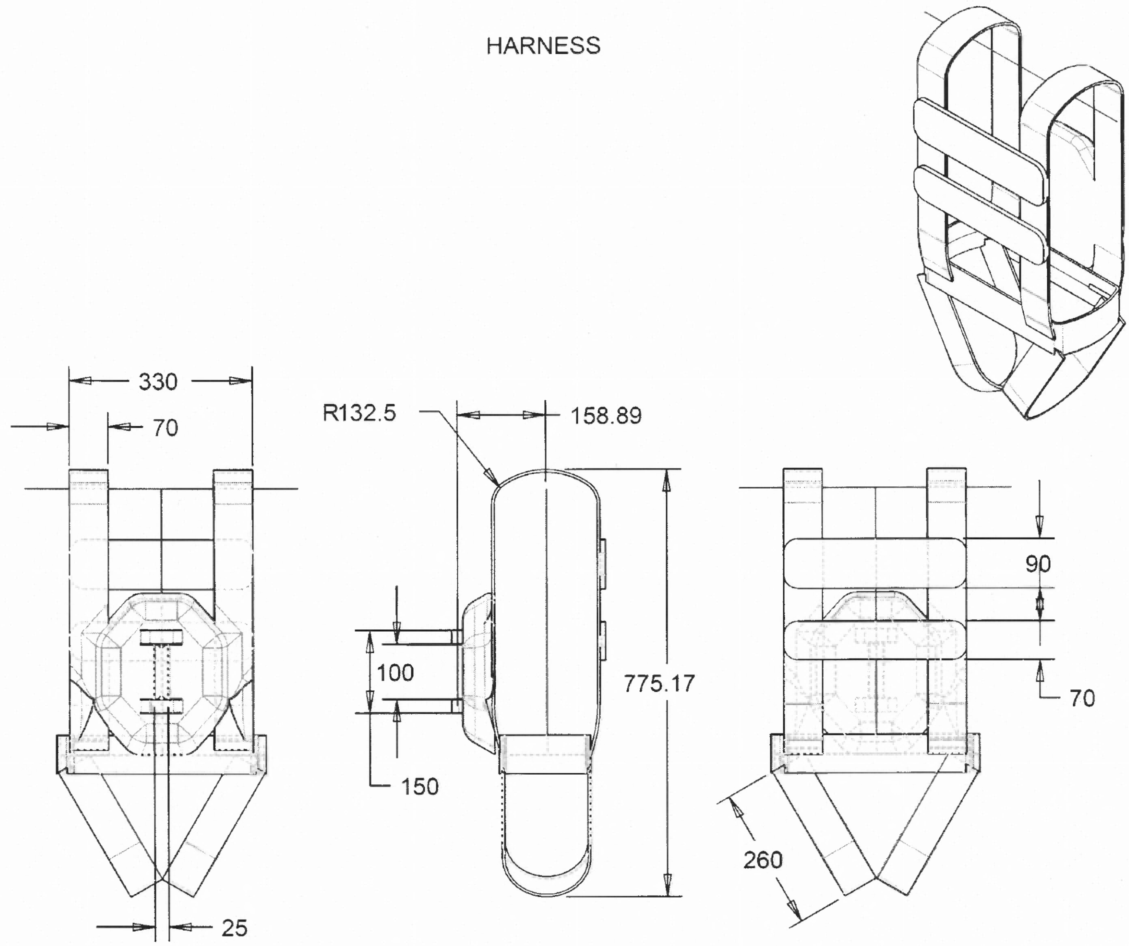

Figure C.9 Harness Detailed Line Drawing

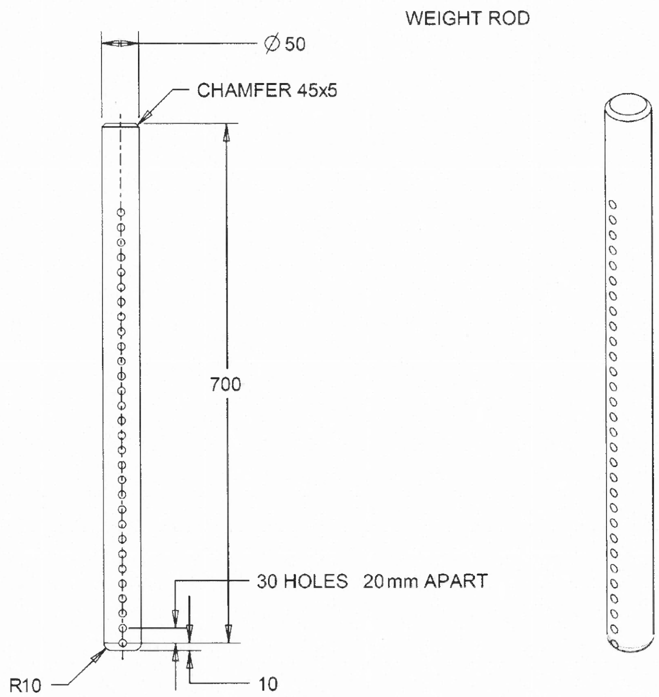

Figure C.10 Weight Rod Detailed Line Drawing

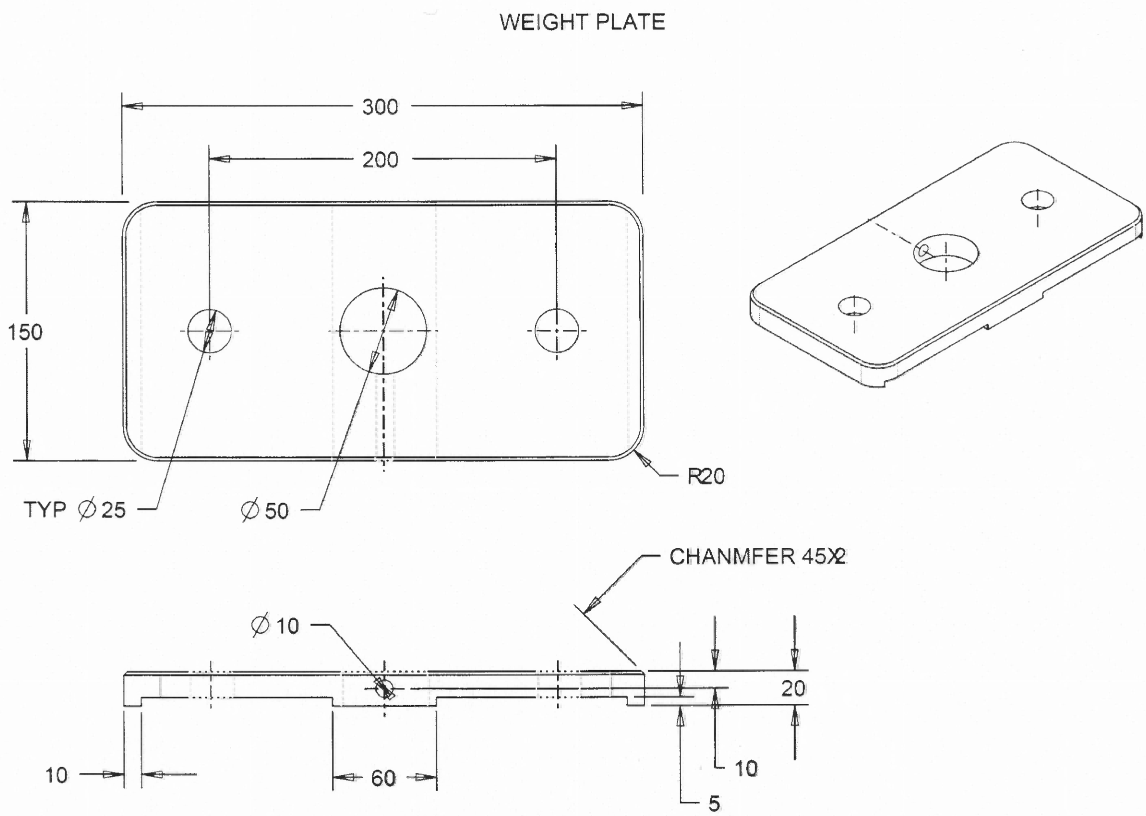

Figure C.11 Weight Plate Detailed Line Drawing

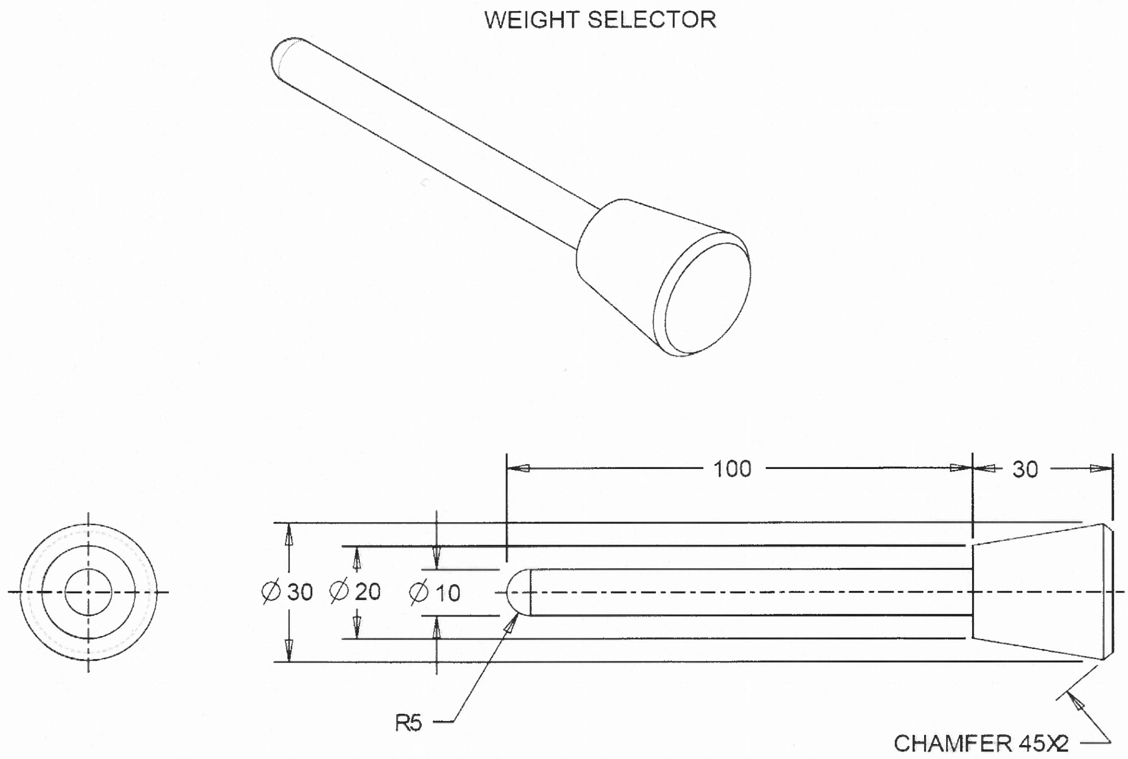

Figure C.12 Weight Selector Detailed Line Drawing

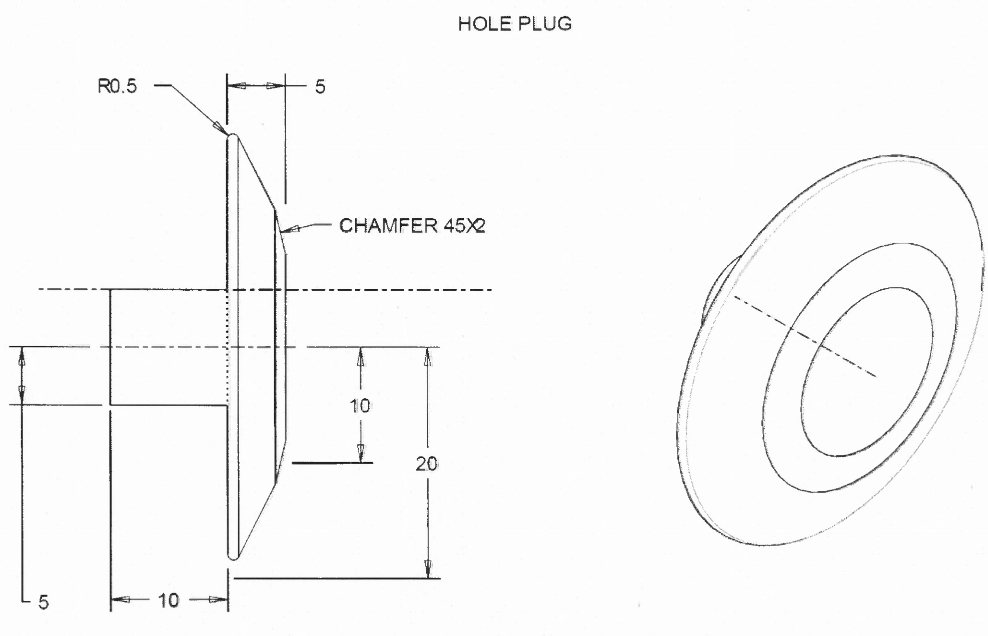

Figure C.13 Hole Plug Detailed Line Drawing

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