DESIGN AND FABRICATION OF AN ELECTRONICALLY CONTROLLABLE,
VARIABLY DAMPED ABOVE-KNEE PROSTHESIS

by

EDWARD GLASSMAN

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREES OF

BACHELOR OF SCIENCE

and

MASTER OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

October 1982

© Edward Glassman 1982

The author hereby grants to M.I.T. permission to reproduce
and to distribute copies of this thesis document in whole or
in part.

Signature of Author...
Department of Mechanical Engineering, October 1982

Certified by .................................................................
Thesis Supervisor

Accepted by .............................................................
Departmental Chairman

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
APR 20 1983
Archives
LIBRARIES
DESIGN AND FABRICATION OF AN ELECTRONICALLY CONTROLLABLE, VARIABLY DAMPED ABOVE-KNEE PROSTHESIS

by

EDWARD GLASSMAN

Submitted to the Department of Mechanical Engineering on October 23, 1982 in partial fulfillment of the requirements for the degrees of Bachelor of Science and Master of Science

ABSTRACT

Countless man-hours of work in the field of prosthetics research have produced dozens of above-knee (A/K) prosthesis systems which attempt to enhance an amputee's mobility and functional range. However, it is the inability of these current prostheses to adapt to amputees' changing gait patterns which brackets their success.

Based on previous research showing the advantages of an adaptive control scheme, a new design incorporating a magnetic particle brake as the active element in an electronically controllable knee damping mechanism has been constructed. The self-contained system will utilize a microprocessor controlled pulse width modulation (PWM) scheme to meter the damping profile in swing phase.

The knee mechanism is based around an anti-backlash lead screw which operates noiselessly. The support structure is a composite fabrication using a foam core wrapped in graphite/epoxy with an outer layer of kevlar for added toughness. The assembly is extremely light and operates smoothly. More work is necessary before the leg is fully operational.

Thesis Supervisor: Woodie C. Flowers
Title: Associate Professor of Mechanical Engineering
ACKNOWLEDGMENTS

You don't often get a chance to write how lucky you've been; to have good friends, people that were even friendlier when you were being a pain, because they knew you needed it more then.

Thanks Woodie. Besides being the most prolific designer around, somehow, you direct without directing. It's been a genuine pleasure.

George Pishenin gave me a place to create all of my machined parts. This made my life much easier. More importantly, his friendship made long, sometimes boring, too often frustrating weeks of machine work far more enjoyable.

To my family, Mom and Dad, Karen and Lawrence, who have supported me with everything that I needed, you're still my highest examples.

To the the host of others, too numerous to list, who have helped me during my tenure here, thank you.

I owe you all.

To that small minority, who seemed to go out of there way to make everything difficult and uncomfortable, I bequeath you a life-time's supply of Lobdell food, in the hope that it will do the same thing for you.

This project puts the final wraps on my five year stint at MIT. Having been both an undergraduate and a graduate student here, I can truly say, there is no other place like it.

This research was performed at the Eric P. and Evelyn E. Newman Laboratory for Biomechanics and Human Rehabilitation and funded by Department of Education, National Institute of Handicapped Research Grant G008200048, National Science Foundation Grant ESC-8023193 and by Hughes Aircraft Co., Ground Systems Group.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>INTRODUCTION</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- The Problem</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>- Normal Gait</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>- In General</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>- Amputee Gait</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>- Rationale for an Electromechanical Damping System</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>2</td>
<td>THE DESIGN</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>- The Mechanism</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>- Structure</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>- Design Details</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>- Graphite / Epoxy</td>
<td>43</td>
</tr>
<tr>
<td>3</td>
<td>CONCLUSIONS AND RECOMMENDATIONS</td>
<td>52</td>
</tr>
<tr>
<td>References</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>Appendix 1 - Dissassembly Procedure</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td>Appendix 2 - Magnetic Particle Brakes</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td>Appendix 3 - Materials and Suppliers</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>NUMBER</td>
<td>TITLE</td>
<td>PAGE</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>1-1</td>
<td>Sequential Gait Parameter</td>
<td>10</td>
</tr>
<tr>
<td>1-2</td>
<td>Typical A/K Prostheses</td>
<td>12</td>
</tr>
<tr>
<td>1-3</td>
<td>Proper A/K Prosthesis Alignment</td>
<td>13</td>
</tr>
<tr>
<td>1-4</td>
<td>Multi-Axis Knee Joint for Increased Stability in Stance</td>
<td>15</td>
</tr>
<tr>
<td>1-5</td>
<td>Passive Level Walking</td>
<td>17</td>
</tr>
<tr>
<td>1-6</td>
<td>Knee Parameters, Normal and Conventional Prosthetic Gait</td>
<td>20</td>
</tr>
<tr>
<td>1-7</td>
<td>Subject Walking With Prosthesis System</td>
<td>22</td>
</tr>
<tr>
<td>2-1</td>
<td>Completed Prosthesis</td>
<td>27</td>
</tr>
<tr>
<td>2-2</td>
<td>Nut Holder, Top View</td>
<td>30</td>
</tr>
<tr>
<td>2-3</td>
<td>Magnetic Particle Brake Assembly</td>
<td>30</td>
</tr>
<tr>
<td>2-4</td>
<td>Entire Mechanism</td>
<td>31</td>
</tr>
<tr>
<td>2-5</td>
<td>Fundamental Ratio Triangle</td>
<td>33</td>
</tr>
<tr>
<td>2-6</td>
<td>Knee Ratio vs. Knee Angle</td>
<td>38</td>
</tr>
<tr>
<td>2-7</td>
<td>Foam with Aluminum Inserts</td>
<td>42</td>
</tr>
<tr>
<td>2-8</td>
<td>Lower Platform with Foam</td>
<td>46</td>
</tr>
<tr>
<td>2-9</td>
<td>Graphited Structure, Bottom View</td>
<td>46</td>
</tr>
<tr>
<td>2-10</td>
<td>Knee Bracket with Loading Plates</td>
<td>47</td>
</tr>
<tr>
<td>Page</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>2-11</td>
<td>Knee Bracket in Structure</td>
<td></td>
</tr>
<tr>
<td>2-12</td>
<td>Vertical Graphite Bands</td>
<td></td>
</tr>
<tr>
<td>2-13</td>
<td>45 Degree Graphite</td>
<td></td>
</tr>
<tr>
<td>A1-1</td>
<td>Mechanism, Exploded View with Close-up</td>
<td></td>
</tr>
<tr>
<td>A2-1</td>
<td>MPB Selection Guide</td>
<td></td>
</tr>
<tr>
<td>A2-2</td>
<td>MPB Input Current vs. Output Torque</td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

Above-knee (A/K) amputees are variations in a world which is physically and mentally equipped for healthy, "normal" people. They have trouble performing the routine daily activities; walking becomes tiring and often painful, running, riding a bicycle, even walking up stairs can become impossible.

Substitutes for the missing limb have been available for centuries. These prostheses, when fitted by a trained prosthetist, can help an amputee to regain some portion of his normal abilities. Unfortunately, even though there are a multitude of different designs available (reference (11,12)), they lack the range of functions of which a normal leg is capable. The fact that tens of thousands of man-hours have gone into the development of artificial legs which are able to return only a portion of the amputees former comfort and mobility, is not a slight to those who have tried. Rather it is a testimonial to the "elegance and sophistication of the human body," reference (4).
The problem therefore, is to design and fabricate a knee unit which is capable of responding successfully to a wider range of user needs. In the most fundamental sense, the device must strive to provide the amputee with a set of characteristics which will enable him (due to the English language's lack of a neuter, third person pronoun, amputees will be referred to, throughout this document, as males) to consistently reproduce a comfortable, natural gait under a widely varying set of circumstances.
-Normal Gait

Normal gait is defined by the cyclical, repetitive pattern utilized by anthropomorphically normal individuals to ambulate across flat, level ground, i.e. the type of walking that most people do every day.

Figure 1-1 represents the gait cycle, normalized with respect to time. In normal gait, each leg goes through two major phases, namely swing phase and stance phase. Stance phase is further subdivided into heel strike, foot flat, heel off and toe off which initiates swing phase. Swing phase ends when this same foot again reaches heel strike, whereupon the cycle is repeated. The time interval when both feet are in contact with the ground is referred to as double support.
Figure 1-1 Sequential Gait Parameters

(reference 6)
- IN GENERAL

A/K prostheses have existed, in the most rudimentary form, since the beginning of recorded history. In fact, there are literally dozens of different knee units available ranging from simple, constant friction pin joints to polycentric hydraulic, units which provide variable resistance as a function of both position and velocity (reference (11,12)). However, as a rule, they are all required to provide certain basic "services for the amputee.

Figure [1-2] depicts a typical A/K prosthesis. The important components being annotated. The suction socket provides the physical connection between the amputee's stump and the prosthesis. It also replaces whatever section of the thigh is missing between the bottom of the stump and the correct knee joint location.
Figure 1-2, Typical A/K Prosthesis
(reference 6)
Figure 1-3. Proper A/K Prosthesis Alignment
(reference 12)
A stabilizing torque, which keeps the knee from buckling during stance phase, (figure [1-3]) is achieved by placing the knee axis posterior to the load vector of the body. Some prostheses use a pin joint to simulate the knee axis while others use multicenter mechanisms such as a four bar linkage mechanism (figure [1-4]) which moves the effective center of rotation even further back, thus enhancing the leg's stability in stance. For a comprehensive overview of available knee mechanisms, consult reference (14).
Figure 1-4. Multi-Axis Knee Joint for Increased Stability in Stance

(reference 4)
In swing phase, the lower leg is acting very much like a pendulum which is driven by the applied hip torques. Modifications of its ballistic path are achieved by absorbing torque at the knee joint. This explains why passive legs are able to reproduce swing phase so successfully.

At the beginning of swing phase (figure [1-5]), the top portion of the prosthesis is driven forward by the hip, causing the heel to rise. If the knee joint is free-swinging, the heel will rise up beyond a desirable height. Also, towards the end of swing, the knee is rotating forward with a very high angular velocity. If it remained undamped it would slam into the hyperextension stops. Clearly, some damping is required. The prosthesis must also be able to support the individual's weight, be comfortable to wear, safe and reliable.

This is only a brief description of a very involved situation. For a more complete discussion, the interested reader should examine reference (7).
Figure 1-5. Passive Level Walking

(reference 5)
AMPUTEE GAIT

The amputation of a lower limb is, to say the least, traumatic. The repercussions are both physical and mental. In a number of ways, the prosthesis must help to ease aspects of both of these types of problems. If an aesthetic, comfortable and functional substitute can be found, the amputee is able to deal with his environment in a more successful manner.

Amputee gait is abnormal. One of the primary reasons for this can be seen in the comparison of knee position of normal versus conventional prosthetic (passive) gait. The passive leg can provide only resistive torques. This is represented in the torque and power versus time plots in figure [1-6]. While the active, sound leg dissipates and then supplies power during stance phase, the passive, artificial leg remains locked. The inability of the amputee to provide the flexion and extension phase of stance requires him to vault or in some manner, circumvent the locked prosthesis.
However, during swing phase, the sound leg is either free swinging or dissipating power, depending on its position in the gait cycle. Thus, a passive leg can be controlled in such a way that it will accurately produce the desired position history during swing phase.
Figure 1-6

Knee Data: Normal and Conventional Prostheses
- RATIONALE FOR AN ELECTROMECHANICAL DAMPING SYSTEM

Work done by Flowers, Darling, Grimes, Hunter et al. [references (1,2,3,4,5,6)] showed that electromechanical damping was both feasible and useful. By providing a "generic" leg which could be readily programmed with almost any conceivable damping profile, this system quickly demonstrated its use as a laboratory aid for new prosthesis design. It also indicated that if a self-contained system containing its own microprocessor, with a damping profile stored in memory, could be run efficiently (low power consumption), an electromechanical brake could be controlled to provide the necessary resistive knee torques. Some past attempts have been very successful in this regard (reference [3]). Cone et al. built and programmed a system which was able to perform all the conventional tasks necessary for flat level walking (figure 1-7). Because of its memory capabilities it can change its damping profile depending on cadence. Thus it will perform properly at any walking pace.
Figure 1-7. Subject Walking with Prosthesis System (reference 5)
In addition, the controller which the subject, in this picture, wears across his shoulder allows him to alter the knee profile by adjusting a set of slide potentiometers. This "user-friendly" method of downloading a new damping profile into the prosthesis means that the amputee can alter the characteristics of his leg. This ability is essential to the man-machine system because the man's gait characteristics will not always be the same as they were when he had his prosthesis adjusted the first time. Perhaps he sprained his sound ankle and would like a bit more damping throughout swing. Maybe, instead of the leather shoes he usually wears, he's wearing sneakers which are making the leg feel too "springy". These are hypothetical examples, but the possibilities are clear. With user-adaptable control, the amputee can tailor the leg's characteristics to his daily needs.

There are also some eventualities in which the damping profile should change without prompting from the user such as stumble response.

When an individual stumbles (amputee or normal), many of the major muscle groups tense up. This activity could be sensed and used as a trigger to over-ride the current damping control program. A predetermined response to such a situation could then be invoked. This type of ability is
particularly attractive to the geriatric amputee because it constitutes a safer leg.

There could also be prerecorded profiles, down-loaded at the touch of a button, for activities like:
- bicycling
- jogging
- stair climbing and descending
- ramb climbing and descending
- tennis
- skiing

This is only a brief list of how the increased versatility provided by electromechanical damping could increase amputee comfort, functional range and safety.

It is interesting to note that the microprocessor industry has advanced so rapidly, that the limiting factor in the size of the controller is no longer the size of the processing unit.
Rather, it is the switches which need to be big enough for the amputee to operate easily. The most recent iteration that has been conceived by the M.I.T. knee group, requires a case about the size of a cigarette package which need only be attached to the prosthesis, while altering the damping profile.

The overall concept is that as the man's needs and characteristics change, the machine can be easily altered to maintain an optimal set of performance characteristics.
CHAPTER 2

THE DESIGN

Using other electromechanically damped prostheses, designed by members of the MIT Knee Group as benchmarks (reference (1,4,6,11), the leg shown in figure [2-1] was designed. The photo on the left hand side of figure [2-1] shows the prosthesis open to 90 degrees flexion (a suction socket would be attached to the vertical knee platform and a SACH foot assembly clamps onto the bottom of the assembly). The photo on the right is the same assembly when closed (stance). It is a passive leg consisting of a MPB which is coupled, via an anti-backlash actuator, to the knee joint. The mechanism is supported within a composite support structure. The completed device, as shown, weighs 1.28 kg. (2 lbs. 13.5 oz.).

In its complete form, the MPB will be controlled using a pulse width modulated (PWM) control scheme which will be regulated by an on board microprocessor. The control electronics, and the MPB are powered from a rechargeable battery pack with ample capacity for one day's use.
Figure 2-1, Completed Prosthesis
-The Mechanism

The simplest solution to this design problem would be to couple the MPB directly to the knee axis (direct-drive). Unfortunately, a MPB capable of providing the amount of torque necessary to directly control swing phase, is excessively large and massive. Therefore, a transmission ratio between the MPB and the knee joint is necessary.

Central to the success of this design is the anti-backlash lead screw, manufactured by KERK Motion Products (Appendix 3). It consists of a five-fluted, stainless steel screw and an anti-backlash Delrin nut assembly. The spring which snaps over the nut, holds the three threaded prongs against the screw, insuring backlash free operation. The nut is manufactured with a large trangular flange on one end which can be used for mounting purposes. To help keep the overall size of the mechanism to a minimum, a slightly different mounting scheme was used. The flange was removed and three equally spaced grooves were cut in the bottom of the nut. A matching set of prongs was fashioned into the nut holder (figure [2-2]). When the hold down nut is threaded into the nut holder, the anti-backlash nut is locked axially and rotationally.
The two ends of the screw are supported by preloaded, angular contact ball bearings. The top end of the screw is coupled to a modified version of a Berg (Appendix 3) flexible coupling. A $0.0625$ inch diameter dowel pin locks half of the coupling to the screw shaft. The same technique is used to mount the other half of the coupling to the shaft of the MPB. As the MPB assembly, figure [2-4] slip fits onto the top of the screw sleeve, the two halves of the flexible coupling interlock. The MPB assembly is held in place with four radial screws.
Figure 2-2 Top View of the Nut Holder

Figure 2-3 Magnetic Particle Brake Assembly
Figure 2-4. Entire Mechanism
The mechanism, figure [2-4], which operates successfully by itself, was tested and found to be smooth and quiet. At 1.5 volts D.C., there is a noticeable increase in the sliding resistance of the nut assembly, while at 5.0 volts D.C., the maximum system voltage, one has to strain to induce movement.

The mechanism, by itself, converts the rotary motion of the MPB to a linear motion along the axis of the screw. To complete the transmission it is necessary to relate this linear motion to the rotary motion at the knee. This can be accomplished using the triangular arrangement shown in figure [2-5].
Figure 2-5, Fundamental Ratio Triangle
where:

\[ KR = \text{knee ratio (angular velocity of [MPB/knee joint])} \]

\[ L = 2.25 \quad \text{Pivot arm length} \]

\[ R = 4.50 \quad \text{Radius} \]

\[ S = \quad \text{variable side length} \]

\[ \alpha = 30\,\text{deg} \quad \text{initial angle (at stance)} \]

\[ \text{between sides } L \text{ and } R \]

\[ \theta = \quad \text{knee angle (CCW is positive)} \]

\[ P = 1.00 \quad \text{pitch of lead screw} \]

\[ \quad \text{(inches of travel/ revolution)} \]

Assume that sides \( L \) and \( R \) are of a fixed length, that side \( S \) will change length to accommodate the distance between points 2 and 3 and that points 1, 2 and 3 are all pin joints, free to rotate. If side \( L \) is fixed in space and side \( R \) is rotated about point 1, in the direction shown, there now
1 and the rate of change in length, of side S. If one end of side S is the lead screw and the other end is the nut that goes with it, then the pitch of the screw establishes a ratio between the rate of rotation of side R about point 1 and the rate of rotation of the lead screw. s.t.

$$S = \left[ (L^2 + R^2) - 2LR\cos(\alpha + \theta) \right]^{0.5}$$  \hspace{1cm} [1]

define quantity under the radical as B,

$$S = (B)^{0.5}$$  \hspace{1cm} [2]

$$\frac{dS}{d(\theta)} = 0.5(B)^{-0.5}LR\sin(\alpha + \theta)$$  \hspace{1cm} [3]
where equation [3] represents the linear rate of change of side $S$ with respect to the knee joint's angular velocity, where point 1 is the representative location for the knee joint. Therefore the ratio of angular velocity of the MPB versus that of the knee joint is:

$$KR = \frac{dS}{d(\theta)} \times 6.283 \times [l/p]$$

Judicious selection of the ratio of the side lengths, pitch of the screw and torque capabilities of the MPB can provide a system that will fit within the anatomical envelope of the lower leg and still provide the requisite torques.

The maximum torque which can be applied at the knee by this MPB system is 35 [Nm], in swing phase. In stance, the torque is applied when the mechanism locks against the hyperextension stops. The ratio between the knee joint and the MPB is plotted versus knee angle in figure [2-6].
ideally, the ratio versus position plot would be the inverse of what is shown. Namely, the ratio would be at its maximum at small or large values of knee angle and lowest during the interim. This is optimal because the highest torques and lowest speeds occur at 50-70 degrees of flexion and 20-0 degrees of extension. In between, the knee is basically undamped. Unfortunately, a satisfactory method for implementing a variable ratio of this type was not found.
Figure 2-6. KNEE TRANSMISSION RATIO

KNEE ANGLE (Deg)
The support structure, serves two purposes:

[1] It acts as a safe, lightweight, structural member capable of being interfaced with a standard SACH (Solid Ankle, Cushioned Heel) foot unit on one end and to a vacuum formed stump socket, on the other.

[2] It will maintain the three pin locations (figure [2-5]), in their proper orientation.

The structure is composed of a foam core which is wrapped in graphite cloth with a protective outer layer of kevlar cloth. Aluminum is used to replace sections of the foam to help distribute locally applied loads.
-Design Details

Pin locations 1 and 3 in figure [2-5], are integral with the housing. The pins located at positions 1 and 2 are stainless steel studs which have been press fitted into the mechanism. They ride in sintered, oil impregnated, bronze bearings which thread into the housing. The knee axis, pin location 1 in figure [2-5], connects the knee platform to the structure. The knee platform has two of the oilite bronze sleeves already in place. Threaded stainless steel studs, which screw into the housing, lock the knee platform to the structure, allowing one rotational degree of freedom. Loctite 22 is used to avoid undesired rotation at any of the threaded joints.

The knee axis is located a bit more posteriorly than is customary. This could lead to a leg which is extremely stable in stance, i.e. make it difficult to initiate swing phase. This problem can be avoided by proper orientation of the head of the femur and the SACH foot, such that the leg is still at the trigger point.

It is not the intent of this document to explain the prosthetic alignment procedure other than to indicate that
this leg can be set up to operate successfully and that a professional prosthetist is essential to the success of any amputee's ambulatory future.

The core of the structure is composed of a polyimide, closed-cell foam. All of the foam pieces are planar sections except for the dorsal face of the housing which is a section of a cylinder. The foam was bent into the desired shape by heating a flat section of it and an aluminum mandrel, with the desired I.D., in a convection oven to 385 degrees Fahrenheit. After twenty minutes of heating, the foam was wrapped around the mandrel and held in place with a piece of cloth.

The finished product maintained a constant thickness, showed no signs of surface degradation and formed quite accurately to the desired inside diameter of 4.25 inches.

The various pieces of foam were held together with Devcon 5-Minute Epoxy. Also, there are a number of aluminum inserts which are attached to the foam using 5-Minute Epoxy (figure [2-7]).
Figure 2-7, Foam with Aluminum Inserts
Graphite/Epoxy

A graphite/epoxy (G/E) composite method was selected to house the device. G/E's have been used in many areas where high strength/weight structures are attractive. However, one must be careful to recognize that this material is not steel or aluminum and that different design techniques are necessary if the structure is to approach its theoretical potential.

The graphite comes as an unimpregnated, loosely woven fabric. Its strength, when locked in an epoxy matrix, lies primarily along the axis of the fibers. Because graphite is a brittle material, there is very little yielding before failure. This gives rise to a potential "zipper effect". If one strand of the graphite is loaded more severely than the others, it can fail passing the load off to its neighbor, which does the same thing on down the line, breaking one strand at a time. To avoid this problem, the load should be distributed across a number of fibers.
The particular areas of concern in this design were:

[1] Pin location 3, where the nut holder pivots in the housing

[2] The bottom of the structure where the loads must be transferred to a standard sized pylon

[3] The top end where the knee moments and forces are to be transferred from the knee platform, across the knee joint to the housing.

At pin location 3, an aluminum hub was inserted into the foam core on both sides of the structure. An aluminum washer was press fit into the inside and outside of each hub, forming a foam sandwich with 0.020 inch thick aluminum bread. Now, when the graphite is glued to the large washers, they should distribute any load applied from pin 3 across many graphite fibers, evenly. In order for the joint to fail, a very large section of graphite must fail in unison or the aluminum washer must plastically deform with respect to the inserted aluminum hub. Both of these possibilities would require loads well beyond those expected.
The bottom of the foam structure was glued to the lower platform, shown in figure [2-8]. In this case, the axial loads are transferred across the entire perimeter. The various moments associated with gait are successfully distributed by increasing the moment arm, thus decreasing the effective load. Also, the graphite, which is strongest in pure tension, is wrapped around the bottom of the lower platform, figure [2-9]. Thus, both the aluminum/graphite glue joints and the fibers themselves need to fail for the structure to be violated at that point. As a weight saving measure, most of the thickness of the straight sides of the lower platform (figure [2-8]) were removed and replaced with foam. A 0.020 inch thick aluminum plate was press fitted over the foam to provide a successful glueing region for the graphite.
Figure 2-3
Lower Platform

Figure 2-9. Lower Platform in Structure  Bottom View
Figure 2-10, Knee Bracket with Loading Plates

Figure 2-11, Knee Bracket in Structure
At the top end, the loads applied across the knee platform are handled in much the same way. Figure [2-10] shows the knee mounting bracket with two of the ten load distribution plates (all load distribution plates are 0.020 inch thick aluminum of varying size) already attached. The foam sandwich method applies to all of the plates except for the rear set. They are there to absorb compressive loads. However, tensile loads would have required a similar set of plates above that area of the knee bracket. Since this would have made the structure significantly taller, the method was altered in this area. Tensile loads are transferred successfully to the graphite because the vertical strands wrap up, over and down through the knee bracket (figure [2-11]). Thus, if the part is to fail in tension at that point, it must break each of the fibers which wrap around the bracket. Rounded inserts were glued into place where the graphite wraps over the bracket, to eliminate stress concentrations.
The overall graphiting scheme consists of a layer of graphite on the inside and outside of the foam (figure [2-12]) oriented vertically/horizontally (the graphite cloth is a square weave) to transmit axial loads. The vertical members are individual bands in order to wrap them through and around various points in the structure. There is another layer inside and outside, oriented at ±45 degrees, to transmit the torsional moments associated with gait (figure [2-13]).
Figure 2-12

Vertical Graphite Bands

Figure 2-13

45 Degree Graphite
All of the graphite sections were applied using a room temperature curing, two component epoxy system consisting of 60% EPON 815 resin and 40%, by weight, Versamid 115 hardener [Appendix 3].

An outer layer of kevlar was glued over the outside graphite surface, using a similar lay-up technique. While the graphite is strong, it can be damaged by cuts from conventional materials. Kevlar [Appendix 3], a material used in bullet-proof vests, is extremely tough and is virtually impervious to most household items.
CHAPTER 3

CONCLUSIONS AND RECOMMENDATIONS

The structural aspects of the leg, the mechanism and its containment structure, are complete. The intrinsic damping due to the maximum actuator efficiency of 85% establishes a minimum achievable damping profile. Under D.C. current control, the leg behaves appropriately. In a purely qualitative experiment, the knee joint became consistently "stiffer" as the voltage applied to the MPB was increased. However, in order to be able to control the prosthesis appropriately, the assembly needs to be bench tested to accurately determine its response characteristics.

The mechanism is sound. It operates smoothly, easily and silently throughout its range of motion. However, there is some concern about the ability of the anti-backlash nut to stand up to the loads involved over an extended period of time. The manufacturer was unable to provide useful data in the desired loading range. Either field testing or laboratory simulations thereof will be needed to provide an answer.

A great deal of experience was gained in the use of composite materials in prosthetic design. The significant improvement in the strength/weight ratio of the structure is testimony to the applicability of such materials to this
situation. However, the wet lay-up procedure used to produce this prototype required many hours of careful hand sculpting. It would be difficult to maintain a consistently high standard using such a technique in a more commercial environment. There are a number of different composite fabrication options which could be investigated. The use of prepreg tubes is particularly attractive. Nested tubes or cones could have excellent stiffness characteristics and high strength capabilities. One of the difficult design aspects of graphite composites is the successful incorporation of load transfer zones. Because it is advantageous to avoid medium changes, a composite leg fashioned with an integral composite foot would simplify the design (reference (15)). This would also provide the opportunity to remove a large mass from the system, namely the SACH foot.

The original goals of creating a passive leg which would be capable of adapting to changes in the user's needs, silent when operating, light and which would fit within the anthropomorphic envelope have been accomplished. More work is needed to guarantee the structural integrity of the prosthesis and to complete the instrumentation and controls necessary to its operation.
REFERENCES


15. Bullington, Sue, Precision Prosthetics Co., Meeting and telcon, Virginia Beach, VA 904-486-7017
APPENDICES

Appendix 1. Dissassembly Procedure

Appendix 2. Magnetic Particle Brakes

Appendix 3. Materials and Suppliers
APPENDIX 1

DISSASSEMBLY OF THE PROSTHESIS

There are a good number of parts which can be disassembled in this prosthesis. This appendix will help to guide you through the disassembly procedure. To put it back together, well, you're on your own.

Before you begin, you will need the following tools:

- allen wrench set
- the large filed down slot head screw driver
- bearing removal jig pieces
- a $0.749 \times 6.00$ bar
- Loctites 680 and 22 (check expiration dates, Loctite does go bad)
- access to an arbor press

1. Using a small allen wrench, remove the two studs from the knee axis. They will probably be fairly stiff as they are set in place with Loctite 22. When replacing them, clean off the threads and reapply Loctite 22.

2. Pull knee platform straight up, off of the structure, so that the mechanism is at full extension.

3. Using the large filed down screw driver, remove the oilite inserts which span the pins immediately below the particle brake mount.

It is very important that you DO NOT REAPPLY ANY LOCTITE to these joints. The residue from the previous insertion should be more than sufficient to keep them from rotating.
Reason: the oiltite bronze is so porous and the radius at which it is applied, in this case, is sufficiently large, that one must mangle the inserts to get them out, once the Loctite has set.

4. Remove the large allen set screws from the bottom two pivot points. The same screwdriver used on the top set of threaded inserts will remove this set of inserts, as well. DO NOT APPLY LOCTITE TO THE THREADED OILITE INSERTS

5. Using a twisting motion, the entire mechanism can be removed from the structure. Beware of particle brake leads, they develop internal cracks fairly easily.

The only other things which can be removed from the structure are:

- the Ø.500 diameter threaded insert (Ø.375-24) which is press fit into the knee bracket.

- the pylon mounting bracket. This can be removed by pressing the Ø.749 diameter bar through the sleeve which holds it from moving vertically and rotationally. This sleeve is attached to the pylon mounting bracket using Loctite 680. There are two locating pins which lock the sleeve to the frame. When reassembling, avoid getting Loctite into the mating holes for the pins, or the sleeve may never come out of there the next time.

THE MECHANISM.

Holding the mechanism so that the magnetic particle brake (MPB) is up, remove the four small radial screws which hold the MPB assembly to the screw sleeve.

The MPB assembly can be taken apart by pressing a piece of drill rod or a small drill (anything smaller than Ø.0625) into the hole which is drilled radially into the coupling gear. This will displace the pin which locks it onto the shaft and the gear should lift off easily. Make note of which side is up on the gear and which way it reattaches; there are a total of four possibilities but only the correct one works easily. When pressing out that pin, avoid pushing very hard. The bearing on the particle brake shaft is just not designed for any large radial loads.
Remove the three allen head screws which are underneath the gear and which hold the MPB to the slip housing.

Use the same technique to press out the pin which holds the matching gear on the screw end. It's a good idea to rest the gear against the surface of the press so that there are no loads on the bearings when the pin is being removed.

Remove the steel ring from the lower end of the mechanism and pull the forks of the sleeve holder open, gently. The two belleville washers and the solid snap ring will come out.

Pull the screw, with the two angular contact ball bearings still attached, out of the screw sleeve. The nut holder and anti-backlash nut will come along with it.

To remove either bearing, it is essential that the bearing removal jig be used. If it has been lost, make a new one. The jig consists of a split ring with an i.d. a bit bigger than the screw and an o.d. smaller than that of the keeper in the bearings. Place the two halves of the split ring under the bearing which is to be removed. Below that, a fork with a very thick (>0.25 in.) cross section needs to be under the ring to support it across the plate of the arbor press.

Line up everything and using a plunger smaller than the i.d. of the bearing, press it off of the screw.

NEVER PUSH ON THE OUTER RACE OF EITHER BEARING

To remove the nut assembly, retract the anti-backlash spring as far as possible and spin the screw out from the assembly. Remove the black spring retaining ring. Unscrew the steel hold down nut. You should now be able to rock the delrin nut out of the nut holder.

The pivot pins are stainless steel and are press fitted into the nut holder and the screw sleeve. I can not envision any reason for removing them.

If a new section of screw needs to be machined, mount it in a Jacobs Flexible Collet. Because it is not a standard O.D., it won't run true in a traditional collet. This is the type of system that KERK uses to put a tang on the screws that they send out.
Figure A1-1
Mechanism, Exploded View with Close-up
APPENDIX 2

MAGNETIC PARTICLE BRAKE

Figure [A2-1] shows the various magnetic particle brakes which are available from Force Limited Inc., their peak torque capabilities (at 5 volts D.C. or less), the transmission ratio necessary to provide the required 35 [Nm], assuming an actuator efficiency of 85%, and the weight of each brake.

Modeling the magnetic particle brake used in the prosthesis, Force Limited Model B20SF4, as a pure inductor connected in series with a resistor, the step response indicated a first order time constant of 43 milliseconds. Force Limited states a release time (time to zero torque, after power is removed) of 2 milliseconds. Figure [A2-2] plots the input current versus output resistive torque. It is interesting to note that the output resistive torque of the MPB is independent of the MPB's angular velocity. Thus a finite amount of electrical power, dissipated in the coil of the brake can cause the brake to dissipate an impressively large amount of mechanical energy.
Figure A2-1,  Magnetic Particle Brake Selection Guide

<table>
<thead>
<tr>
<th>MODEL</th>
<th>PEAK TORQUE [in-lbs]</th>
<th>REQUIRED RATIO</th>
<th>WEIGHT [oz]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>@ REQUIRED POWER [W]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B16SF5</td>
<td>6.6</td>
<td>2.2</td>
<td>39.9</td>
</tr>
<tr>
<td>B18SF2</td>
<td>28.0</td>
<td>18.8</td>
<td>9.40</td>
</tr>
<tr>
<td>B20SF4</td>
<td>22.0</td>
<td>7.5</td>
<td>11.9</td>
</tr>
<tr>
<td>B21SF31</td>
<td>30.0</td>
<td>3.6</td>
<td>8.77</td>
</tr>
</tbody>
</table>

The following abbreviations have been used for units:
Figure A2-2. Input Current vs. Output Torque. Schematic Force Limited Brake, model B2OSF4
APPENDIX 3

LIST OF VENDORS

Material: KEVLAR CLOTH, style DPB-6
Supplier: STERN and STERN HUGUET TEXTILES, INC.
188 Thacher Street
P.O. Box F
Hornell, NY 14843
tel: 607-324-4485

Material: GRAPHITE CLOTH, style 4163
Supplier: TEXTILE PRODUCTS, INC.
2512 W. Woodland Drive
Anaheim, CA 92801
tel: 714-761-0401
contact: John McGrath, Sales Manager

Material: PARTICLE BRAKE, model D20SF4
Supplier: Force Limited Inc.
2217 Main Street
Santa Monica, CA 90405
head engineer: Paul Adkins
tel: 213-39 2-2021

Material: ANTI-BACKLASH SCREW ASSEMBLY, model ZBC6100
Supplier: KERK Motion Products, Inc.
P.O. Box 578
1 Kerk Drive
Hollis, N.H. 03049
contact: Ken or Keith Erikson
tel: 603-465-7227

Material: FLEXIBLE COUPLING, model CC6-44
Supplier: Winifred M. Berg Inc.
499 Ocean Avenue
East Rockaway, LI, NY 11518
tel: 516-599-5010
Material: POLYIMIDE FOAM, rohacell 71  
Supplier: CYRO Industries  
155 Tice Boulevard  
Woodcliff Lake, NJ  07675  
tel: 201-930-0100  
contact: Michael Dorf,  
Sales Development Manager

Material: EPOXY MIXTURE, EPON 815 and 828  
and VERSAMID 115  
Supplier: Allied Resin Corporation  
Weymouth Industrial Park  
Pleasant Street  
East Weymouth, MA

Material: BALL BEARINGS, model 38H, ABEC 7  
Supplier: THE BARDEN CORPORATION  
200 Park Avenue  
Danbury, Connecticut  06810  
tel: 203-744-2211

Material: BELLEVILLE WASHERS, model EL-8  
Supplier: SCHNORR-NEISE  
DISC SPRING CORPORATION  
56-02 Roosevelt Avenue  
Woodside, NY  11377  
tel: 212-426-2683

Material: NICKEL-CADMIUM BATTERIES, model 800 SCL  
Supplier: A.W. MAYER, Inc.  
34 Linnell Circle  
Billerica, MA 01821  
tel: 617-225-6600  
contact: Jacque Walsh